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Quali-Logical: A Water Quality Model for Surface Water Systems to Support Sanitation and Land-use Planning

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Abstract

A mathematical simulation model is conceptually the ideal tool to decide which pollutant loads to treat first, given limited funds, or to determine the admissible loads to a given water body. The model is indeed a tool that allows to explore the effects of hypothetical actions on water quality prior to their implementation. Unfortunately, the application of 'orthodox models', i.e. those based on mass balance and physical laws, faces difficulties so harsh to prevent their real utilisation, at least at the wide-area level, with feasible time and costs. But not everything is lost. In this paper a very simple model is developed which borrows from physics a very basic principle: 'if there is no load, water is clean', and assumes that in each given water body there exists a linear relationship between load reduction and water quality improvement (but not necessarily between load and quality in the overall system); an assumption generally acceptable from the practical point of view. The rest is borrowed from logic, this is why I named it 'quali-logical'. This model can provide answers to the questions raised above. It assigns to the measured water-quality-state a key role (contrary to orthodox models that use it basically in model calibration only), yet it does not require to comply with strict data collection protocols as imposed when modelling is the aim. It does not require to quantify pollutant loads, but just to (qualitatively) assess how the total load is partitioned amongst: load carried by the upper reach, the possible tributary, non-point sources, and point-wise sources. It does not require the knowledge of water flows. It even does not need calibration, although this can be carried out. And it does not assume that water quality compounds are conservative. Being very simple, it can be easily implemented.

KEYWORDS: *water quality; mathematical models; empirical models; simulation; water resources systems; land-use planning; water treatment.*

Introduction

When is a mathematical model needed? Synthetically, there are two main uses:

- ex-ante assessment (prediction) of the effects of possible actions: load reduction, water flow increase, change of hydraulic regime (depth, velocity,..), etc.
- investigations about the physical system to answer questions like: how is the load structured (role of exchange with aquifers,...)?, how important is dilution with respect to decay?, etc.

Since Streeter and Phelps (1925), the answer has been to develop models based on mass balance and on the knowledge of physical processes ('orthodox models'). By looking at the real world, however, it is apparent that the actual application of such models is more an exception than a rule. Why?

The key answer probably lies in the difficulties associated with calibration, and specifically with data collection campaigns. One indeed needs to: i) identify the loads, ii) identify all relevant water inputs/outputs by checking the water balance, iii) measure flow-rate and concentration (of possibly each compound) in each relevant inflow (discharge or tributary), iv) assure the significance of each water quality datum (particularly by avoiding plumes), v) organise data collection coherently with model requirements (usually by proceeding along a characteristic line and assuring steady state hydrological-hydraulic conditions to allow for velocity forecast and to avoid 'wild-discharges'), vi) guarantee the coherence of analysis from different laboratories, vii) dispose of time, energy, money and sufficient logistic capacity.

It should not be forgotten that a badly calibrated model, even if supported by a beautiful software program, will not escape the GIGO law (Garbage In, Garbage Out), that is, if fed with bad data, it will supply bad or worse answers. Moreover, the feeling will grow in the subjects responsible for water resources management that models are not reliable and hence should not be used.

In Nardini and Soncini-Sessa (2001a,b,c), these specific themes are developed in depth. The first one (a) investigates the limits of applicability of the method of characteristics; this method, together with the assumption of absence of dispersion, is indeed the milestone for the design of feasible data collection campaigns. The finding is that its applicability is much wider than previously thought. In the second (b), the possibility to calibrate a model with data already collected for routine monitoring is explored, and the conclusion reached that –at least for the Arno river (Italy) - most of them are not usable. In the third one (c), practical guidelines for the design of ad-hoc data collection campaigns are laid down and discussed through another case study.

Developing 'orthodox' models is not impossible and in many cases it is recommendable. However, what can be done in the meantime while real land-use planning and water resources management takes place? Actions need to be taken and are taken; limited funds are allocated. And too often there is a lack of rationality and transparency to support these choices, at least in Italy.

In this paper I try to answer the following question: is it possible to develop a kind of water quality mathematical model that can support the planning process, without demanding too much effort for data collection?

Conceptual basis

Water quality in a water body is a function of the total load of pollutants (external and internal), as well as of other factors that for the moment we can think of as constant. If the load is eliminated, the quality will assume the best value (in the range of practical interest). Generally, the actual load is unknown; it can only be estimated more or less indirectly and in any case with significant errors.

Notice that to carry out model calibration, it is necessary to know the load present during the campaign itself that is sometimes quite different from the 'average' load ([1]). For instance, it is too often common practice to release highly polluted water from waste-storage tanks during the week-ends, or in other moments when a monitoring check is very unlikely.

It is much easier to assess how the (unknown) total load is partitioned amongst different load typologies that for a river reach can be schematised as follows (in parenthesis, the symbol representing the fraction of total load, of that given typology, associated with the i-th reach at the initial situation) ([2]):

- *Head load,* carried by the upstream reach (if present) ($\alpha^H(i)$)
- *Affluent load*, carried by possible tributaries to the reach ($\alpha^A(i)$)
- *Point-wise load,* typically carried by urban-industrial loads that can be subject to collection and treatment ($\alpha^P(i)$)
- *Diffused load,* non-point load typically carried by run-off of agricultural fields, by exchange with the shallow aquifer, or by diffused urban-industrial settlements ($\alpha^D(i)$).

The estimation of such a partitioning (i.e. the fractions $\alpha^j(i)$) can be carried out in different manners: from an assessment and comparison of pollutants mass based on real data of quality and flow-rate, to a qualitative assessment (by sight).
Moreover, this estimation can be carried out 'off-line', that is, not necessarily within the time frame of a given water quality data collection campaign.

A similar point can be made about the possible interventions for water pollution control: it is quite hard to determine the load that can be removed with a given intervention (e.g., treatment plant, sewerage system). Loads to-be-removed are usually expressed in terms of equivalent inhabitants; this implies that, apart from the uncertainties in their estimation (what 'equivalent' really means), one never really knows the actual per-capita load, and thus the load in absolute terms. It is rather much easier to establish whether the intervention will remove 20% or 90% (or whatever) of the point-wise load, or of the distributed load.

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[1] Often models are calibrated on the base of data obtained as average of measurements taken in different campaigns. For a given model structure, the least-square parametrization so obtained does not coincide with that obtainable on the basis of the original data. This fact would not be a problem as far as the model is used to simulate average conditions. From the theoretical point of view, however, this approach is correct only if the loads (together with all other exogenous driving factors) are rigorously periodic so to generate a periodic state and thus give a precise meaning to the averaging operation. In practice, however, loads and state are too often non periodical (think of 'wild-discharges'), while measurements are sometimes affected by structural errors (e.g. plumes). As a consequence, the averaging is likely to smooth out everything and the resulting model is likely to completely loose its links with the dynamic cause-effect relationships that one was trying to capture in model equations. It basically is closer to an input-output regression, or black-box model. Quali-logical is in this sense better, because while claiming less honour, it makes the assumptions and role of different factors transparent.

[2] Discretization of water bodies introduces a different form of load due to the downstream boundary condition and to the effect of dispersion. However, this effect, as demonstrated in Nardini and Soncini-Sessa (2001), is totally negligible for most practical riverine applications.

Let us now adopt an indicator x -defined on a suitable cardinal scale of the following type- to measure water quality:

Tab.1 – Water quality indicator and its scale [dimension-less, or mass/volume].

Numerical value of the indicator (x)	*Meaning in terms of pollutant concentration*	*Name of water quality class*
$x_0 \div x_1$	absent	optimal (no load)
$x_1 \div x_2$	low	good
$x_2 \div x_3$	medium	sufficient
$x_3 \div x_4$	high	bad
$x_4 \div x_5$	very high	very bad

Notice that the meaning attributed to such an indicator can differ depending on the purpose. It can be either a surrogate of a pollutant concentration for a given compound (e.g. BOD), as in the first column, or a holistic quality judgement, as in the last column. In the first case, the rating can be objective if a quantitative relationship is specified between the indicator x and the real concentration (e.g. '3' stands for 3 times the law standard; in such a case the scale is not limited upwards). Or (second column) it may be subjective, but more flexible, if mental reference is made to something, for instance the conditions of a pretty natural river body in the area. In the second case (last column), the choice of a particular quality class can be made only after a given value-type (use or non-use) is specified for that water body. The same water can indeed be 'good' from a given point of view (e.g. irrigation) and 'bad' from another (e.g. swimming). When moving from the first to the last of these options, the indicator acquires a more holistic character, while losing objectivity.

Suppose now that water quality (or a given variable) of our water body has been measured with this indicator, that the corresponding load has been partitioned (fractions $\alpha^j(i)$), and that the load to be removed has been quantified in terms of percentage, we are ready to introduce the key model hypothesis: a relative improvement in water quality state is induced, which is equal to the relative load reduction ([3]). If for instance the point-wise load is 40% of the total, when it is removed at a 100% level, an improvement of water quality (current WQ) is induced which is equal to 40% of the distance between current WQ and best WQ state. If only 50% of the same load-type is abated, the improvement ranges to 20% only. Vice-versa, if it is increased by 100%, WQ will worsen by 40% of the distance between current WQ and best WQ state (unless it escapes the scale limits).

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[3] This hypothesis of linearity, theoretically speaking, is not correct when the underlying dynamics is non-linear (eg. Michaelis-Menten's saturation effects). From the practical point of view, however, this hypothesis is generally acceptable. An accurate investigation on the validity range would of course be recommendable.

More precisely, in case of a treatment, WQ is moved from the initial state x_0 to a new state x_1 such to fulfil the following proportion: the improvement (x0-x1) relates to the total interval of potential improvement (x0-x*), as the abated load (L0 –L1) relates to the total initial load (L0) on the reach. Accordingly, we can write the following relationship (it is assumed that the water body is not 'pure' at the initial state):

$$(x_0-x_1)/\,(x_0-x^*) = (L_0 - L_1)/\,L_0 \qquad \text{(Eq.1a)}$$

where:

L_0 , L_1 : initial and post-intervention (unknown) total loads [mass/time]

x^* : best value of the WQ indicator [dimension-less, or mass/volume]

Eq.1 can be solved for the unknown x_1 thus obtaining:

$$x_1 = x_0 - \lambda\,(x_0 - x^*) \qquad \text{(Eq.1b)}$$

where λ is the known reduction ratio:

$$\lambda = (L_0 - L_1)/\,L_0 \qquad \text{(Eq.1c)}$$

In graphical terms the situation can be represented as follows: one moves (figure 1a) from initial state x_0 to the new state x_1 along the straight-line shown; that is, from the situation (0) to the situation (1). The peculiar thing (figure 1b) is that the straight-line cannot be drawn because the total initial load L_0 is not known, neither is the post-intervention L_1 , but just the ratio λ between removed load (L_0-L_1) and L_0 ; nevertheless, it is possible to determine x_1 . In fact, this is possible for any situation of initial load and load reduction that will produce the same reduction ratio λ (see as an example the dotted line): virtue of similar triangles.

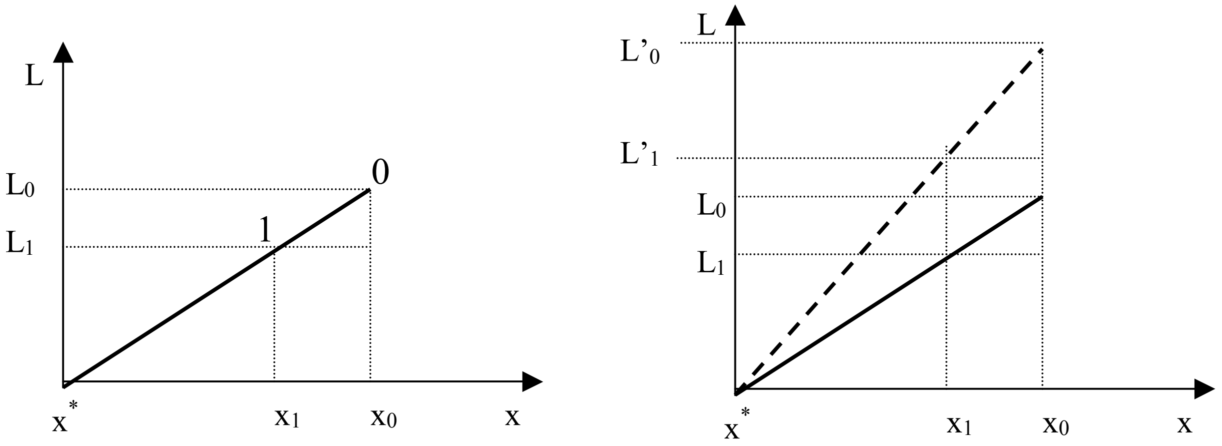

Fig.1 – (a) Hypothesis of proportionality between load reduction and water quality improvement; (b) similar situation of initial load and load-reduction produce the same quality x_1.

Once an intervention of load reduction is implemented, water quality will change in the reach directly affected. It is interesting to note, however, that if the Head load fraction of the following reach is not null, its quality will also change, and so forth along the whole downstream network. Furthermore, the fractions of load partitioning will also change in all such reaches. The model represents then the propagation of the improvement effect along the river network; this effect is progressively reduced if the Head-load fractions are less than unity as usually is.

It must be pointed out that the model is not based on a mass-balance, and hence does not comply with the mass conservation principle. Furthermore, the model is static and cannot cope with the real mass transport dynamics. Water quality has the meaning of steady-state value under constant loads.

However, it is not 'conservative', that is it admits and considers the presence of auto-purification decay processes, because it is based on the initial water quality as measured on the real system: that is indeed a situation in which auto-purification is already intrinsically 'considered' both in the WQ state value itself (a reach may be 'clean' even when there is a significant load upstream), and in the load partitioning (Head fraction may be lower than that corresponding to a lack of auto-purification upstream).

Schematizsation of a real system

Consider the water system shown in figure 2 (the portion in the circle is considered later in further detail):

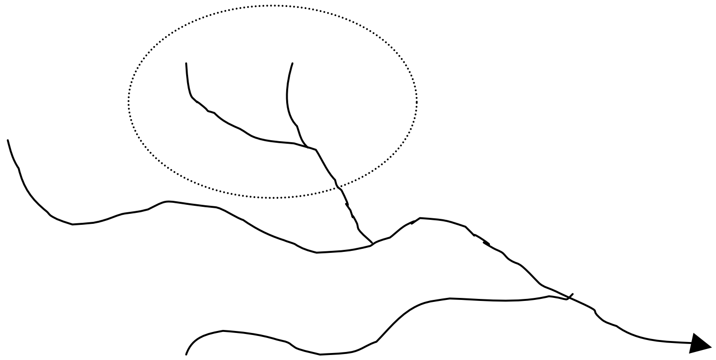

Fig. 2 – Example of a water system.

In general, we can schematise it (figure 3) as an oriented collection of reaches. Each reach may be connected to an upstream and/or downstream reach, may receive a tributary, and a point-wise and diffused load.

The portion of the network identified in the circle (Fig.2 above) gives then rise for instance to the following scheme (the number of reaches is arbitrary and so is their spatial position):

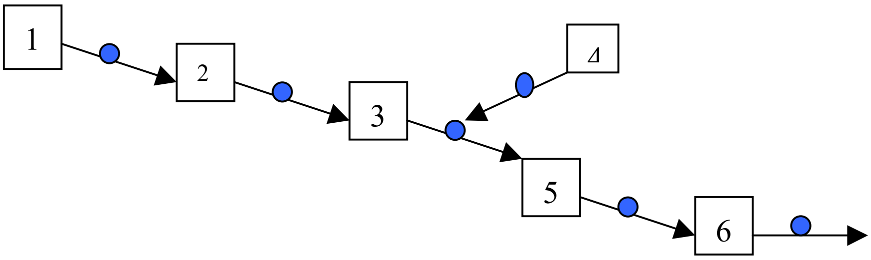

Fig.3 – Example of schematization of a water system.

By proceeding in this way it is possible to represent even very articulated networks. The algorithm presented later can be applied also to non-tree networks given that they can be 'linearised', that is it must be possible to identify a *sweeping sequence* that allows one to determine the (updated) water quality in all the reaches that have an influence on any given reach.
The same kind of schematization can be applied to water bodies characterised by a significant retention time (lakes, reservoirs).

The model

In this section, the model for a single reach (or water body) is formalised. For sake of simplicity, but without loss of generality, I assume from now on that only the point-wise load can be subject to treatment (i.e. reduction); everything however applies to the diffused load as well.
We first need to specify the information conveyed by the following type of table (Tab.2):

Tab.2 – Information needed to characterise the ith reach at the initial state (the index i is omitted for simplicity)

Identifier of reach	Sweeping order	quality (x)	Head load fraction (α^H)	Affluent load fraction (α^A)	Point-wise fraction (α^P)	Diffused load fraction (α^D)	Degree of load removal (η)
1							
2							

Note: the Head load fraction for the first reach must be null; fractions α^s (s=H,A,P,D) must sum to unity or be all null.

It can be noted that the load carried by the previous reach (upstream or tributary) is given by the flow-rate times the corresponding quality (concentration of given compound). Assuming (by hypothesis discussed later) that the flow-rate does not change, the new load will be equal to the initial one times the ratio between updated and initial quality of previous reach. The 'dynamics' (4) of water quality, in agreement with the reasoning already presented, is then ex-

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[4] The term refers to the successive application of packages of intervention and not to the temporal dimension of the pollution-autopurification phenomena that, as said, is considered statically (at the equilibrium).

pressed by the following equation (where sub-index '1' stands for 'updated') and graphically depicted in figure 4:

$$\begin{aligned} x_1(i) = x(i) - (x(i) - x^*)\,[\,&\delta(i,i-1)\,\alpha^H(i)\,(1-(x_1(i-1)-x^*)/(x(i-1)-x^*)) + \\ &+ \delta(i,j(i))\,\alpha^A(i)\,(1-(x_1(j(i))-x^*)/(x(j(i))-x^*)) + \alpha^P(i)\,\eta(i)\,] \end{aligned} \qquad \text{(Eq.2a)}$$

where:

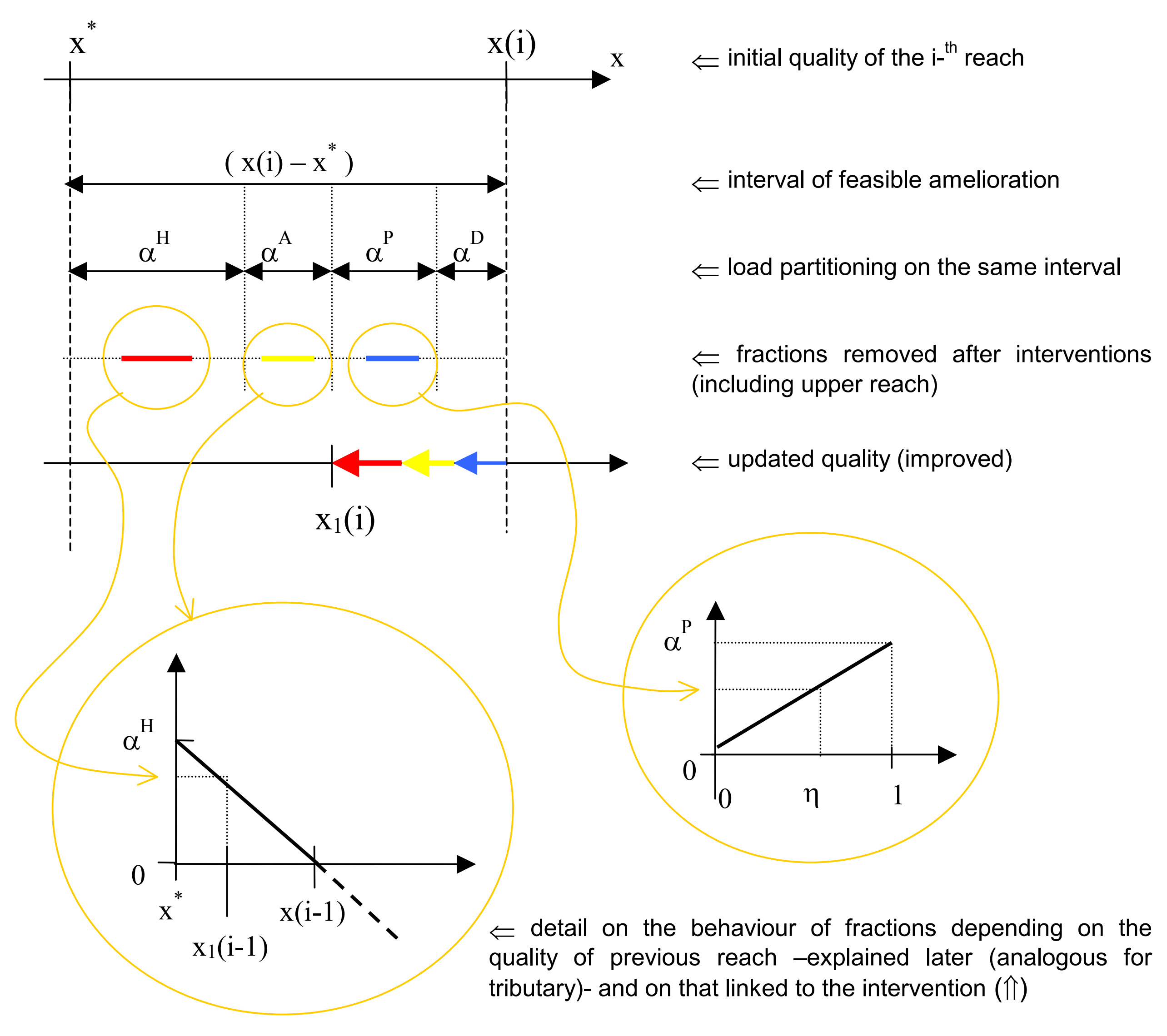
$j(i)$: identifier of affluent reach (if any) connected to reach i

$\delta(i,j)$: operator that nullifies the term that it multiplies if current water quality of the j-th reach ($x(i-1)$ or $x(j(i))$ depending on the case) is already the best one possible and therefore the denominator would get the zero value, while no effect would derive on the current reach. It assumes the value 1 otherwise.

$\eta(i)$: degree of removal of the (point-wise) load affecting reach i. It is positive for removal interventions (between 0: no removal, and 1: total removal) and negative for a load increase (the value –1 means doubling the load)

Notice that the formulation assumes to have determined first the quality of the upstream reaches, by sequentially applying the same equation according to the sweeping sequence predefined.

The concepts already explained verbally, are shown graphically in figure 4 where it is assumed that a package of interventions have been applied which affected the reach (i) considered as well as others possibly upstream (sub-index ‘1’ stands for ‘updated’):



⇐ initial quality of the i-th reach

⇐ interval of feasible amelioration

⇐ load partitioning on the same interval

⇐ fractions removed after interventions (including upper reach)

⇐ updated quality (improved)

⇐ detail on the behaviour of fractions depending on the quality of previous reach –explained later (analogous for tributary)- and on that linked to the intervention (⇑)

Fig. 4 – From conceptualization to the model (for simplicity the reach identifier is omitted where non essential; the ordinate of graphs in circles represent the corresponding horizontal segments)

It is easy to verify that if the quality of the upstream and tributary reaches keeps constant (i.e. is not affected by the upstream interventions), the corresponding term in equation 2a is null, when the (Point-wise) is totally removed ($\eta(i)=1$), the current water quality $x(i)$ is improved exactly of the quantity $\alpha^P(i)\ (x(i) - x^*)$, i.e. of a portion of the feasible improvement interval equal to the fraction of point-wise load. With similar reasoning, it is easy to understand the other cases. In the most drastic case, in which the quality of previous and tributary reaches is improved to the maximum extent, and the (point-wise) load totally removed, the best quality for the current reach is obtained if and only if the sum of the three fractions $\alpha^s(i)$ ($s=$ H,A,P) is equal to unity. The improvement will be just partial if there exists a diffused (non treated) load as well.

In case the quality indicator is given the meaning of holistic quality (third column in table 1), which is therefore limited superiorly, by the worst value $\underline{x}$, it is necessary to introduce an operator that 'cuts' the excess with respect to such a limit to deal with the cases of load increase. Equation 2a takes then the form:

$$x_1(i) = \min(\underline{x};\ \text{Eq.2a}) \qquad \text{(Eq.2b)}$$

The model so formalised is valid for all interventions of load reduction. Attention must be paid, instead, for interventions of load increase. In these latter cases, it is necessary that all Head-load fractions ($\alpha^H(i)$) be non-null, exception made for the initial reaches. In fact, if for a generic i-th reach it occurs that $\alpha^H(i)=0$, this means that the quality of its upstream reach (i-1) is at its best (no load, and hence $x(i-1)=x^*$); then, if the quality of this (i-1)-th reach worsens (load increase), equation 2a will keep 'seeing' a null Head-load fraction for reach i because the same null fraction $\alpha^H(i)$ is multiplied by the amplifying factor (a function of the ratio between concentrations). The only manner to get out from this impasse, is to specify as a new exogenous input (i.e. described outside equation 2) also the updated fraction of the Head-load ($\alpha^H{}_1(i)$), as well as the others for coherence. This fraction cannot be determined indeed within the present schematization because no flow-rate is considered and, therefore, a given increment Δ of the indicator x may correspond to a very small or a very huge load increment with respect to total load. A similar point holds for the Affluent.

It is important to note, however, that this difficulty would occur very seldom in a real case because real water bodies of interest are practically never in optimal water quality conditions (therefore no fraction $\alpha^H(i)$ or $\alpha^A(i)$ is null), and it is very unlikely that amelioration interventions succeed in abating completely the load in some reach.
In conclusion then this limitation is more theoretical than practical. Moreover, it exists only for the case of load increase.

Algorithm for a water system subject to a package of interventions

While applying a package (set) of interventions one needs to proceed from upstream reaches downwards according to the pre-defined sweeping sequence (whose existence is assured, by definition, for any linear network). It is important not to confuse the term ‘sweeping sequence’ (logical order) with the term ‘previous’ (or upstream): this latter refers to a topological criterion.

The algorithm is then as follows:
Step 1) start from the first reach (i=1) in the network (which is also the first one according to the sweeping sequence)
Step 2) update water quality of that reach with equation 2 (no Head-load or Affluent-load fractions are present)
Step 3) if the reach is not the last in the network consider the next reach according to the sweeping sequence and repeat from Step 2, otherwise exit the procedure.

Example

Consider the simple network shown in figure 3 for which suppose we have the following initial situation:

Tab.3 – Information characterising the example network at the initial state

Identifier of reach	Sweeping order	quality (x)	Head load fraction (α^H)	Affluent load fraction (α^A)	Point-wise fraction (α^P)	Diffused load fraction (α^D)
1	1st	4	0	0	1	0
2	2nd	4	0.8	0	0	0.2
4	3rd	4	0	0	0.5	0.5
3	4th	4	0.2	0.1	0.5	0.2
5	5th	4	0.6	0	0	0.4
6	6th	4	0.3	0	0.6	0.1

This characterisation says that all reaches are initially at very bad quality. Reaches 2 and 5 do not receive load that can be treated and it is then useless to spend money in some interventions specific to them. As in figure 2, the only reach which receives a tributary is reach 3. Furthermore, the first reach is anomalous because the whole load is Point-wise and therefore, if subject to a complete treatment its quality will improve to the optimal level. Hence, it may provoke the nullification of the Head-load fractions of downstream reaches (see following example) with subsequent error in case of load-increase interventions.

By applying the model (implemented on an Excel sheet), three alternative treatment plans were evaluated; the corresponding new situations are summarized in the following table ([5]):

Tab.4 – Information characterising the example network after Plan A is implemented: total treatment (100%) of Point-wise load in reaches 1 and 3.

Identifier of reach	Sweeping order	Degree of load removal (η)	quality (x)	Head load fraction (α^H)	Affluent load fraction (α^A)	Point-wise fraction (α^P)	Diffused load fraction (α^D)
1	1st	1	0	0	0	0	0
2	2nd	0	0.8	0	0	0	1
4	3rd	0	4	0	0	0.5	0.5
3	4th	1	1.4	0.12	0.29	0	0.59
5	5th	0	2.4	0.34	0	0	0.66
6	6th	0	3.5	0.21	0	0.68	0.11

In this case, as anticipated, the quality of the first reach is brought to the best possible value (0) and the corresponding load fractions all nullified. This improvement significantly affects also the downstream reach (2) which gets a quality value of 0.8, does not receive any longer Head-load (null fraction), but just Diffused (non treatable) load. The Affluent reach remains as it was, since it is not subject to any direct or indirect load reduction. Reach 3 experiences the effect of the direct load reduction as well as the indirect amelioration of the upstream reach, thus significantly improving its quality and moving ($\alpha^D{}_1(3)$) the majority of the load on the non-treatable component. Also the last two reaches are positively affected by the upper stream intervention. By acting on only two reaches, we got a considerable improvement in almost the whole network (sum of improvements equal to 11.9 units).

Tab.5 – Information characterising the example network after Plan B is implemented: total treatement (100%) of reaches 4 and 6.

Identifier of reach	Sweeping order	Degree of load removal (η)	quality (x)	Head load fraction (α^H)	Affluent load fraction (α^A)	Point-wise fraction (α^P)	Diffused load fraction (α^D)
1	1st	0	4	0	0	1	0
2	2nd	0	4	0.8	0	0	0.2
4	3rd	1	2	0	0	0	1
3	4th	0	3.8	0.21	0.05	0.53	0.21
5	5th	0	3.9	0.59	0	0	0.41
6	6th	1	1.6	0.74	0	0	0.26

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[5] A specific dynamic equation can be written which governs the dynamics of the load fractions. It is not reported here for reasons of space.

In this case the global improvement is dramatically less (only 4.8 units). If the 100% interventions implied the same cost, the result obtained would convey a very clear indication. Of course, an economic analysis should accompany this 'physical' analysis; or even better, the economic-environmental values at stake are to be made explicit as the same WQ improvement may be worth more for a reach with a higher inner value.

Tab.6 – Information characterising the example network after Plan C is implemented: 50% treatment of reach 1 and increase (doubling) of load in reach 3.

Identifier of reach	Sweeping order	Degree of load removal (η)	quality (x)	Head load fraction (α^H)	Affluent load fraction (α^A)	Point-wise fraction (α^P)	Diffused load fraction (α^D)
1	1st	0.5	2	0	0	1	0
2	2nd	0	2.4	0.67	0	0	0.33
4	3rd	0	4	0	0	0.5	0.5
3	4th	-1	5.7	0.08	0.07	0.70	0.14
5	5th	0	5.0	0.68	0	0	0.32
6	6th	0	4.3	0.35	0	0.56	0.09

In this case it is immediate to notice a significant improvement in reach 1 and 2, while in reach 3 the fraction of Point-wise load is significantly increased and so is its pollution degree which propagates downstream, although with progressively decreasing effect.

The behaviour of the river network subject to the three alternative treatment Plans is shown in figure 5 (notice that reach 4 is the affluent and not a discontinuity of the main water course):

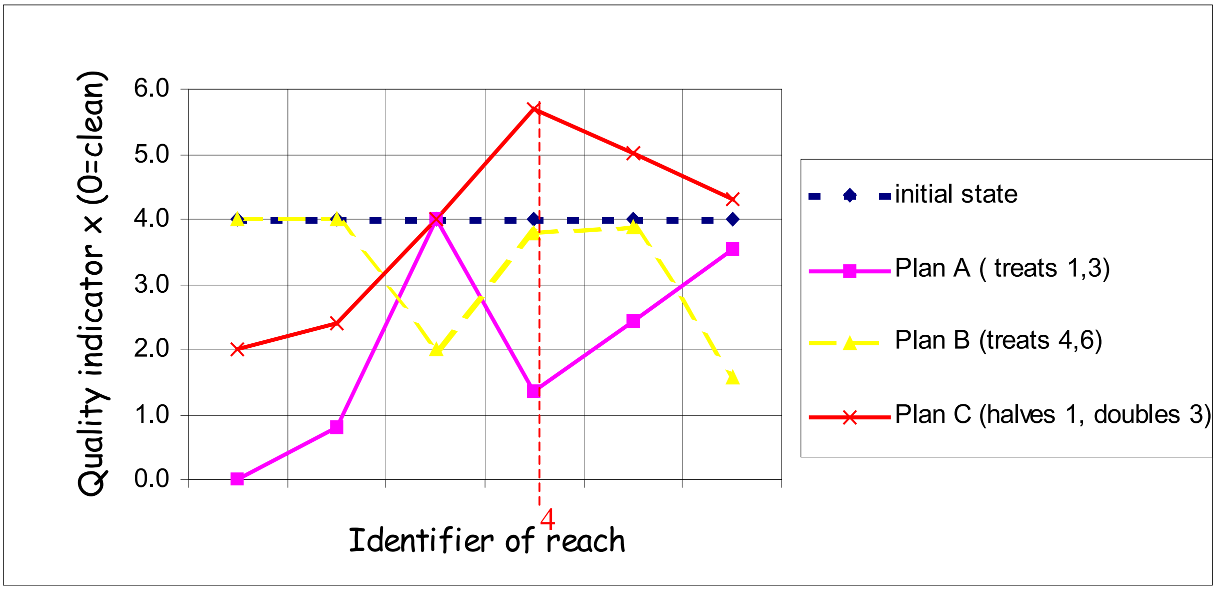

Fig. 5 - Water quality state in the example network

Validation

I could not carry out a true validation on real data obtained on a river before and after some interventions. But another indirect kind of validation can still be meaningful which is described now. The idea is to compare the answer of 'quali-logical' with that obtained from a reference 'orthodox' model assumed to be exact. For simplicity, I used a very simple first order decay, no-dispersion, mass balance model, like a typical Streeter-Phelps BOD model (implemented again on an Excell spread-sheet). Of course, the initial load fractions of quali-logical are those correct, i.e. computed on the base of the known loads and state described by the orthodox model. In fact, the validation discussed here is intended to explore possible mistakes committed by the model itself, not by the operator who feeds it (this too, however, deserves an ad hoc investigation).

In figure 6 results can be easily appreciated:

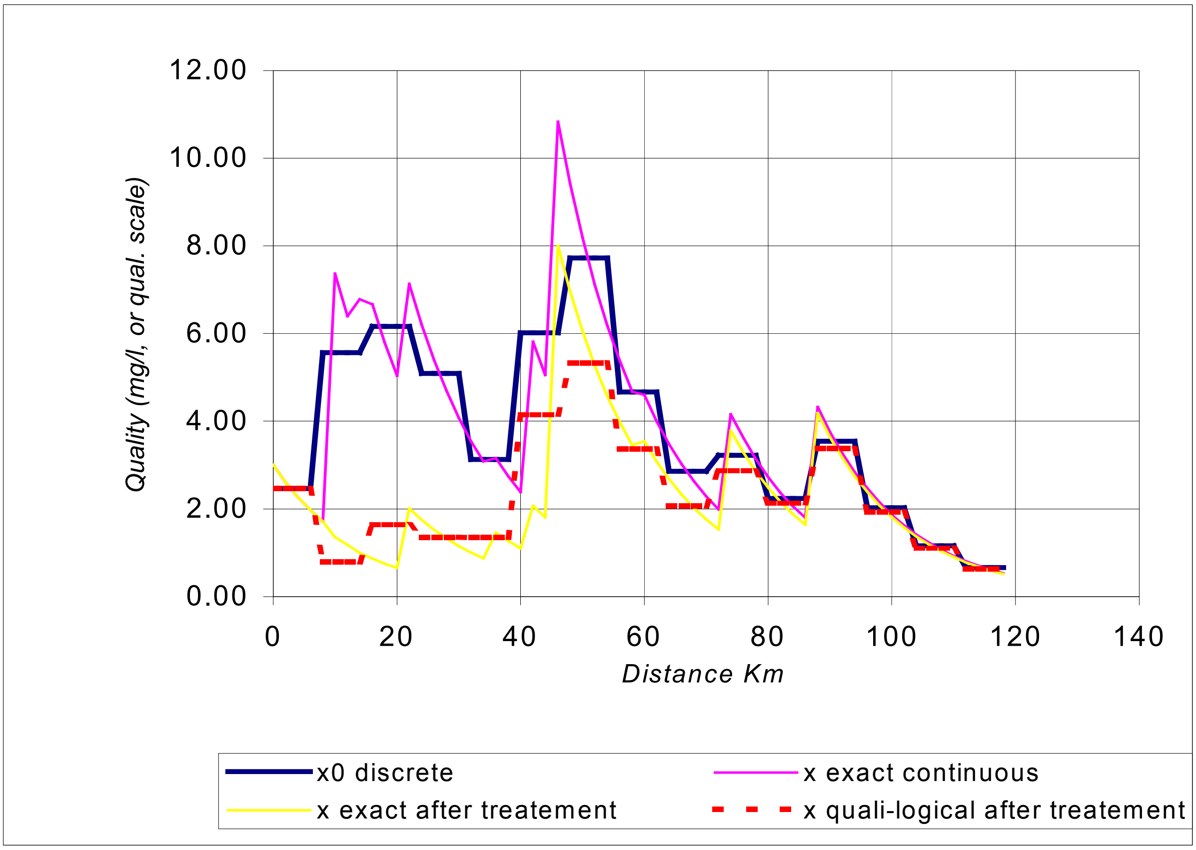

Fig. 6 – Validation of Quali-logical with a first order decay no-dispersion, mass balance model

The highest continuous curve (violet) reproduces the 'real' quality (initial pollutant concentration) along the river subject to a series of (point-wise) loads. They can be easily located because they provoke a sudden increase of the concentration (the second and the third are however so close to look visually as one). It can be noted that downstream of Km 86 approx. there are no longer any loads. The curve is computed with the orthodox model. The (black) bold, piece-wise line, is the discretization of the previous one with reaches of 2 Km length (the graphic resolution shows non-existant small 'ramps', but it is always a step-wise increase or decrease). This curve has been derived from the previous one just through a simple discretization procedure (average of concentrations in the reach); there is no other underlying 'model'. The discretization, furthermore, is certainly not the 'best' one, but just one that fits the purpose of getting an initial classification of the water bodies in terms of quality.
It can be noted that although the discretized curve (by construction) follows faithfully the original curve, it strongly under-estimates peaks. This is an unavoidable problem accompanying discretization in general. The important point is that this curve constitutes the initial state of Quali-logical.
The (yellow) continuous curve (exactly coinciding with the original one until approx. Km 12, and again after Km 85 approx.) represents the answer of the system when subject to four treatment interventions (all acting on the point-wise load): the first three remove 100% of first three loads (assumed to be all treatable); the fourth intervention only removes 50% of the fourth load (approx. Km 20). Also this curve is supplied by the orthodox model.
Finally, we have quali-logical with a (red) dotted, bold piece-wise line.

It is apparent that this curve reproduces well enough the general behaviour of the orthodox updated one (yellow). The error committed is nothing else than a consequence of the discretization error introduced from the beginning and independent on quali-logical itself.

It must be pointed out that this exercise cannot be considered exhaustive, as it depends on the particular system geometry, loads magnitude, hydrological-hydraulic conditions (velocity and flow-rates), decay coefficient, degree of load removal, and so on. Nevertheless, it can be concluded that 'quali-logical' behaves quite well because it is unlikely that modifications of these factors will change such a conclusion. Perhaps, some surprise may pop up when a non-linear dynamics (e.g. Michaelis-Menten's) is assumed for the orthodox model. But this is an issue for another investigation.

Limitations

- The model is static, describes the equilibrium under steady loads. It cannot then describe transient processes. However, for planning purposes what is of major concern, is exactly the steady state.
- The algorithm is applicable only to a 'linear' network, in the sense specified before. Natural networks are almost always linear; artificial ones often.
- It requires to discretise the water network in reaches (this may apply also to lakes and reservoirs); but this fits quite well the common practice of quality classification based on 'homogeneous' reaches.
- In case also interventions of load increase are considered, it is necessary to assure that no Head-load fraction (except the first ones) gets a null value. However, this limitation has scarce importance in practical problems.
- It does not guarantee the fulfilment of the mass balance of the compounds. However, if what really counts is water quality prediction, this weakness is not that important.
- The model does not allow to consider the effect of hydrological-hydraulic variations (dilution, travel times, solar radiation linked to water depth,...), nor that of the thermal regime or of bio-chemical composition of loads. This, however, does not mean that these aspects are ignored: they are implicitly considered through the initial state (measured on the real system). Of course, as they are not described explicitly, the model cannot take into account what happens if they are modified. This is a major limitation.
- It does not consider the interaction amongst compounds. However, if the dynamics of a compound is linked to another one (e.g. nitrates to ammonia), there still is a cause-effect relationship between the load and each one of such final or intermediate compounds. And this relationship still follows the same simple law: 'absence of load implies no pollution'. Another difficulty however follows: when a given compound (e.g. DO) is linked to more than only one load type (e.g. carbonaceous BOD and nitrogenous BOD) such loads might not be partitioned in the same fashion (different fractions α^s). To overcome this problem, one should introduce a set of such fractions for each load type.

Conclusions

The model proposed here is subject to a series of limitations that certainly reduce the field of potential applicability. Nevertheless, it can supply significant reliable information at low cost that may be of high value for large scale land-use planning or for preliminary assessments. It is trues that from the physical and bio-chemical point of view the model is 'neanderthalian'. However, it is based on an 'iron logic', very transparent that simply formalises in a structured and quantitative way what is the usual common sense of sectoral technicians. More than a true simulation model, it is a support to logical reasoning. But it is much more than a simple intuition because it is based on real information about the physical system (particularly the initial state), structured, and formalized within a mathematical model.

It is a tool well suited to constitute the core of a Decision Support System (DSS) aimed at the preparation of sanitation or land-use plans, being simple, economic and reliable enough. Actually, a similar version including a dependency on the flow-rate has been implemented in the water quality model within the prototype DSS developed by the Strategic Research Unit of the National Water Research Center (Ministry of Irrigation, Cairo, Egypt) through a bilateral co-operation project of the Italian Ministry of Foreign Affairs and the Egyptian Environmental Affairs Agency (Nardini and Fahmy, 2002).

It is spontaneous to wonder 'why didn't we think about it before?'. However, I could not find similar approaches in the literature. I mentioned in the references basically only works of mine because the difficulties associated with the development of orthodox models are discussed there in depth, and a rich bibliography presented.

Quite probably, some of the limitations of quali-logical may be removed, e.g. by introducing some kind of dependency on the flow-rate. To this aim it may not be difficult to take into account the dilution effect. However, it would be very hard to include the effects that variations of the flow-rate induce on the decay process; in particular because of changes in the travel time. This requires further research, but there may still be many practical planning exercises where the flow-rate modifications do not play a central role so that quali-logical may still give a significant help.

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