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Opportunities from low-resolution modelling of river morphology in remote parts of the world

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Abstract

The study of rivers morphodynamics requires modelling of a variety of processes ranging from the typical small scale of fluid mechanics (e.g. flow turbulence dissipation) to the large scale of landscape evolution (e.g. fan deposition). However, simplifications inherent in the long-term modelling of large rivers derive from limited computational resource and the high level of processes detail (i.e. spatial and temporal resolution). These modelling results depend on processes parameterization and calibration over detailed field data (e.g. initial morphology). Thus, in these cases, simplified tools are attractive. Here, a simplified 1-D code is used for the modelling of very large rivers. A synthetic description of the variation of cross-sections shape is implemented on the basis of satellite images, typically available also in remote parts of the world. The model's flexibility is highlighted here, by presenting two applications. In the first case the model is used for analysing the long-term evolution of the Lower Zambezi (Africa) related to the construction of two reservoirs for hydropower exploitation; while, in the second case, the same code is applied for studying the evolution of the Middle and Lower Parana (Argentina) in light of climate variability. In both cases, having only basic data for boundary and initial conditions, the 1-D model provides results that are in agreement with past studies and that may be used to assist sediment management at watershed scale or at boundaries of more detailed modelling.

1 Introduction

One-dimensional (1-D) models for river hydraulics simulations have been used since the 70's by a lot of agencies around the world dealing with water resources management and flood control. Aiming to describe the dynamics of water free surface and river bed (i.e. bed level changes), a variety of open source and commercial 1-D codes has been realized. These models solve the equations of water flow and, in several cases, also the sediment continuity equation in the longitudinal direction. Among others, the

Hec-Ras by US Army Corps of Engineers; the Full Equations (FEQ) model by US Geological Survey; the Sedimentation and River Hydraulics (SRH) 1-D by US Department of Interior-Bureau of Reclamation; the Telemac Mascaret 1-D by a European consortium based in France, Germany and UK; the Mike11 by Danish Hydraulic Institute; and the Sobek 1-D by Deltares (NL) are well tested codes for river engineering that apply the 1-D longitudinal simplification. It is worth noting that, while open source codes were optimized to specific applications, (e.g. the FEQ is particularly suited for simulations of unsteady flow in open channels network with a variety of control structures), commercial software packages were largely improved to easily integrate detailed data from Geographic Information Systems (GIS), boundary conditions from climate-hydrology models and for downscaling to more detailed simulations (i.e. 2-D and 3-D modelling). Albeit in the last decades 1-D and 2-D codes were provided with modelling of bed level changes to be coupled with hydraulic computations, the simulating of large rivers at watershed scale remains a difficult task because of involved space and time lengths ranging within 10^2–10^3 km and years, respectively (Di Silvio and Nones, 2013).

Sediment management in large rivers is particularly relevant when evaluating damming or climate changes impacts, as instance. This is most challenging in remote parts of the world, where frequent and detailed topographic surveys of river cross-sections are uncommon, which may largely limit the application of numerical codes. While conventional 1-D and 2-D morphodynamic models require detailed inputs describing initial morphology and boundary conditions, the code proposed here is able to describe the longitudinal evolution of a river reach at non-detailed spatial and temporal scales by using a basic database. To reduce computational effort and simulation results depending on field database (e.g. river channel bathymetry, detailed spatial distribution of alluvial deposition), a series of testable simplifications are introduced in the hydraulics equations, such as the kinematic propagation of the water flow and the Local Uniform Flow (LUF) hypothesis (Fasolato et al., 2011). Under these assumptions, it is possible to simulate river bed dynamics by implementing a simplified description of river morphology that can be derived from maps and satellite images. The use of satel-

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lite images rather than detailed topographic surveys noticeably extend the 1-D model applicability to large rivers in undeveloped countries by drastically reducing modelling effort and results depending on detailed field database.

Two applications of this simplified 1-D code are presented here. These case studies show the 1-D model's performance in providing long-term predictions to support sediment management in large rivers, which is related to natural and anthropic pressures (e.g. climate variation, hydropower exploitation). Given the lack of detailed and extensive data, in remote parts of the world, the simplified model may substitute-support multi-parameters 2-D modelling of river watersheds (Coulthard and Van de Wiel, 2013) or be coupled to detailed 2-D modelling of some river features (e.g., junctions and bifurcations) such as the typical downscaling approach used in Guerrero et al. (2013b). 2-D modelling requires detailed field data for accurate calibrations and validations, that fix model's parameters and influence final results reliability (Guerrero and Lamberti, 2013; Guerrero et al., 2013a; Williams et al., 2013). The model used here prevents this limit by coupling a 1-D morphodynamic model (physically based on water flow and river bed profile equations) with a cross-sections sub-model. The 1-D model simulates river bed aggradation-degradation rate and corresponding sediment sorting along the watercourse, although at non-detailed scale, while the sub-model describes the empirical relationship between river width and hydrological cycle.

The first application regards a lower branch of the Zambezi River (Africa) that has been regulated since the construction of various dams during the last century. These dams strongly modified the natural pattern of flow variations in time and quantity (Suschka and Napica, 1986). Several authors studied the impact of the two major reservoirs (namely, Kariba and Cahora Bassa dams) on the Zambezi River system. Most of them focused on biological, ecological and economic effects (biodiversity, fisheries, wetlands, etc.) of these reservoirs (Bowmaker, 1960; Attwell, 1970; Hall et al., 1977; Du Toit, 1984; Dunham, 1989; Beilfuss and Davies, 1999; Beilfuss et al., 2001; Tilmant et al., 2012; McCartney et al., 2013). Fewer works addressed morphological changes correlated to dams impacts on sediment and water discharges (Guy, 1981;

Suschka and Napica, 1986; Beilfuss and Davies, 1999; Davies et al., 2000; Brown and King, 2012). These two major dams noticeable changed the hydrological cycle of Lower Zambezi. Data collected at the gauging station of Tete (Mozambique, about 135 km downstream of Cahora Bassa) show a modified pattern of monthly runoff characterized by the increase of minimum and decrease of maximum values. As far as the effects on river morphology are concerned, some authors have evaluated changes of the lower part of the Zambezi after dams' construction (Suschka and Napica, 1986; Beilfuss and Davies, 1999; Davies et al., 2000; Ronco et al., 2010). The removing of sediments from gorge sections, the stabilizing of braids and bars in some sections and of an individual channel in others, the delta erosion and the concurrent increasing of salt-water intrusion have been attributed to these impoundments (Chenje, 2000). Unfortunately, no systematic and detailed surveys of observed morphological changes are reported in literature, which might have been applied to validate a 2-D model. Alternatively, the simplified 1-D modelling was performed on the basis of the river bed profile before damming, river stage records, few sedimentological samples and available satellite images.

The second application addresses climate variability effectiveness in modifying the morphology of the Middle and Lower Parana rivers in Argentina. Amsler et al. (2005) and Castro et al. (2007) analysed how the streamflow variation affected the Parana morphology at its middle and lower reach, respectively, during the 20th century. These authors related the climate interdecadal variability (i.e. the variation between decades) to the discharge value most effectively modifying morphology (namely, the effective discharge) and, as a consequence, to river morphological changes observed. In particular, Amsler et al. (2005) observed that the dry midst of the last century (1930–1970) was characterized by low effective discharge, which promoted a decrease in width, braided index, thalweg sinuosity, width to depth ratio and channel volume in the Middle Parana, with opposite patterns found in the beginning and end of the same century. Differently, Castro et al. (2007) investigated the Lower Parana morphology to be not straightforward correlated to hydrological variability as much as the Middle Parana. In particular,

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it was observed a continuous and progressive oversimplification of the river channel planimetric morphology toward a lower width to depth ratio regardless the occurred oscillation in hydrology. Reasons of these different responses to the same climate variability were pointed out in alluvial planes, which noticeable enlarge and decreases in slope when passing from the Middle to Lower Parana. These morphology constrains together with driving increase of precipitations during the last part of the 20th century would have produced sediment deposition at secondary reaches and therefore the streamflow gathering in a single straight and deep reach. Although these channel divagations may be simulated with a 2-D morphodynamic model, the large scale morphology (i.e. river slope and width, sediment sorting) was modelled by means of the simplified 1-D code. Thus, in this study, the combined effects of climate variation and morphological constrains during the 20th and 21st centuries were simulated in the Middle and Lower Parana. Future hydrology was computed by applying four climate scenarios spanning the period 1991–2098, that were provided from different combinations of Global and Regional Climate models (Saurral et al., 2013). A significant increase of effective discharge and flow-discharge variability was highlighted passing from the 20th century time-series to forecasts, which slightly increase the rate of change of river bed levels. However, the river bed profile appeared pretty stable, confirming that the present river-alluvial slopes will remain fixed constrains to channel divagation.

2 Case studies

2.1 The Zambezi River

The Zambezi River (Fig. 1) is the fourth-longest river in Africa, with a basin of 1.39×10^6 km^2. This river, with a total length of about 2500 km, has its source in Zambia and flows through Angola, along the borders of Namibia, Botswana, Zambia and Zimbabwe, to Mozambique. The Zambezi system can be divided up into three reaches, each differing in geological template, biodiversity and landscape characteristics: the

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Upper, Middle and Lower Zambezi (Hughes and Hughes, 1992; Main, 1992; Timberlake, 1998).

The Upper Zambezi flows into Angola for about 250 km. The Victoria Falls represent the boundary between the Upper and Middle reaches. About 240 km below the Victoria Falls, the river flows into the Kariba Lake, created in 1959 by the Kariba Dam, which has a storage capacity of 180.6×10^9 m^3 (Reeve, 1960; Davies et al., 2000). The Middle Zambezi flows into the Cahora Bassa Lake (Mozambique) that is the storage capacity (72.5×10^9 m^3, HCB, 2004) resulting from the construction of the Cahora Bassa Dam in 1974. The Lower Zambezi is long about 650 km from the Cahora Bassa Lake to the Indian Ocean. This reach is typified by a broad floodplain, with parallel channels and shifting sandbanks, while the coastal portion includes extensive grasslands and freshwater swamps, dunes and mangroves.

The construction of these two dams has considerably changed the hydrological cycles in the Lower Zambezi: effective discharge downstream Cahora Bassa decreased from around 3500 m^3 s^{-1} during the 50's to around 1800 m^3 s^{-1} during the 90's. Some authors (Walling, 1984; Walford et al., 2005) estimated sediment yield of the Zambezi within the range of $10–20 \times 10^6$ t per year, by means of observed delta modifications and sedimentary records.

2.2 The Parana River

The Parana River, with a watershed of about 2.6×10^6 km^2, is the most important tributary of the La Plata Basin (LPB), which has a basin of about 3.2×10^6 km^2 within Argentina, Brazil, Paraguay, Uruguay and Bolivia and outflows in the Atlantic Ocean near Buenos Aires (Fig. 2a). Figure 2b reports the studied river reach from Corrientes to Villa Constitución, (i.e. the Middle and Lower Parana) with main cities and their kilometric labels along the water way.

The Parana River flows from north to south through Brazil and Argentina for about 1000 km; its mean annual discharge is around 12 000–15 000 m^3 s^{-1} and the total sediment transport is around $130–135 \times 10^6$ t yr^{-1} (Amsler et al., 2005). The Paraguay River

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joins the Parana just upstream the city of Corrientes. No more significant tributaries that supply water and sediments are present downstream this confluence (Amsler and Drago, 2009).

The Middle and Lower Parana play a significant role in the LPB's sediment transport and morphodynamics. Clay and silt materials coming from the Bermejo River (a tributary that flows from northern Argentina) represent around the 80 % of the total solid discharge and are transported as wash-load to the Parana delta and large wetlands during flood periods. The remaining 20 % is fine sand, which is transported as bed- and suspended-load, modifying river morphology. The channel bed is composed mostly of fine and medium sand, and its planform pattern is classified as anabranching with meandering thalweg (Latrubesse, 2008). In planform, a succession of wider and narrower nodal sections is observed, with mean channel widths and depths ranging between 600 to 2500 m and 5 to 16 m, respectively.

3 1-D mathematical modelling

The 1-D model used here was firstly developed various years ago by Di Silvio and Peviani (1989) for analysing the longitudinal evolution of small rivers at watershed scale. Conventional 1-D morphological models require a detailed description of river geometry. On the contrary, the applied code couples the 1-D equations of water flow with the sediment continuity ones (i.e. De St. Venant Eq., and Exner and Hirano Eqs., respectively) to describe the longitudinal evolution of a river reach at non-detailed scales. To reduce the computational effort, a series of acceptable simplifications are introduced in the hydraulic equations, such as the Local Uniform Flow (LUF) hypothesis (Fasolato et al., 2011) and the kinematic propagation of water flow. Under this latter hypothesis, the energy line, water and bed profiles have the same slope, which is applied to describe the bed profile evolution by modelling the water profile at appropriate length and duration scales, namely "morphological box" and "evolution window", respectively. It is worth noting that the Local Uniform Flow Morphodynamic (LUFM) model was imple-

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mented for long-term analyses that on average fulfil the applied simplifications. In fact, modelled river features are averaged over a relative long period τ (i.e. time window), which was fixed to one year for both performed studies on the basis of resulting Froude numbers as described in Fasolato et al. (2011).

The sediment transport formula, Eq. (1), applied in the model, is derived from the Engelund-Hansen formula for computing the bed- plus suspended-load (i.e. total-load) as described in Ronco et al. (2009) and Nones (2013). In Eq. (1) the rate of suspended sediment transport at yearly scale, $G_s(\tau)$, depends on energy slope (corresponding to water and bed slopes under the LUF hypothesis), $J(\tau)$, active width, $B(\tau)$, sediment mean diameter, $d(\tau)$, and effective discharge, $Q_{\text{eff}}(\tau)$, at each morphological box (around 50–80 km for both studies).

$$G_s(\tau) = \alpha' \cdot \frac{Q_{\text{eff}}(\tau)^m \cdot J(\tau)^n}{B(\tau)^p \cdot d(\tau)^q} \quad (1)$$

The active cross-section is defined as the river channel width that conveys the annual sediment transport, except for wash-load (Ronco et al., 2009). The effective discharge defines the flow that cumulates most of channel sediments (Biedenharn et al., 1999), i.e., following the Schaffernak approach, the maximum value of the product of interval frequencies fr with solid discharges G_s occurring in the interval as assessed for corresponding hydrological conditions. The coefficient α' and the exponent m were calibrated by assuming the long-term equilibrium between effective discharge and sediment transport rate, while other exponents used in Eq. (1) are functions of m. More details on these parameters can be found in Di Silvio (1983).

Initial river widths, $B(\tau = 0)$, were derived from satellite images, initial water slopes, $J(\tau = 0)$, from low-resolution topography (i.e. watershed cartography), while sediment distributions were available from some samples along the river. Such a basic database is usually available also in remote parts of the world, which noticeable extends the model applicability to large rivers with respect to more advanced 2-D codes.

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In order to describe the seasonal widening and narrowing of river sections, a basic calibration method was introduced, that combines satellite images with flow discharge records. The 1-D model was coupled to a simplified description of river cross-sections (Nones, 2013), which accounts for river width changing at a smaller time-scale (i.e. seasonal oscillation) with respect to the bed level evolution simulated. This synthetic cross-sections model computes the active river width as a function of flow discharge. Indeed, the statistical distribution of river width $B(d)$ was expressed by means of the statistical distribution of flowing discharges $Q(d)$, where d is the event frequency at the analysed section and during the calibration period (i.e. 2000–2010 for both applications). Thus, for discharges lower than the bankfull value (the minimal discharge flowing over alluvial plains) the at-a-site hydraulic geometry relationship was assumed (Eq. 2) for the synthetic description of active cross-sections (Singh, 2003):

$$B(d) = \alpha \cdot Q(d)^{\beta} \tag{2}$$

where α and β are the calibration parameters (see, as example, Leopold and Maddock, 1953; Yalin, 1992; Parker et al., 2007; Wilkerson and Parker, 2011). The river widths for the calibration period were obtained from Landsat-7-satellite images (USGS database). The corresponding discharges were derived from the available river stage records. Images corresponding to flood events were discarded; in those cases wetted areas were not providing evidence about the active channel geometry but the flooding (Fig. 3).

4 Results

4.1 Evolution of the Zambezi River during the 20th century

The LUFM model was applied to simulate the morphological behaviour of the Lower Zambezi starting from 1907, when first systematic measurements were recorded at the gauging station of Zumbo, Mozambique. These measurements were analysed to assess the effective discharge of Zambezi and its main tributaries, together with the

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corresponding sediment input, during the 20th century. These data were applied at model boundaries and for characterizing river width-discharge relationships along the simulated reach.

Previous simulations performed with LUFM model on Zambezi River (Ronco et al., 2010) did not consider river width-discharge relations. In that case, the model results show an enduring process of sediment deposition, which slowly propagates towards the downstream direction. The long-term evolution was apparently dominant, with respect to the recent evolution related to dams' construction.

Our computations also accounted for seasonal oscillations which simulated river widening and narrowing. These modelling confirmed that the lower reach presents a widespread tendency to a progressive deposition, especially in the flat zones downstream of the gorges, where some tributaries flow into the main channel (Fig. 1c). This undisturbed trend resulted affected by the two reservoirs to some degree. Dams trap sediments which slowly modifies river bed morphology and corresponding bed composition. In more detail, the undisturbed river aggradation corresponded to a progressive fining of river bed sediment. In the case of dams' implementation, two opposite effects altered the natural process yielding a more stable river bed: (1) the water flow reduction rapidly propagates downstream, (2) the sediment sorting is delayed because of trapping.

The simplified modelling of cross-sections change at seasonal time scale bore out a typical evolution from braided to unicursal morphology. The simulated flow decreasing because of water impounded in the reservoirs corresponded to narrowing of active cross-sections. This simplified modification of cross-sections shape reflects the observed tendency to unicursal morphology and accretion of vegetated floodplains, which limits channel divagations. In other words, lower flows were simulated with sections narrowing which agrees with the observations of vegetation density increase and abandoned secondary channels. This behaviour was also reported by Davies et al. (2000).

The performed simulations also gave evidences on the delta shoreline evolution (Fig. 4), which has been recognized as a key indicator of sediment yield in various

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large rivers of the world. This evolution was evaluated on the basis of seven satellite images (from the USGS's database) spanning the period 1970–2013, which confirmed the general negative trend of the delta surface extension. Figure 4a shows the negative trend over the years with the exception of a recovery between 1991 and 2000. In total, erosions prevailed yielding a loss of the delta area of around 50 km^2 in the analysed period.

The simulated time series of sediment transport rate in the most downstream morphological box confirmed the observed erosional trend for the Zambezi's delta. In fact, this time series should reflect the historical sediment supply to the delta. The simulated rate of sediment transport appeared correlated to the observed variation of delta area (Fig. 4b), notwithstanding the satellite images used may be affected by occasional water levels and the shoreline morphology is also affected by the Indian Ocean dynamics.

4.2 Evolution of the Parana River during the 20th and the 21st centuries

In this case, outputs from four regional climate models (RCMs) were used to produce future hydrological scenarios at the La Plata Basin. These scenarios were boundary conditions of the performed modelling, covered much of the 21st century and were provided in the research project "A Europe-South America Network for Climate Change Assessment and Impact Studies in La Plata Basin" (CLARIS-LPB). In particular, the four RCMs are: PROMES (UCLM, Spain) covering the period 1991–2098, RCA (SMHI, Sweden) from 1981 to 2098, RegCM3 (USP, Brazil) having information in period 1981–2048 and LMDZ (IPSL, France) with information in period 1991–2048. In addition, the 20th century scenario was produced from climatology-hydrology records. The details about these datasets are reported in Saurral et al. (2013). Figure 5 shows a comparison among applied scenarios in terms of frequency distribution of monthly flow discharges at Corrientes, which is the upstream boundary of the River Parana reach simulated by means of the LUFM model. It is possible to observe a relatively large dispersion among the different RCMs and a general increase in the frequency of large discharges for prediction with respect to past century, which is particularly evident for the RegCM3 scenario.

Literature data regarding the Parana River morphology at watershed scale mostly concern the transported sediment volume per year and corresponding most "effective discharge" in conveying this volume at some sections. Thus, the LUFM model results were used to assess sediment volumes per year and corresponding effective discharges for future and past scenarios. The average effective discharges for each decade of the 20th century from literature are compared to LUFM corresponding results in Fig. 6, showing a good correlation with maximum deviations in the order of some per cents, with few exceptions for largest discharges.

The sediment volume per year was divided into discharge classes of 2000 $m^3 s^{-1}$ width and was compared among scenarios (Fig. 7). Whatever the analysed scenario, the average volume per year was almost the same (changing within the range of 20–30 $\times 10^6$ t yr^{-1}), but the distributions among classes were pretty different. The distribution for the 20th century did not present a very high maximum, and the maximum volume per year was detected in the interval of 13 000–17 000 $m^3 s^{-1}$ (i.e. the average effective discharge for the 20th century), which roughly agrees with Amsler et al. (2005) investigation. In fact, using records from last century of water level and monthly flow discharges in Corrientes, Amsler et al. (2005) assessed the effective discharge to change within 15 400–24 500 $m^3 s^{-1}$, among five periods with different length in time from 1904 to 1990, which yields the weighted average of 16 800 $m^3 s^{-1}$. When comparing this value to LUFM results, the model resolution must be considered. The interval of 13 000–17 000 $m^3 s^{-1}$ was detected using discharge classes derived from the yearly time series simulated (one year is the LUFM's evolution window), while Amsler et al. (2005) applied monthly records that present larger picks.

As far as concern the resulting morphology, the cross-sections width appeared with the largest sensitivity to flow regime at the Lower Parana, which exacerbated the deviation between various scenarios in terms of resulting bed profiles and average wetted area. The model gave almost fixed slope at the Lower and Middle Parana in the in-

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terval of around 2–3 cm km^{-1} and 3–5 cm km^{-1}, respectively, and mostly depending on the sub-reach location (morphological box), while the corresponding cross-sections change was also correlated to the variability of forcing time series (scenarios). The river width at the Lower and Middle Parana varied in the range of 1600–3300 m and 1200–2400 m, respectively.

The resulting bed levels in terms of cumulate variation (i.e. final depositions and erosions at each morphological box) were assessed for the 20th century and the two continuous time series available from future projections (PROMES and RCA scenarios). Although the noticeable increase in the forcing and effective discharges (Figs. 5 and 7, respectively) when passing from past to future scenarios, the bed level changes along the river maintained almost the same aggradation or degradation tendencies as for the 20th century, with maximal values of few tents of centimetres in one century (Fig. 8). The bed level resulted pretty stable along the river and especially at the Lower Parana.

Some morphological data of the Parana River can be retrieved in literature. Amsler et al. (2005) and Castro et al. (2007) observed different response of the planimetric morphology at the Middle and Lower Parana, respectively, to the same climate variability. Reasons were pointed out in the alluvial plane morphology, which noticeable enlarges and decreases in slope in the Lower Parana. Although the observed braided and bifurcated morphologies at the Middle and Lower Parana, respectively, may be simulated with detailed 2-D models, the performed simulations corroborated the arguing that river slope and width are almost fixed constrains. The variability along the river's course of these constrains and the driving increase of the precipitations during the last part of the 20th century would have produced different channel divagations at the Middle and Lower Parana. In addition, it is worth noting that the performed 1-D simulations provided boundary conditions for more detailed 2-D modelling of a Lower Parana sub-reach (Guerrero et al., 2013b).

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5 Discussion

The changes of effective discharge, sediment transport rate, river bed level, bed sediment sorting and cross-section width occurred during the 20th and the 21st centuries along the Zambezi and Parana rivers were analysed with the LUFM model. This 1-D code introduces some important simplifications in the mathematical description of the river hydraulics (among others, kinematic propagation of water flow and local uniform flow hypothesis) and in the schematization of the channel geometry (namely, cross-sections synthetic profile). These simplifications gave some opportunities with respect to more detailed modelling (e.g. 2-D codes). In fact, the LUFM simulated the long-term morphodynamic processes related to natural and anthropogenic pressures at non-detailed spatial and temporal scales by implementing a very basic database. This is particularly relevant in remotes part of the world, such as in the presented case studies.

The performed analyses confirmed that the LUFM model is able to simulate average variations at large temporal and spatial scales. In fact, the schematizations used for the two applications accomplished to reduce the computational effort and the topographic resolution usually required to implement standard 1-D models and even more for detailed 2-D modelling. Notwithstanding the lack of geometrical resolution, the LUFM model responses appeared pretty reliable and less sensitive to inaccuracies induced by model parameters calibration on the basis of detailed field data. Indeed, the estimation of induced biases is not trivial, especially for detailed modelling that includes a lot of processes parameterization and for long-term simulations that extrapolate to a timeline far from initial conditions. The operated synthetic description of transversal cross-sections, based on satellite images, presents some advantages with respect to occasional surveys. The LUFM model accounted for sediment transport variation due to the active channel modifications driven by hydrological changes at seasonal scale.

Therefore, the simplified model applied presents a potential to overcome the lack of detailed field data providing, at the same time, reliable results for a variety of en-

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gineering and environmental practices ranging from long-term sediment management to environmental impact studies. Basic databases (i.e. historical cartography for initial geometry and river stage records for boundary conditions) are usually available also in remote parts of the world, which noticeable enlarges the model applicability to large rivers with respect to more advanced 2-D codes.

Furthermore, it is worth noting that the simplified modelling of river cross-sections variation refines the code resolution to seasonal oscillation, although the larger evolution window was used for updating the bed profile and sediment sorting which fulfils the LUF hypothesis. To this end, the additional river width-discharge database is required, which introduces the model's validation on statistic distributions from a certain period. Indeed, satellite images, historical cartography and river stage records are largely available also in remote parts of the world and dating back from decades, for satellite images, to centuries in the case of historical records and maps.

6 Conclusions

Two large rivers were analysed with a simplified 1-D model, which highlights the opportunity of using basic databases to simulate river morphology at low-resolution in remote parts of the world. The proposed 1-D code couples the longitudinal modelling of river bed with a synthetic description of cross-sections shape and was applied for studying past and future river evolution on the basis of topographic basic data, stage records and satellite images. In addition, future projections were produced from available climate-hydrology scenarios. Our results indicate the potential of non-detailed models for analysing the long-term impact of anthropic and natural pressures, especially in the case of large rivers. This is particularly relevant with respect to 2-D modelling that implies results depending from processes parameterization and calibration on detailed field data usually not available in remotes part of the world.

In the application to the Lower Zambezi River only a topographic basic survey was applied to describe the initial morphology, while satellite images and stage records pro-

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vided river cross-sections shape and boundary conditions. The impacts of hydropower reservoirs on river morphology during the 20th century were simulated. Our results agree with the river bed aggradation and delta erosion observed during the last century.

In the second case study, in addition to basic data, climate-hydrology scenarios were used at model boundaries to study the impacts of climate variability over the Middle and Lower Parana. Our results corroborate the hypothesis that climate driver differently affected the channel divagation because of river bed slope and width decreasing and increasing, respectively, when passing from the Middle to Lower Parana.

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References

Amsler, M. L. and Drago, E. C.: A review of the suspended sediment budget at the confluence of the Parana and Paraguay Rivers, Hydrol. Process., 23, 3230–3235, 2009.

Amsler, M. L., Ramonell, C. G., and Toniolo, H. A.: Morphologic changes in the Parana River channel (Argentina) in the light of the climate variability during the 20th century, Geomorphology, 70, 257–278, 2005.

Attwell, R. I. G.: Some effects of Lake Kariba on the ecology of a floodplain of the mid-Zambezi valley of Rhodesia, Biol. Conserv., 2, 189–196, 1970.

Beilfuss, R. D. and Davies, B. R.: Prescribed flooding and wetlands rehabilitation in the Zambezi Delta, Mozambique, An Int. Perspective on Wetland Rehabilitation, 143–158, 1999.

Beilfuss, R. D., Moore, D., Dutton, P., and Bento, C.: Patterns of vegetation change in the Zambezi Delta, Mozambique, Working paper #3 of the Program for the Sustainable Management of Cahora Bassa Dam and the Lower Zambezi Valley, International Crane Foundation, USA, 2001.

Biedenharn, D. S., Thorne, C. R., Soar, P. J., Hey, R. D., and Watson, Ch. C.: A practical guide to effective discharge calculation (Appendix A), U.S. Army Corps of Eng., Vicksburg, Mississippi, USA, 1999.

Bowmaker, A. P.: A Report on the Kariba Lake Area and Zambezi River Prior to Inundation, and the Initial Effects of Inundation with Particular Reference to the Fisheries Training Centre on Fishery Survey for the Countries of African Region (Report), FAO Library Fiche AN, 59986, Rome, Italy, 1960.

Brown, C. and King, J.: Modifying dam operating rules to deliver environmental flows: experiences from southern Africa, International Journal of River Basin Management, 10, 13–28, 2012.

Castro, S. L., Cafaro, E. D., Gallego, M. G., Ravelli, A. M., Alarcón, J. J., Ramonell, C. G., and Amsler, M. L.: Evolución morfológica histórica del cauce del río Parana en torno a Rosario (km 456 – 406), Proceedings of the XXI Congreso Nacional del Agua, CONAGUA 2007, Tucumán, Argentina, 2007.

Chenje, M.: State of the Environment Zambezi Basin, SADC/IUCN/ZRA/SARDC, Maseru/Lusaka, Harare, 2000.

Coulthard, T. J. and Van de Wiel, M. J.: Climate, tectonics or morphology: what signals can we see in drainage basin sediment yields?, Earth Surf. Dynam. Discuss., 1, 67–91, doi:10.5194/esurfd-1-67-2013, 2013.

Davies, R. D., Beilfuss, R. D., and Thomas, M. C.: Cahora Bassa Retrospective, 1974–1997, effects of flow regulation on the Lower Zambezi River, Limnology in the developing world, 27, 1–9, 2000.

Di Silvio, G.: Modelli matematici per lo studio di variazioni morfologiche dei corsi d'acqua a lunga e breve scala temporale, Studi e Ricerche, 356A, 1983.

Di Silvio, G. and Nones, M.: Morphodynamic reaction of a schematic river to sediment input changes: Analytical approaches, Geomorphology, doi:10.1016/j.geomorph.2013.05.021, in press, 2013.

Di Silvio, G. and Peviani, M.: Modelling Short- and Long-Term evolution of mountain rivers, an application to the torrent Mallero (Italy), Lecture Notes in Earth Sciences n. 37, Fluvial Hydraulics of Mountain Regions, Armanini, A. and Di Silvio, G. (Eds.), Springer Verlag, 1991, 293–315, 1989.

Dunham, K. M.: Vegetation-environment relations of a Middle Zambezi floodplain, Vegetatio, 82, 13–24, 1989.

ESURFD

1, 407–435, 2013

Low-resolution modelling of river morphology

M. Nones and M. Guerrero

Du Toit, R. F.: Some environmental aspects of proposed hydro-electric schemes on the Zambezi river, Zimbabwe, Biol. Conserv., 28, 73–87, 1984.
Fasolato, G., Ronco, P., Langendoen, E. J., and Di Silvio, G.: Validity of Uniform Flow Hypothesis in One-Dimensional Morphodynamic Models, J. Hydraul. Eng.-ASCE, 37, 183–195, 2011.
Guerrero, M. and Lamberti, A.: Bed-roughness investigation for a 2-D model calibration: the San Martìn case study at Lower Paranà, Int. J. Sediment Res., 28, in press, 2013.
Guerrero, M., Di Federico, V., and Lamberti, A.: Calibration of a 2-D morphodynamic model using water-sediment flux maps derived from an ADCP recording, J. Hydroinform., 15, 813–828, 2013a.
Guerrero, M., Nones, M., Saurral, R., Montroull, N., and Szupiany, R. N.: Parana River morphodynamics in the context of climate change, International Journal of River Basin Management, doi:10.1080/15715124.2013.826234, in press, 2013b.
Guerrero, M., Re, M., Kazimierski, L. D., Menéndez, A. N., and Ugarelli, R.: Effect of Climate Change on Navigation Channel Dredging of the Parana River, International Journal of River Basin Management, doi:10.1080/15715124.2013.819005, in press, 2013c.
Guy, P. R.: River bank erosion in the mid-Zambezi valley, downstream of Lake Kariba, Biol. Conserv., 19, 199–212, 1981.
Hall, A., Valente, I., and Davies, B. R.: The Zambezi River in Mozambique, the physicochemical status of the Middle and Lower Zambezi prior to the closure of the Cabora Bassa Dam, Freshwater Biol., 7, 187–206, 1977.
Hidroeléctrica de Cahora Bassa (HCB): Technical Reports on Cahora Bassa Project, Songo, Mozambique, 2004.
Hughes, R. H. and Hughes, J. S.: A Directory of African Wetlands, IUUCN/UNEP/WCMC, Gland, Switzerland, ISBN 2-88032-949-3, 1992.
Latrubesse, E.: Patterns of Anabranching channels, the ultimate end-member adjustments of mega-rivers, Geomorphology, 101, 130–145, 2008.
Leopold, L. B. and Maddock Jr., T.: The Hydraulic Geometry of Stream Channels and Some Physiographic Implications, Geological Survey Paper 252, 1953.
Main, M.: Zambezi, Journey of a River, Southern Book Publishers, Halfway House, South Africa, ISBN 1-86812-257-3, 1992.

ESURFD
1, 407–435, 2013

Low-resolution modelling of river morphology

M. Nones and M. Guerrero

McCartney, M., Cai, X., and Smakhtin, V.: Evaluating the Flow Regulating Functions of Natural Ecosystems in the Zambezi River Basin, Research Report n. 148 of IWMI (International Water Management Institute), 2013.

Nones, M.: Riverine dynamics at watershed scale: hydro-morpho-biodynamics in rivers, Eds. LAP Lambert Academic Publishing, p. 140, ISBN-13 978-3659367854, 2013.

Parker, G. P., Wilcock, P. R., Paola, C., Dietrich, W. E., and Pitlick, J.: Physical basis for quasi-universal relations describing bankfull hydraulic geometry of single-thread gravel bed rivers, J. Geophys. Res., 112, F04005, doi:10.1029/2006JF000549, 2007.

Reeve, W. H.: Progress and Geographical Significance of the Kariba Dam, Geogr. J., 126, 140–146, 1960.

Ronco, P., Fasolato, G., and Di Silvio, G.: Modelling evolution of bottom profile and grainsize distribution in unsurveyed rivers, Int. J. Sediment Res., 24, 127–144, 2009.

Ronco, P., Fasolato, G., Nones, M., and Di Silvio, G.: Morphological effects of damming on lower Zambezi River, Geomorphology, 115, 43–55, 2010.

Saurral, R., Montroull, N., and Camilloni, I.: Development of statistically unbiased 21st century hydrology scenarios over La Plata Basin, International Journal of River Basin Management, in press, 2013.

Singh, V. P.: On the theories of hydraulic geometry, Int. J. Sediment Res., 18, 196–218, 2003.

Suschka, J. and Napica, P.: Ten years after the conclusion of Cabora Bassa Dam, The impacts of large water projects on the environment, Proceedings of an international symposium, UNEP/UNESCO, Paris, France, 1986.

Tilmant, A., Kinzelbach, W., Juizo, D., Beevers, L., Senn, D., and Casarotto, C.: Economic valuation of benefits and costs associated with the coordinated development and management of the Zambezi river basin, Water Policy, 14, 490–508, 2012.

Timberlake, J.: Biodiversity of the Zambezi basin wetlands, review and preliminary assessment of available information, Final Report IUCN, Harare, Zimbabwe, 1998.

Walford, H. L., White, N. J., and Sydow, J. C.: Solid sediment load history of the Zambezi Delta, Earth Planet. Sc. Lett., 238, 49–63, 2005.

Walling, D. E.: The sediment yields of African rivers. Challenges in African Hydrology and Water Resources, Proceedings of the Harare Symposium, IAHS-AISH P., 144, 265–283, 1984.

Wilkerson, G. V. and Parker, G.: Physical Basis for Quasi-Universal Relations Describing Bankfull Hydraulic Geometry of Sand-Bed Rivers, J. Hydraul. Eng.-ASCE, 137, 739–753, 2011.

ESURFD

1, 407–435, 2013

Low-resolution modelling of river morphology

M. Nones and M. Guerrero

Williams, R. D., Brasington, J., Hicks, M., Measures, R., Rennie, C. D., and Vericat, D.: Hydraulic validation of two-dimensional simulations of braided river flow with spatially continuous aDcp data, Water Resour. Res., doi:10.1002/wrcr.20391, in press, 2013.
Yalin, M. S.: River mechanics, Eds. Pergamon Press, Oxford, England, 1992.

ESURFD
1, 407–435, 2013

Low-resolution modelling of river morphology

M. Nones and M. Guerrero

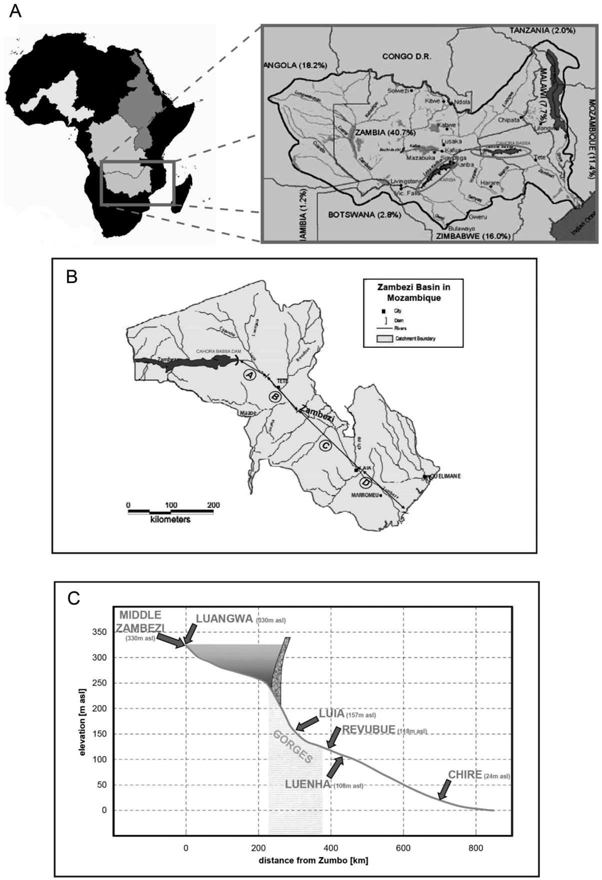

Fig. 1. (A) The Zambezi River basin. **(B)** Lower Zambezi downstream the Cahora Bassa dam. **(C)** The main channel and principle tributaries of the lower reach.

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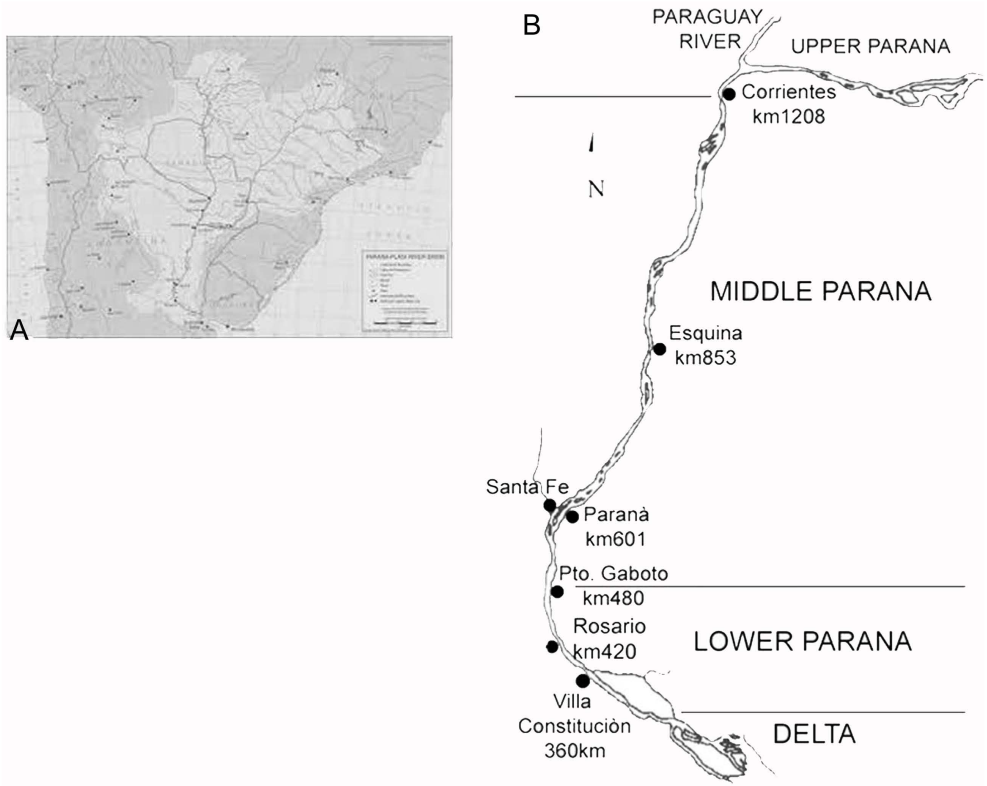

Fig. 2. (A) La Plata Basin. **(B)** The Middle and Lower Parana with the principal cities and corresponding kilometric labelling of the navigation way.

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1, 407–435, 2013

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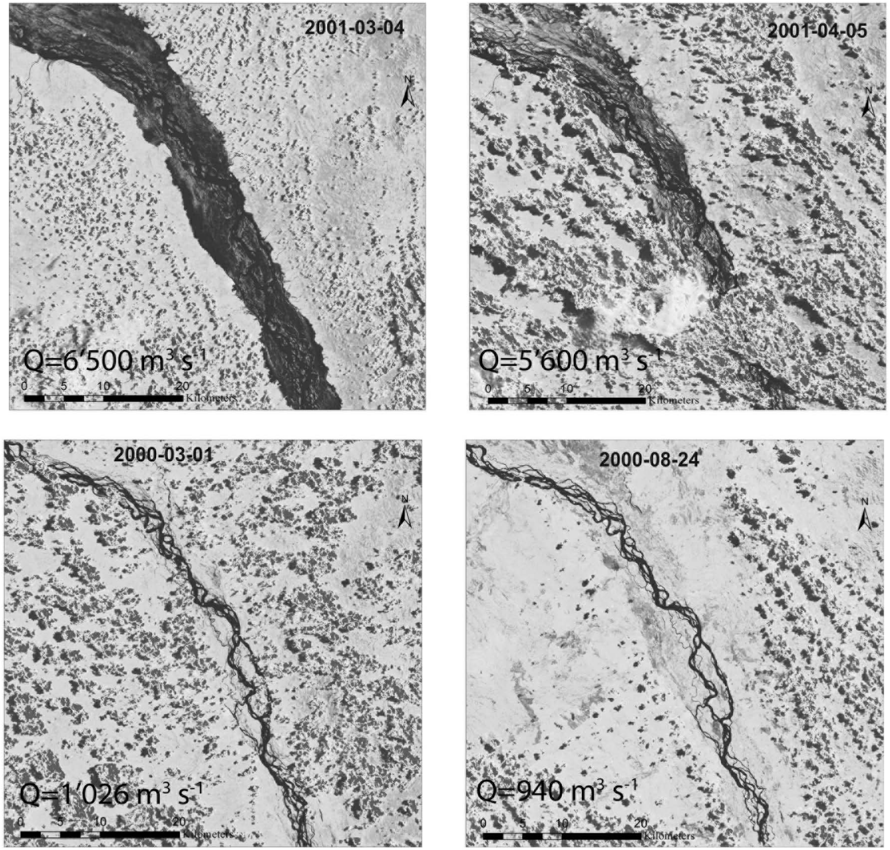

Fig. 3. Example of satellite images of the Lower Zambezi River upstream Caia (Mozambique): variation of the active river width related to the variation of the river discharge.

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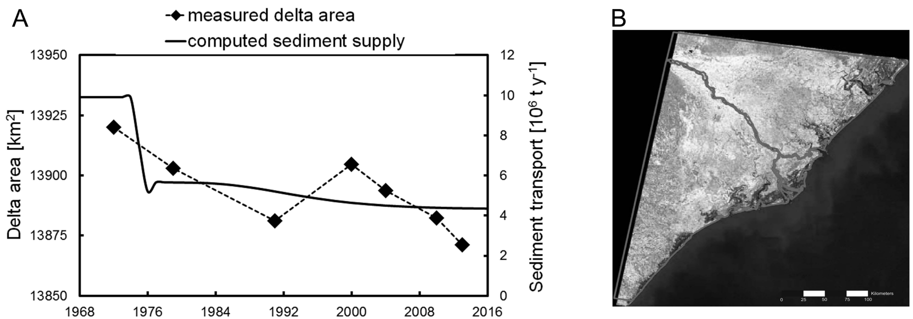

Fig. 4. (A) Simulated sediment yield and observed evolution of the Zambezi delta. **(B)** Image from satellite of the Zambezi's Delta.

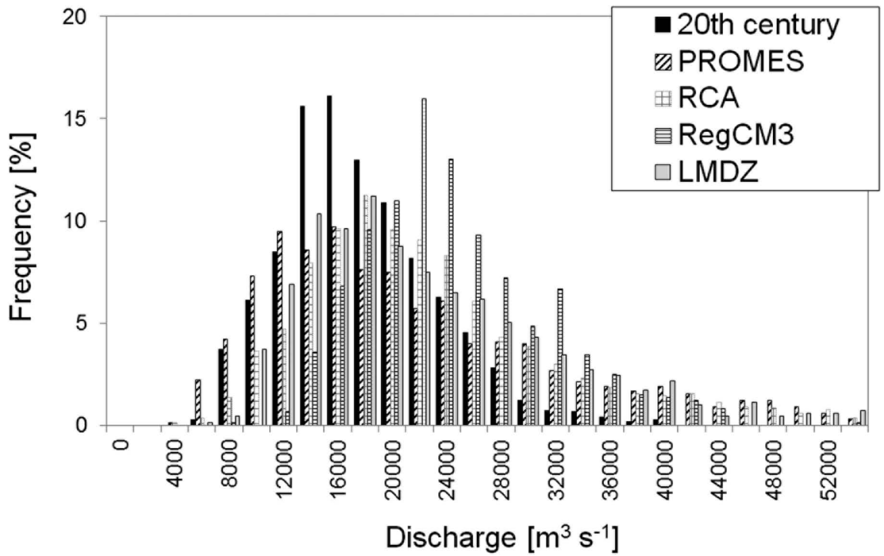

Fig. 5. Frequency distributions of monthly flow discharges of applied scenarios for LUFM modelling (20th century and future prediction from listed RCMs) at Corrientes.

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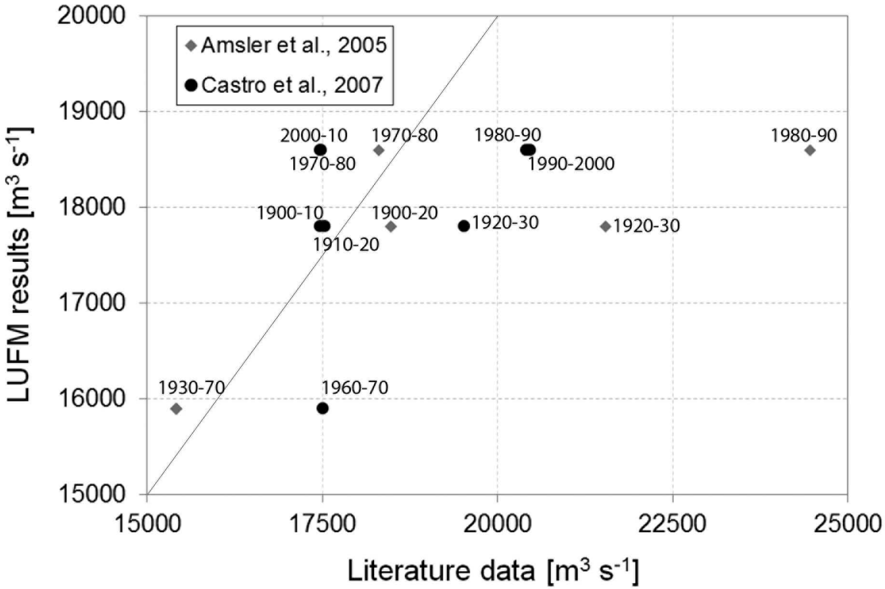

Fig. 6. Comparison of effective discharges over decades at Corrientes.

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1, 407–435, 2013

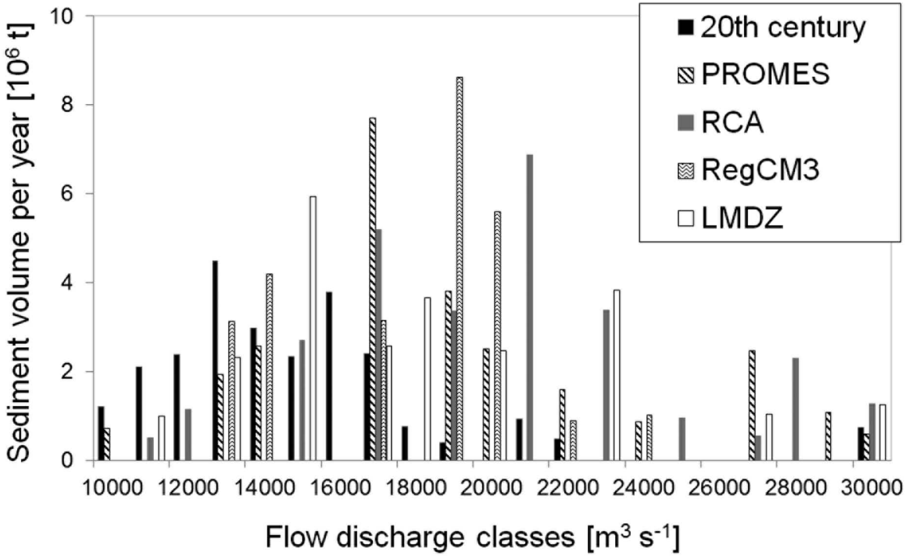

Fig. 7. Sediment volume per year from LUFM modelling over corresponding flow discharge classes at Corrientes, characterizing past and future scenarios.

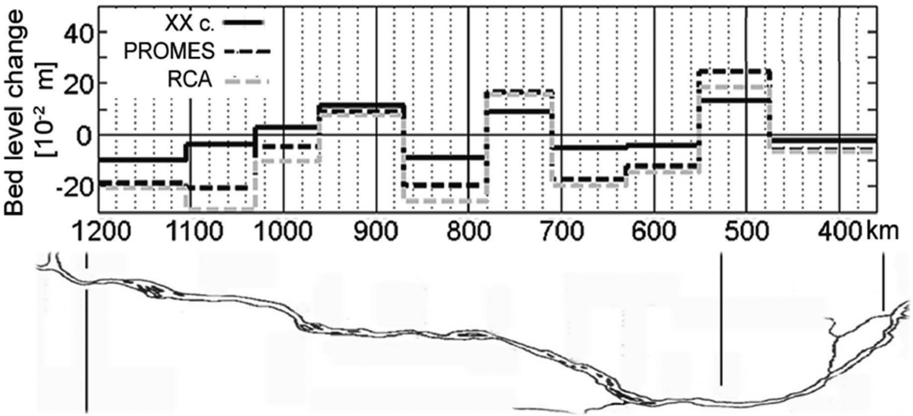

Fig. 8. Simulated cumulate variation of the bed level for the continuous time series: past century and 21st century predictions (PROMES and RCA scenarios).

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1, 407–435, 2013

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