Morphological modeling of river perturbations due to hydroelectric structures at watershed scale

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ABSTRACT: Advanced numerical models are currently available to predict the morphological impacts of several types of perturbations in rivers, but in general they are not efficient to do assessments at the watershed scale in fluvial systems with complex hydraulic structures. Our objective is to create a tool that allows a semi-quantitative prediction of morphological responses of rivers to the building and operation of complex systems of hydraulic structures at the watershed scale. This model is based on the disturbances due to alterations of the hydrological flow regime and sediment supply and it determines a morphological response. The output model is a combination between the alteration degrees of the control factors and the expert knowledge, in qualitative terms. The model has been applied to the Isère watershed and it was able to predict the morphological response of the river in the past in reaction to hydropower equipment.

Keywords: Trajectory of morphological river responses, impact of hydroelectricity on rivers, conceptual model.

1 INTRODUCTION

1.1 *Context and issues*

Rivers have been modified by human activities in Europe for centuries. Yet, more significant perturbations have appeared since the advent of the industrial era, along with the potential for deep modifications of the river bed, sediment sources, or of the capacity of the river to transport its material and to carve its bed. In Piedmont rivers, where the gravel bed transport is particularly active, such perturbations have strong effects on the river morphology. As a consequence the ability of the river to convey high flows may lessen, threatening human activities along the river and changing its ecological properties. Examples of such anthropogenic perturbations in alpine valleys include the embankment of formerly braided rivers, the extensive gravel mining that took place in the second part of the 20th century, and the modifications of runoff or slope erosion at large scales.

The construction of important hydropower systems with large reservoirs and complex water transfers along large distances or to another basin is one of the strongest pressures on the hydrological regimes and on the sediment continuity governing river morphology (Grant, 2010). Alterations from a stable or pseudo-stable situation may happen when new equipment is built, after dam removals, or when operating rules are changed.

There is a great amount of literature about the impact of the hydropower equipment and in particular about the impact of large dams on river morphology. This field of investigations still has today an interest for both technicians and scientists (e.g., Graf, 2006; Schmidt & Wilcock, 2008; Baker et al., 2010, Csiki & Rhoads, 2011; Draut et al, 2011).

Our contribution to these efforts is a reflexion at the basin scale, with the objective of developing a model. This model is integrated into a tool devoted to the evaluation of ecological impacts of hydropower equipment, with a specific application to a large basin heavily equipped with hydropower facilities, influencing the morphological characteristics of the river at the basin scale (SHARE, 2010).

1.2 *The numerical and conceptual models for river responses*

Several tools have been developed during the last decade for numerical modeling of river beds. They are founded on a physical description of the major driving processes, taking into account different levels of river complexity (steady or unsteady flow, one or two dimensions, total load or bed load only, more or less details of sediment size distribution, with the inclusion or not of sorting processes of the river bed). Some of these models were developed with the aim of scientific investigation (e.g. MHYSER 1.0, Mahdi, 2009) and others were developed for solving engineering questions (e.g. Mike 21C, DHI 2003, Sedicoup, Belleudy, 2000).

The deterministic models are relevant when a detailed description of the morphological behavior is needed in terms of processes, time, and space. For a reliable result, they need precise and detailed input data for the system description and the calibration of the parameters.

These models are not suited for large scales, when an overall quantitative prospective assessment of the river behavior is needed. A detailed quantification of the morphological changes of the river bed is both useless and unreachable, even if considerable data is available.

The conceptual models have been, and continue to be, useful tools to predict complex river responses (from Schumm, 1977 to Dust & Wohl, 2012). Such models are better suited than deterministic models in the context of decision support systems, with the practical aim of improving river basin management plans, environmental management programs, or for assessing the environmental impact of projects. In such contexts, impacts must often be evaluated for the whole river system, instead of one or a few river reaches.

1.3 *Objectives*

This paper aims at describing the principles of a model for semi-quantitative predictions of morphological changes occurring in alluvial rivers, as a consequence of the modification of the main control factors of their morphological equilibrium. Those control factors are on the one hand the hydrological regime, and on the other hand the availability of solid material. This conceptual model is based on a set of elementary expert models and must be able to give reliable evaluations of the changes of the river morphology, even in the case of data scarcity. This evaluation must be quantified in terms of characteristic parameters, with the objective of evaluating the morphological impacts of the alteration of the control factors in a suitable way for the assessment of ecological consequences and risk issues.

The model described in this work can potentially be used for the prediction of the morphological evolution of alluvial rivers in response to any alteration (land use or climate changes, construction or removal of large hydraulic structures, etc.). The time scale considered here is the time scale used in engineering issues. It covers years and decades, but not centuries or millennia.

A first validation of the principles of this model is presented with the example of the Isère watershed, a Piedmont catchment with a large variety of river types, and under the influence of an important system of hydropower equipment which was developed during the 20th century. The maturity of this equipment allows for the observation of its morphological impact, and subsequently for some validation of the model.

2 MATERIALS AND METHODS

At historical time scales, out of the influence of recent perturbations, the river is in a dynamic equilibrium, which can be conceptualised as an agreement between morphological driving conditions and the characteristics of the channel (slope, width, grain size distribution, etc.). This conception of "channel stability" has been synthetized by Rosgen (2001). The control factors are of three types (i) upstream boundary conditions, (ii) intermediate conditions, especially the lateral sediment load and (iii) downstream base level control (Morisawa & Vemuri, 1975; Montgomery & Buffington, 1998; Buffington et al., 2003; Piégay & Schumm, 2003).

Any perturbation within the watershed can be evaluated as a deviation from a reference, which consists of the initial conditions, if not necessarily the pristine state of the river. In the case of hydropower equipment, the control factors of type (ii) and (iii) have no influence, thus we shall only consider the alterations following from the upstream boundary conditions, that is type (i).

Those perturbations, if they are maintained, result in an alteration of the river equilibrium. It evolves into another equilibrium state corresponding to the new conditions. The perturbations propagate downstream, but in a limited fashion. This is explained first by the river bed reaction immediately downstream of the location of the initial perturbation, and second by lateral water and sediment inputs mitigating the perturbation.

At first, the model is segmented: the watershed and the different water bodies are represented as a series of homogenous reaches with similar sensitivity, according Schumm's terminology (1991). Their morphology is controlled by two factors, namely water discharge and sediment supply. Then, the spatial connection from an upstream reach to a downstream reach, and the downstream propagation of perturbations, is taken into account using a GIS software to manage spatial information. The upstream conditions for one reach depend on the conditions of the upstream reach. Thus, the morphological changes are assessed for each reach.

2.1 *Typology of homogeneous river reaches and hydroelectric structures*

In regard to fluvial processes, there are different types of water bodies in the watershed. They result from dynamic morphological processes, which are a consequence of the control factors, and are linked to the physical characteristics of the water bodies. The river network is made of a variety of river reaches with specific morphological responses to a perturbation of the control factors.

The watershed and river network are segmented into morphologically homogeneous reaches, as determined by their slope, bank conditions, and topology, taking into account the tributaries and the hydropower equipment.

This equipment has been classified according to the way it alters water discharge and sediment continuity. Alteration of discharge may consist of water withdrawal, water release, or alteration of the flow regime at different time scales (from annual management in large reservoirs to daily hydropeaking). Generally speaking, a water withdrawal limits the sediment transport capacity of the river. As a consequence, the river adapts in order to restore its capacity to convey downstream the solid material received from upstream and from the intermediary watershed, for example by narrowing its cross-section. A water release at the outlet of a hydropower plant generally increases the transport capacity of the river and is responsible for scouring of the river bed. In rare cases, hydropeaking is responsible for an increase of the sediment transport capacity. Yet in general a change of the flow regime consists of a regulation of the natural variability of discharges, and thus of a reduction of the annual transport capacity of the river. Regarding the impacts of hydraulic structures on sediment continuity, one must distinguish between static dams, which block all sediment inputs, and mobile dams, where sediment continuity is partly restored during floods and artificial flushing operations.

All considered reaches are different from eachother either by their physical characteristics or by an intersection with a natural (tributary) or artificial (hydropower equipment) modification of water and sediment supply.

2.2 *Responses of river reaches and effects at the watershed scale*

As explained by Thorne (1997), the morphological characteristics of rivers (planform, cross sections, grain size distribution, and bed slope) are the result of erosion, transport, and deposition of sediments, operating within the constraints imposed by the watershed characteristics. The river channels are constantly adjusting and evolving in response to the variability of water and solid discharges. As Werritty wrote (1997), “*in some cases the change is accommodated by the river by its inherent variability*”. The adjustment to a disturbance of the control factors is realized through variable responses, which are not constrained in the river system. It may be for example bed elevation, grain size distribution, or the width of the river. These responses may significantly change the river style (Piégay & Schumm, 2003), so that “*at its most extreme, this process has attracted the term ‘river metamorphosis’ since the morphology of the channel is completely changed*” (Werritty 1997). Figure 1 shows two extreme types of responses to an initial perturbation, from a small adjustment (C’) to a change of river type (C).

At the time scale considered by our model (several decades), the alterations of the hydrological regime are translated into a change of the flow-duration curve and of the return period of characteristic morphogenic discharges. We define a parameter FQ that describes this alteration of the hydrological regime. In a symmetrical way, we define a parameter AS that evaluates the alterations of sediment supply from its original estimated value, with the assumption of an unperturbed state (or of an equilibrium obtained after an ancient perturbation). The alteration of the control factors is then defined by the alteration vector whose components are FQ and AS. It is assumed that the river is initially in a state corresponding to a dynamical equilibrium, and it is acknowledged that the variables FQ and AS represent an extreme simplification of the actual perturbations on the control factors. Those perturbations force the river system to a different dynamic morphologic equilibrium. The transition is realized at the occasion of a series of morphogenic events and becomes perennial if the perturbation of the driving conditions is maintained. The perturbation of the control factors is propagated downstream with a time delay and a certain damping as a result of the river response and of water and sediment inputs from the intermediary watershed and from the tributaries.

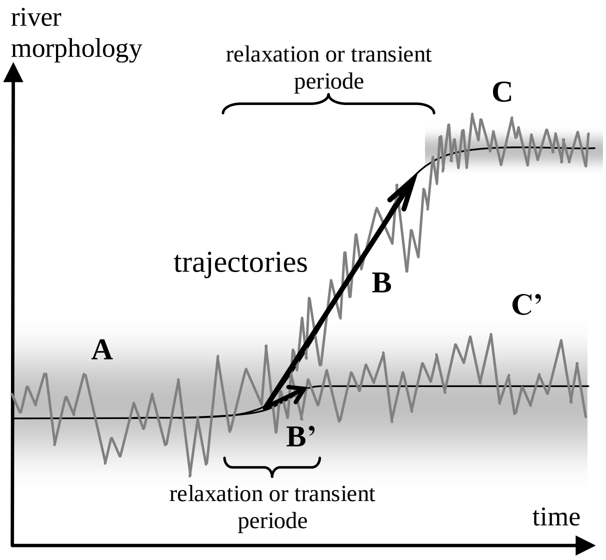

Figure 1. Schematization of the trajectories from state A to state C or C’ in response to two permanent disturbances of the control factors with different magnitudes (adapted from Werritty, 1997 and Petts & Gurnell, 2005). The A, C and C’ are in a dynamic equilibrium state. The B’ trajectory leads to river morphological characteristics close to the initial conditions; the changes are only an *accommodation*. The B trajectory is stronger and the magnitude of the associated changes is higher; it may even result in a *river metamorphosis*.

Basically, the transformation of the river as a response to an alteration of the control factors affects the geometrical and textural characteristics of the river bed, which are described through the so-called response variables (Schumm, 1977; Werritty, 1997; Malavoi & Bravard, 2010). The model considers the following response variables: bed elevation (aggradation/degradation), bed slope (s), width (w), depth (d), cross-sectional area (C), width to depth radio (w/d), mean particle size (d50), sinuosity (S), terrace formation (T), and armouring of the bed (ar).

An expert-based model describes the transformation of each of the individual reaches as a function of the alteration vector and of the actual characteristics of the river reach. This is illustrated on Figure 2 where the orientation of the vector defines a trend, and its modulus defines the amplitude of the transformation possibility leading to changes of the morphological style of the river if a threshold is reached. The basic principles of the model were defined from the literature and from expert knowledge, and expressed in the form of a cause-to-effect function. Each effect is specific to a direction of the alteration vector and to the characteristics of the river reach. As far as possible, and in spite of the continuous process of schematization of this modelling approach, this elementary model tries to consider all the processes and feedbacks in the river system (e.g. the role played by fine material and/or vegetation in the alteration of the river bed).

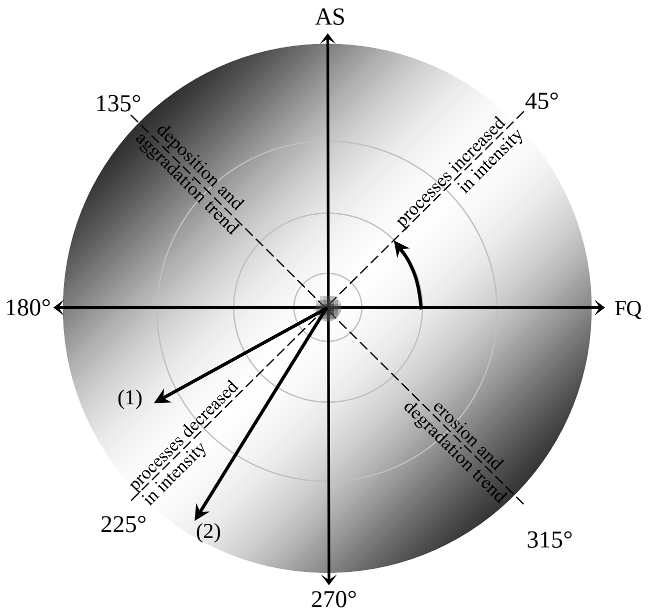

Figure 2. A trend of alluvial river responses in polar coordinates as a function of FQ and AS. In the same graph, the vectors for the river reaches (1) and (2), discussed in section 3.3.

Table 1 summarizes the individual trends of each of the response variables. It describes each of the eight characteristic directions of the alteration vector, as documented from different works and observations from the literature (in particular Lane, 1955; Schumm, 1969 and 1977; Petts, 1980, Williams & Wolman, 1984; Kellerhals & Church, 1989; Brandt, 2000; Grant, 2003 and 2010; Dust & Wohl, 2012) and from the authors' personal experience. For each of the response variables, the trends are coherent and continuous, when considering the different values of the angle. It must be noticed that the gathering of this expertise from the literature may lead to some inconsistencies, and create the need for adjustments according to specific situations.

Table 1. Directions and most probable trends of response variables considered in the model.

	0°	45°	90°	135°	180°	225°	270°	315°
A/D	D	=	A	A	A	=	D	D
s	-	+/-	+	+	+	+/-	-	-
w	+	+	+	-	-	-	+	+
d	+	+/-	-	-	-	+/-	+	+
C	+	+	-	-	-	-	+	+
w/d	+	+/-	+	+/-	-	+/-	-	+/-
d50	+	+/-	-	-	-	+/-	+	+
S	+	-	-	-	-	+	+	+
T	Y	N	N	N	N	Y	Y	Y
ar	Y	Y/N	N	N	N	Y/N	Y	Y

D : degradation ; A : aggradation ; = : invariable; + : increased ; - :decreased; +/- increased or decreased; Y: occurrence of phenomena; N: non occurrence of phenomena; Y/N: occurrence or non occurrence of phenomena .

The modulus of the alteration vector integrates several notions, including the intensity of the transformation, and also its probability of occurrence and the relaxation time. Three classes have been defined with reference to the modulus: (i) [0.0 - 0.5] soft; (ii) [0.6 - 1.5] medium, and (iii) [1.6 – 3.0] strong.

This evaluation must be adapted to the characteristics of the reach under consideration, taking into account the possibility that some response variables may be constrained, or that thresholds concerning the river behaviour may be reached. All situations have not yet been evaluated and should be specified with experience.

2.3 *Estimation of alterations on the hydrological flow regime*

The hydrological regime of a river is a concept that encompasses several properties of the river discharge series, in particular the magnitude and the variability at different time scales. All of those components have an influence on the river morphology, but the most important is the frequency of events capable of moving the bed material and the amplitude of those events. The morphological properties of a river are the result of the full range of flow conditions.

In the aim of evaluating the impacts of changes on the transport conditions, alteration of the control variables, or interventions within the river bed, geomorphologists have for long introduced the idea of a discharge that is characteristic of the actual river morphology (e.g. Iglis, 1941; Wolman & Miller, 1960; Dunne & Leopold, 1978; Brandt, 2000a, Biedehrn et al., 2008). This is a very simplistic but efficient idea and the discussion should then turn to the best value for this discharge, from the critical discharge for transport initiation used for bed stability studies, to the bankfull discharge defined by Biedehrn et al. (2008) as the channel-forming or dominant discharge. This characteristic dominant discharge has also been associated to a return period, with usual values in the range of 1 to 3 years.

Independently from the method used to determine this channel-forming discharge Q_{chf}, the alteration of the hydrological regime FQ is defined in this model as the relative variation of the number of days of exceedance of Q_{chf} per average year.

$$FQ = \frac{NQ_{post}}{NQ_{pre}} - 1 \quad (1)$$

where FQ is the index for the frequency change of a channel-forming discharge; NQ_{post} and NQ_{pre} are the numbers of days of exceedance of the channel-forming discharge respectively after and before the disturbance.

FQ is evaluated at the upstream boundary of the river reach under consideration, where this parameter is representative of the perturbation of the hydrological regime. FQ is the quantification of the alteration of the average return period of the discharge that has the most important morphological influence. It indirectly quantifies the changes of the river capacity, the average value of the total annual sediment flux and of the size range of bed material.

2.4 *Estimation of alterations on sediment supply*

According to Malavoi & Bravard (2010), there is no available method for a simple evaluation of the solid material supply to a river. As the model should not rely on any measurement of solid transport, an original method has been developed and is presented in this section.

The evaluation of the alteration of the sediment supply AS is based on the assumption that the initial state is in equilibrium, which means that the unperturbed sediment supply at the upstream boundary of a river reach corresponds to its physical properties, namely its cross-section, grain size distribution, and slope in its initial hydrological conditions.

Sediment supply properties are evaluated in each point of the drainage area considering three different characters: (i) lithology (rock type and mechanical resistance properties) and soil type (erodability), (ii) hillslope gradient, and (iii) land-cover and land-use. Those properties are described spatially in three layers within a Geographical Information System (GIS) and synthetized pixel-by-pixel through the production of an index characteristic to each pixel, the parameter c with values ranging from 1 to 9. For example an area with a shale lithology, steep slopes, and bare vegetation is classified as having a high erosion activity, c=9; on the contrary a mild surface in a metamorphic lithology and covered with forests is given a very low activity, c=1.

The index for sediment supply SS of a sub-basin is evaluated in proportion to the number of pixels of each class within the sub-basin as in equation 2.

$$SS = \frac{\sum_{i=1}^{9} \left(n_i c_i \right)}{N} \quad (2)$$

where SS is an index for sediment supply; n is the number pixels whose class is i in the sub-basin; c is production index; N is the total number of pixels in the sub-basin GIS description.

In the case of a modification of the sediment supply properties of the watershed, the alteration of the sediment supply AS is computed as the relative variation of SS at the upstream boundary of the reach.

$$AS = \frac{SS_{post}}{SS_{pre}} - 1 \quad (3)$$

where AS is the index for sediment supply alteration; SS_{pre} and SS_{post} are the indexes for sediment supply respectively before and after the disturbance.

The method is suitable for any type of modification of the sediment supply properties within the watershed. It is applied here considering the impacts of hydropower equipment, which are essentially a modification of the properties of sediment continuity from the most upstream drainage areas to the outlet of the watershed. For future applications of the model, it could be applied to evaluate any modification of the properties of the drainage area, for example a modification of land cover.

3 APPLICATION AND RESULTS

3.1 *The Isère river basin*

The Isère watershed, shown on Figure 3, is located in South-Eastern France, on the western side of the Alp Mountains, between 45°54’ and 45°03’ North, and between 05°42’ and 07°11’ East. It is a subbasin of the Rhône River. Its drainage area is 5.570 km² at Grenoble City. The Isère watershed is one of the pilot case studies of the SHARE project (SHARE, 2010). The Isère natural hydrology is that of a mountain river. Thus one can classify the Upper Isère at Val d’Isère as a nivo-glacial regime. The regime becomes nival in the middle valley at Moûtiers, with a maximal discharge in June. At Grenoble, the Isère River has a pluvio-nival regime. It retains a strong nival character with maximal discharges in June, yet it also presents an increase in discharges as soon as March, resulting from snow melt in areas located under 1000 m above sea level (Peiry et al., 1999).

The Isère river basin is an anthropic hydrosystem. The hydrological flow regime and the sediment supply are altered by water extractions realized by hydropower stations, especially those that retain water and those where some portions of the water are court-circuited or where water is diverted into other basins. The hydropower system of the Isère basin is among the oldest, densest, and certainly most sophisticated in the word (Peiry et al., 1999). There are many impoundments, sometimes considerable, as the Tignes dam (Chevril reservoir, 225 10^6 m^3) and Roselend dam (187 10^6 m^3), and some transbasin diversions as the Arc-Isère diversion (nominal discharge 70 m^3s^{-1} at Cheylas pumped-storage hydropower plant) and the Isère-Arc diversion (nominal discharge 120 m^3s^{-1}).

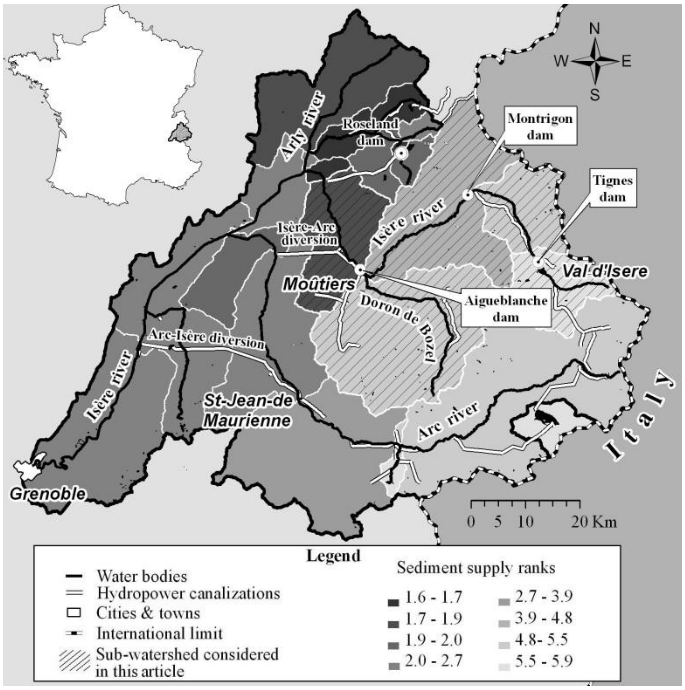

Figure 3. Location of the Isère watershed, hydraulic network and main hydropower canalizations and dams. Sub-watersheds and intensity of sediment supply for each sub-watershed associated with a river reach

3.2 *Data sources*

In the Isère river basin, discharge time series exist for approximately 15 gauging stations, available from the French national server Banque-Hydro http://www.hydro.eaufrance.fr/.

A typological classification of river reaches and a sub-watershed delimitation for each reach was realized from a Digital Elevation Model (DEM), the river network, the water intake and restitutions points, and the dams, according to section 2.1. It resulted in a total of 25 reaches and sub-watersheds, each subwatershed being associated with a specific river reach. Figure 3 shows the 25 sub-watersheds used in the Isère model, as well as the structures incorporated in the model, and the sediment supply classes (ranging from 1 to 9) obtained by the methodology explained in section 2.4.

3.3 *Results*

As an example, we present the results for two river reaches: (1) downstream Montrigon compensation dam, and (2) downstream Aigueblanche dam, and the associated sub-watersheds (Fig. 3). Both reaches show the presence of large storage dams, water intakes and water restitutions, as well as water diversions. Thus, the flow regime and the sediment supply have been modified as compared to a reference state. In terms of flow regime, the combined effects of all these infrastructures are integrated in the changes of the flow duration curve, shown on figure 4. In both reaches, high flows were reduced and low flows where increased after the construction of the dams and diversions. The channel-forming discharge was overall decreased.

In the case of reach (1), the model takes into account the alterations introduced by Tignes and Montrigon dams, but also the damping effects of water and sediment supplies from the intermediary watershed (between Montrigon dam and the confluence of Isère and Doron de Bozel). The values of the channel-forming discharge (Q_{chf}) were defined as the 2-year return period discharge (Table 2). We obtained the values for FQ after and before the construction of hydropower structures (between 1952 and 1954) from the duration curve of average daily flow (Fig. 4). The FQ values for (1) and (2) are shown in table 2. The Q_{chf} frequency of occurrence decreased of 76% and 59% respectively.

In the case of sediment supply, AS were obtained from the intensity map of sediment supplies (Fig. 4), using equation 2 (area weighted average of sediment ranks). For reach (1), the sediment supply before dam construction (AS_{pre}) is 5.1. After dam construction, the drainage area between Montrigon compensation dam and the Isère-Doron confluence is the only source of sediments, since sediments coming from upstream are blocked by the dams. Thus AS_{post} is 2.7, a lower value than AS_{pre}.

Table 2. Values for the reaches (1) and (2)

Values	Reach (1)	Reach (2)
Q_{chf}	35 m^3s^{-1}	150 m^3s^{-1}
NQ_{pre}	13.5 days	7.1 days
NQ_{post}	3.2. days	2.9 days
FQ	-0.76	-0.59
AS_{pre}	5.1	4.6
AS_{post}	2.7	0.27
AS	-0.47	-0.94
Norm	0.87	1.11
Angle	210°	238°

Following the exposed methodology, the results are placed on figure 2. Both reaches are expected to show a decrease in process intensity. Thus the adjustments are rather an accommodation than a channel metamorphosis (figure 1). The fact that the directions are similar (210° and 238°) expresses that in both cases only slight changes are expected. Yet the responses are different. We expect the following trajectories: for reach (1), a minor deposition and aggradation, increased bed slope, slightly finer material, and possibly colonization of the banks by vegetation; for reach (2), soft incision and degradation, decreased bed slope, and slightly coarser material.

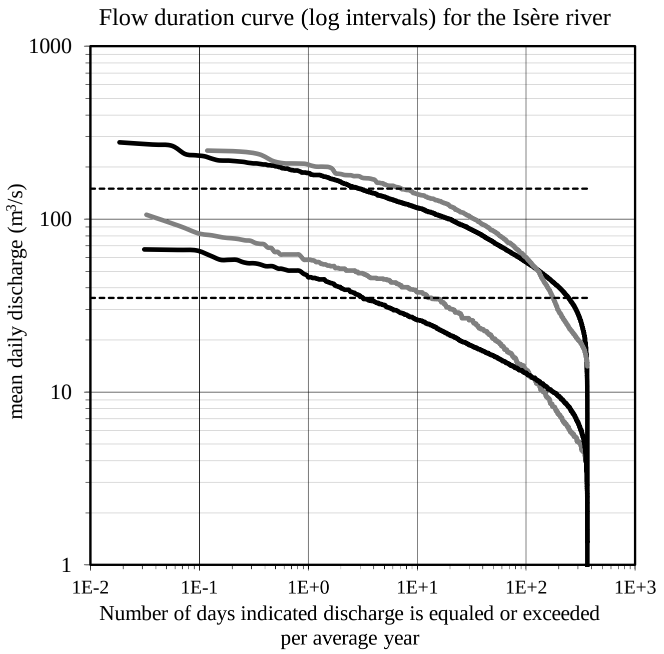

Figure 4. Flow duration curve for the Isère River after and before construction of: (1) Tignes dam (1953) and Montrigon dam (1954) and (2) Aigueblanche dam (1954).

4 DISCUSSION AND CONCLUSIONS

Concerning the interpretation of the results given by the model for the Isère watershed, two issues must be considered: i) all hydropower structures have not been built at the same time, and ii) there were other disturbances on the control factors, in addition to the hydropower structures. Mineral extraction from the river bed, developed mainly in the lower part of watershed, is one of the most important disturbances. This issue has significant implications which cannot be ignored. Indeed the current morphology of the river results from complex overlapping anthropological and natural processes. This is why we chose to present the results for two reaches where the hydropower structures were built in near periods and where the disturbances on the control factors came mainly from the hydropower structures.

In these reaches, the results given by the model are coherent with the assessment done by Peiry et al. (1994). Their work showed an accelerated incision of the bed during the period from 1950 to 1980, due to a combination of natural but mainly human alterations of the control factors.

The main advantage of conceptual models relative to other modelling approaches lies in their relative simplicity and ease of application. However these factors are simultaneously their main limitation (Darby & Van de Wiel, 2003). The current limitations are as follows. (1) The modelling approach only considers the initial and final states of the channel as dynamic equilibria. The duration of the transition is not taken into account, and neither are the overlapping effects of non-simultaneous perturbations. (2) The sediment supply is estimated with uncertainty; in particular the deposition processes in the channels are not taken into account. (3) Synergetic or antagonistic mechanisms in the channel during the transient period may stop or accelerate the processes, and divert the original trajectory. For example, an incision can be stopped by armouring of bed, or the deposition of fine sediments can be subsequently colonised by vegetation. (4) We do not take into consideration the frequencies and effectiveness of flushing operations and their actual consequences on the morphology.

5 PERSPECTIVES

This model is integrated as a pre-processor for a multicriteria analysis of different hydropower management alternatives, in order to evaluate their consequences on aquatic habitats and on other river uses, for instance flood risks (SHARE, 2010). In the multicriteria analysis, the complexity of morphological impacts requires a pre-treatment in order to provide relevant indicators.

In this study only the hydroelectric equipment is considered as a forcing on the control factors. Yet this model could be used to assess the impacts of other pressures on flow regime and sediment supply at the basin scale, for example other hydraulic structures, sediment mining, or landuse and climate changes.

This kind of model can be useful to river managers, as it can answer key questions about river behaviour. Yet this approach must be complemented with actual monitoring of the river morphological evolution.

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