doi:10.20944/preprints201712.0131.v1

Article

Is equilibrium modelling outdated for recent challenges in river management?

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Abstract: To date, several different approaches are available to study sediment dynamics at reach or watershed scale, based on very different hypothesis. One of such assumptions, the so-called "morphodynamic equilibrium hypothesis" is becoming little unpopular for its embedded simplifications. The aim of this work is to demonstrate how this approach proves yet effective in modelling landscape morphodynamics at the watershed scale, for what concerns the longitudinal profile of a river and the sedimentary aspects. The application of a 1-D model based on the equilibrium hypothesis has been implemented for several large rivers worldwide. Geomorphological parameters have been analysed, which describe the evolution of longitudinal profile (concavity) and sediments characteristics (aggrading and fining), and the results show a reasonably good correspondence with qualitative estimation of the same parameters. At the scale of analysis and for the chosen systems, which show high inertia to geomorphological changes likely owing to their longitudinal extension, the model can detect where the present conditions reflect a big disturbance to the "natural equilibrium" thus allowing water managers to identify present issues to be addressed.

Keywords: 1D modelling; large rivers; morphodynamic equilibrium, river concavity, bottom fining

1. Introduction

Nowadays, long-term configurations of natural systems are the result of intrinsically coupled natural, social and economic feedbacks that have only begun to be explored and therefore needs additional research. In this context, studies focussed on the equilibrium of natural riverine systems, free of anthropogenic interventions, should be considered as a basis for palaeohydrological research [1] as well as a powerful tool to understand the long-term effects of localized interventions that can cause a larger scale impact [2]. In this sense, the research can be performed by either a direct observation of geological records and modelling techniques.

In the last years, the development of advanced modelling techniques permitted to model sediment transport and morphodynamics in river assuming non-equilibrium conditions, thus involving the non-stationarity of the boundary conditions and accounting for all the grainsize. In fact, although ordinarily applied in engineering practice, the hypothesis of local equilibrium hardly holds for the fine fractions of material found in the bottom of most natural streams [3] and should be removed for every grainsize fraction, either transported as bedload or in suspension, with no distinction between bed material and wash load.

Despite such approaches, the hypothesis of long-term longitudinal equilibrium profile is still very popular, since it permits to describe large watershed in a quite simplified manner, frequently observed through laboratory experiments [4], indirect analysis of field data [5], numerical and analytical runs [see, among others, 6-9]. Moreover, alluvial sedimentary systems, which evolve under the combination of geological (sedimentology and morphology) and hydrological (hydrodynamics) components, are prone to attain a long-term configuration which sees the (dynamic if short-scaled) balance of external and internal processes, thus allowing for models assuming equilibrium conditions [2]. Indeed, on the one part, field observations suggest that, on a relatively small temporal scale (years or decades depending on the river size) and in the absence of major anthropogenic effects, the average longitudinal profile may be in quasi-equilibrium conditions [7]. On the other part, considering the inertia of large river systems to adapt to changing boundary conditions, at the long-term alluvial rivers tend to evolve towards a quasi-equilibrium state, under the assumptions of stationary boundary conditions, i.e. climate remaining sufficiently stable and absence of anthropic pressures [10]. Generally, in water management quasi-equilibrium conditions are assumed, since common numerical models account for short-term dynamics and only in a few cases long-term changes are considered. Depending on the scale of interest, and the processes involved, equilibrium modelling can be a good simplification of the actual behaviour of the river system.

2. Materials and Methods

The 1D model applied here, firstly presented by [11] and then developed by various authors [9,10] assumes that only two grain-size classes composing the bottom characterize the solid phase evolution. Morphological changes are described via the sediment continuity [12] and the mass balance [13] equations, while an Engelund-Hansen type formula [10] describes the sediment transport, given the geometrical, hydrological and sedimentological constraints. Assuming two representative grain-sizes classes (coarse *c* and fine *f* fractions), $d=d_f/d_c$ represents the diameter ratio, which gives an indication of the bed sorting.

The river is schematized in two connected uniform-slope channels representing, from a physical point of view, respectively the highland reach with steeper slopes and coarser grain-size, and the lowland reach, characterized by milder slope and finer sediments. The upstream reach, indicated with the subscript *U*, starts from a point where one can locate the barycentre of the watershed, feeding solid and liquid supply to the main course, while the downstream reach (subscript *D*) ends at the river outlet, assumed as fixed. The two reaches are connected in the point where the watershed area, from a surface source of sediments, becomes an alluvial depositional surface (Figure 1). The mountain reach measures L_U and has a constant valley width B_U, while the lowland part is long L_D and large B_D. The sediment input *G* is concentrated at the upstream end, while P_U and P_D indicate the sediment transport from the upstream reach and the sediment flow that comes out from the river, respectively.

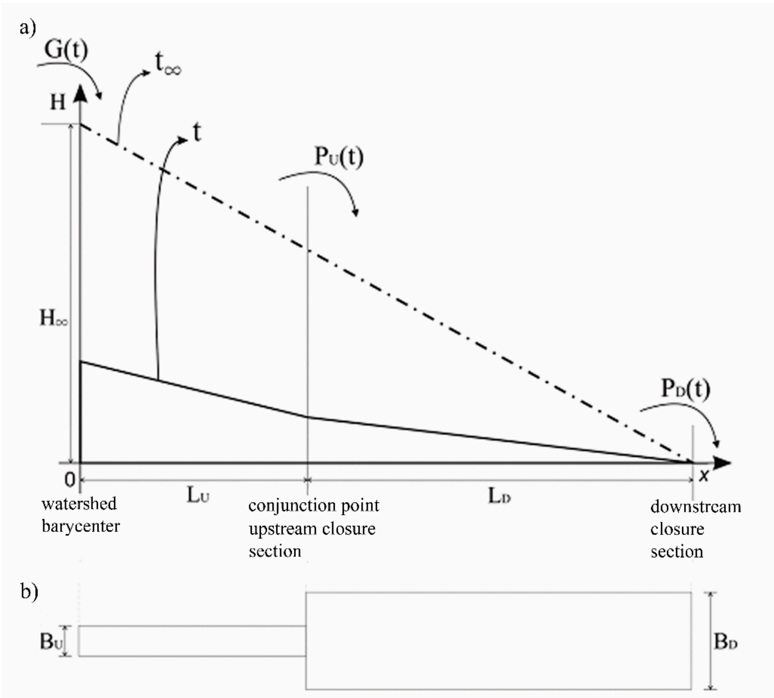

Figure 1. Modelling scheme: a) longitudinal and b) planimetric view.

 doi:10.20944/preprints201712.0131.v1

As suggested by [11], the model can be written in a dimensionless form (Table 1).

Table 1. Dimensional and dimensionless morphometric characteristics of the river.

dimensional parameter	dimensionless parameter	quantity
β_U, β_D	b_U, b_D	bottom composition
S_U, S_D	s_U, s_D	slope
P_U, P_D	p_U, p_D	sediment transport
G	g	sediment input
Q^m	q^m	water discharge
M_U, M_D	$m_{orph,U}$, $m_{orph,D}$	morphological parameter

Integrating the above reported equations over the two reaches L_U and L_D [10] and accounting for the filling time of the two reaches [14], one can obtain three morphometric parameters necessary to characterize the evolution of a watercourse towards its morphological equilibrium:

$$\begin{cases} \mathrm{X}(t) = \dfrac{S_U(t) - S_D(t)}{I_\infty} = s_U - s_D \\ \Phi(t) = \dfrac{\beta_D(t) - \beta_U(t)}{\beta_\infty} = b_D - b_u \\ A(t) = \dfrac{M_U(t) - M_D(t)}{M_\infty} = m_{orph,U} - m_{orph,U} \end{cases} \tag{1}$$

where the longitudinal profile concavity $X(t)$ represents the ratio between the upstream and downstream slopes with respect to the long-term equilibrium slope reached at $t=\infty$. Bed sediment fining $\Phi(t)$ and bottom aggrading $A(t)$ give information about the long-term sediment composition, showing how far the bed grainsize of the two reaches is from equilibrium.

An analysis of the available sources of input data [14-17] suggested that, besides the geometry, there are several uncertainties regarding the sedimentological parameters of the large rivers studied, as observed by [10], pointing out the uncertainties. Moreover, given that the used input data referred to the actual conditions, they are not representative of the pristine state of the river basin but rather of a state already affected by human drivers, therefore, the results here presented refer to a future long-term equilibrium, eventually attained assuming stationary boundary conditions.

The difficulty in finding up-to-date sediment parameters, beyond the geometrical schematization of two extensive reaches representing the highland and lowland channel for which static sediment classes were to be chosen, required a sensitivity analysis on the two sedimentological input parameters. Therefore, the fine composition α_G and the dimeter ratio d of the input material were chosen spanning respectively between 0.75-0.99 and 0.10-0.50, neglecting larger differences between the two grainsize classes (namely, without considering possible washload).

3. Results

To point out the different behaviour between rivers deeply affected by the human presence and watercourses closer to their pristine state, the model was applied to the Orinoco River, representing non-affected conditions, and two highly impacted rivers, namely the Congo and the Mississippi rivers. As presented in the next sections, the river behaviour is schematized by means of the maximum values of the time-variable morphometric parameters (eq. 1), evaluating them for a changing diameter ratio d of the sediments and fine input α_G, since these parameters can be largely variable along the stream and are deeply affected by anthropogenic drivers [10]. Those maxima are to be interpreted as referring to the present state, hence indicating whether the river, given the initial

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conditions which relate to the current situation, shows a tendency towards a quasi-equilibrium state, either stable or dynamic.

By analysing the present conditions at varying sedimentological parameters, two different behaviours are to be noticed: a clear and smooth trend shown by less impounded rivers, such as the Orinoco, and a fuzzier tendency, indicating a sort of dynamic conditions proper of highly impacted rivers such as the Congo and Mississippi. A detailed analysis of each watercourses is reported in the following.

3.1. Orinoco River

For large watercourses having a high inertia and poorly impacted by large-scale anthropogenic activities (e.g., dams, bottom mining, etc.), the maximum concavity X (Figure 2a) increases with the sediment ratio d, covering a larger range for lower sediment input α_G: the higher the fine input, the more constant the maximum concavity, showing a quasi-independent evolution of this parameter from the sediment ratio, namely from the sorting of the bed material.

The maximum fining Φ (Figure 2b) shows a similar behaviour, but, in this case, higher fine input α_G corresponds to lower values of fining, because sediments in input are already fine and therefore the adaptation process is very rapid.

Maximum aggrading A (Figure 2c), as it can be expected, has a trend like the concavity, but spanning a narrower range (0.69-0.79 for aggrading with respect to 0.47-0.80 for concavity). In this case, for high values of sediment ratio d (well-sorted material), the trend has some small irregularities, especially for very fine sediments imposed as input (α_G=0.999).

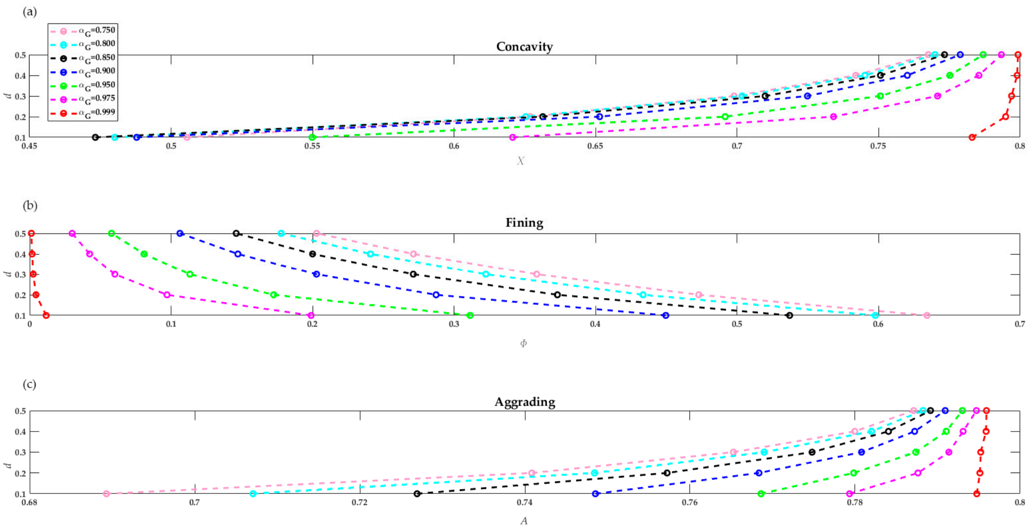

Figure 2. Maximum values simulated for the Orinoco River: (**a**) concavity; (**b**) fining and (**c**) aggrading. y-axis represents the diameter ratio d, and the maximum values of the parameters computed for each percentage of fine input α_G are on the x-axis.

3.2. Congo River

The basin of the Congo River, in Africa, is highly dammed, and therefore the river cannot be yet considered in quasi-equilibrium conditions like the Orinoco described above. As visible from Figure 3, in fact, the trend of the morphometric parameters is not smooth, in particular in the case of aggrading A (Figure 3c), indicating that the used input values are not representative of a stable state. Differently from the Mississippi River reported in the following, however, the maxima for the concavity and fining are representative of a relatively stable behaviour, which could be related to the large inertia of the river to the changes that allows for an adaptation of the grainsize composition and the longitudinal slope.

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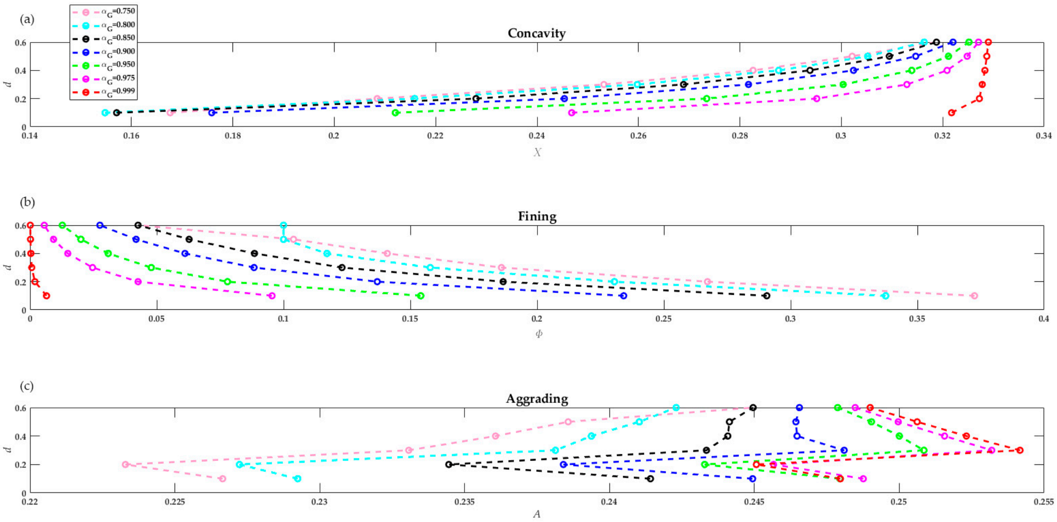

Figure 3. Maximum values simulated for the Congo River: (**a**) concavity; (**b**) fining and (**c**) aggrading. y-axis represents the diameter ratio d, and the maximum values of the parameters computed for each percentage of fine input α_G are on the x-axis.

3.3. Mississippi River

The Mississippi River has in all the three graphs several irregularities, when compared to the results obtained for the Orinoco River and even for an anthropized watercourse like the Congo. This indicates that probably other forcing terms strongly related to human pressure or also to large scale drivers like climate change should be considered in a future revision of this application.

Using the input data corresponding to the present configuration, the river does not reach stable quasi-equilibrium conditions neither at short- or long-time scale, but shows a very dynamic behaviour, evidently in the maximum values reported in Figure 4, as well as observing the temporal variations of the three morphometric parameters [10]. Despite the irregularities, a general behaviour is clearly discernible: the finer the input α_G, the lower the influence of the sediment sorting d on all the morphometric parameters.

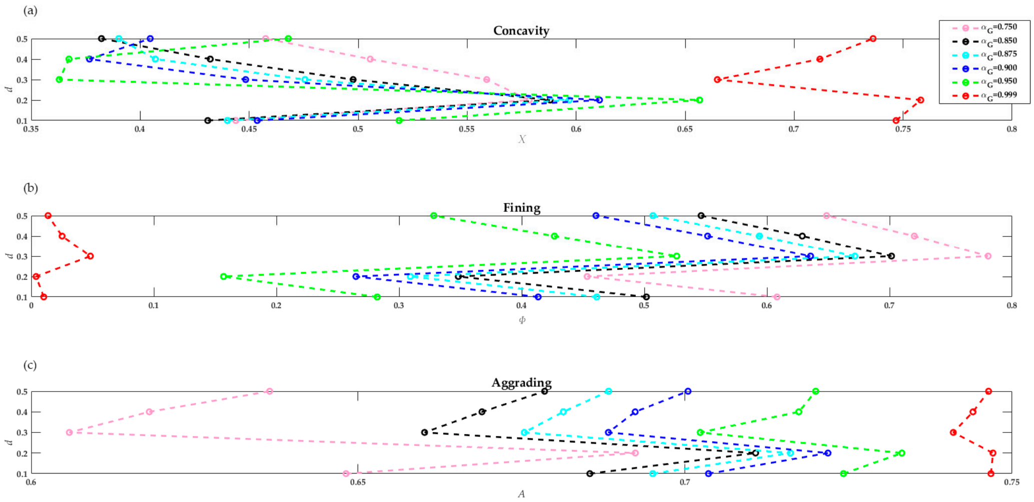

Figure 4. Maximum values simulated for the Mississippi River: (**a**) concavity; (**b**) fining and (**c**) aggrading. y-axis represents the diameter ratio d, and the maximum values of the parameters computed for each percentage of fine input α_G are on the x-axis.

4. Discussion

Generally, large alluvial rivers show a concave profile, having a slope of the upstream (mountain) reach higher that the downstream (lowland) one, accompanied by a longitudinal fining of the bottom composition and an aggradation downstream. As discussed by many researchers since several decades, this configuration may be explained by a variety of mechanisms, like abrasion, distributed input of finer sediments and increase of the active river width [see, among others, 9,18-28]. At the same time, often, such a behaviour is disproven by geological constraints called knickpoints (e.g., rocky gorges) or localized fed material (e.g. bank failure), which evidence a coarsening of the bed composition, but also human drivers (e.g., dams) can alter this natural mechanism. The present application of a schematic 1D model suggests a further justification for this behaviour, basically consisting in the notion of quasi-equilibrium conditions, which apply to most of the present alluvial large rivers worldwide.

As observed comparing a few case studies, particularly significant for the scope of this work is the evolution of three dimensionless morphometric quantities; profile concavity $X(t)$, bottom fining $\Phi(t)$ and bed aggrading $A(t)$, functions of the non-dimensional long-term time t. Moreover, this time is a function of the river filling (or response) time T_{fill}, frequently used to characterize the response velocity of the phenomena involved in fluvial morphodynamics [9,14,16,17,29].

The application to real data of large river systems more or less anthropized, characterized by a high inertia and therefore a moderately slow morphological evolution towards quasi-equilibrium conditions, carried out in this research, has proven reasonable results for the scale of analysis and the adopted assumptions. It must be considered that the simplifications adopted hold only for large systems, having a particularly high inertia to changes triggered by external forcings, in favour of attaining a morphological steady state, which can mean a quasi-equilibrium state. Watercourses characterized by much smaller dimensions are more prone to abrupt variations induced by oscillations in their boundary and initial conditions, thus not allowing for being adequately modelled at long-term using the hypotheses here proposed.

The evaluation of the trend of the maximum values represents an indicator of the perturbations to which these systems are subjected with respect to their equilibrium conditions, eventually reached at the very long-term $t=\infty$, but a thorough analysis of the spatial validity of the used data and the temporal evolution of the morphometric parameters (concavity, fining and aggrading) is required to corroborate the results reported here and completely characterize the long-term evolution of the watercourses studied.

Focusing on the more anthropized basins, on the one part it is interesting to notice that, in the case of the Congo River, fining and concavity have a relatively stable trend, while aggrading is fuzzier. This behaviour could be related to the sediment trapping exerted by the dams located along the watercourse, which causes a reduction of the variance of the grainsize, giving rise to sediment ratio like the once adopted in this research. On the other part, it is evident that more research on the morphology of the Mississippi River is required, since this watercourse is clearly not yet in equilibrium and, therefore, very sensitive to external human-induced forcing like dams. In fact, this watercourse is highly dammed and, therefore, the present condition, here used as input, could be very far from the equilibrium one.

The management of large rivers sees the implementation of strategies typically based on the results of models and simulations, in that the final state is assumed as related to some equilibrium condition, usually considered as stable. Indeed, natural river systems can show a more complicated behaviour, referred here as dynamic equilibrium, presenting oscillations from an assumed mean trend. Relating to cases of the Congo and the Mississippi rivers, the model here implemented shows that both rivers are not able to attain an equilibrium state given the present conditions, thus giving an indication of a potential problem when managing such watercourses at the basin scale.

5. Conclusions

The paper proposed the application of a simplified 1D model to evaluate the long-term evolution of alluvial rivers forced by initial conditions representing the actual state, comparing rivers highly anthropized with more natural watercourses. In the case of rivers poorly affected by the human pressure like the Orinoco River, the studied parameters shown a consistent general pattern, while the presence of many dams can clearly alter such behaviour, giving rise to a very fuzzy trend as visible in the case of the Mississippi River. On these bases, it may be assumed that the conditions obtained by the model portray the present pattern of the watercourses and, therefore, depend on the non-dimensional parameters describing each river basin.

For the future, specific aspects in the modelling procedure should be improved by: i) analysing, in a systematic way, the relationship between the quasi-equilibrium configuration and the morphometric parameters considered; ii) accounting for a more realistic description of alluvial rivers, by introducing lithological discontinuities in the longitudinal profiles (knickpoints, waterfalls, lakes, etc.) and changing water and sediment inputs; iii) considering other parameters that could affect river concavity, bottom fining and bed aggrading processes; iv) consider additional, both natural (climate change, extreme events, eustatism, etc.) and anthropic (levees, etc.) drivers acting at many scales. Moreover, for a coherent application of the schematization here proposed, an evaluation of the sensitivity of the model and its hypotheses to the scale is needed, aiming to assess the field of validity: i.e. up to what scale (starting from the whole river and reducing the dimension) can this model be valid and applied? This is meaningful because this 1D model is meant to be valid for the whole river, but for practical uses it might be required to analyse the quasi-equilibrium at the local scale, via application to a sub-system. Indeed, the very simple altimetric configuration with two reaches points might be not enough appropriate for small-scale problems, yielding to inconsistency of the results.

Equilibrium long-term modelling of large rivers can indicate criticalities in the present situation, like the one clearly evidenced here for the Mississippi River. For highly anthropized watercourses, it is clear how the changes imposed alter the system, which adapts to such disturbances, but only occasionally is able to reach an equilibrium. The temporal scale of such process of self-adjustment should be considered when planning any further activity on disturbed watercourses, but not always estimates on this time are available.

Acknowledgments: The authors would like to thank Prof. Giampaolo Di Silvio and Dr. Mariateresa Franzoia for their fruitful comments on the background of the model and the proposed approach.

Author Contributions: Arianna Varrani performed the simulations and analysed the data, while Michael Nones developed the numerical model. Both authors contributed in equal manner to the writing of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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