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Integrating sediment dynamics into physical habitat models

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In the last years there has been increasing recognition of the key role played by sediment transport on the definition of physical habitat in streams. In particular, human-induced changes in sediment dynamics can cause severe changes on stream morphology (e.g. channel incision and/or widening) and on substrate composition (e.g. through sediment fining or coarsening processes), resulting in drastic consequences to stream ecological health.

Taking into account sediment dynamics is especially important in the case of urban streams, where many restoration efforts fail to define morphologically stable conditions, mainly due to the lack of precise, reliable tools to predict stream morphological response.

Despite the significant importance of sediment dynamics on habitat characteristics, it has not yet been integrated into physical habitat models (PHM). Available PHM rely on the assumption that both bed shape and substrate composition remain unchanged, which is in many instances patently flawed.

This paper firstly proposes an integrative technique to incorporate sediment dynamics into PHM. The approach solves the one dimensional unsteady flow equations (full dynamic St. Venant equations) along with the sediment continuity equation. Sediment transport is calculated for different sediment size fractions in order to allow the simulation of changes in substrate composition (e.g. coarsening/fining). After each time step the updated morphology and sediment composition are then used to calculate habitat characteristics.

Secondly, a conceptual simulation is presented to depict the general capabilities of the model to qualitatively predict morphological and substrate composition changes. The results of the proposed sediment-integrative model are compared with typical PHM results. Results have shown that significant differences between the results given by the proposed model and typical PHM in predicting habitat characteristics may be found. Also, the changes induced by sediment dynamics must be analyzed together and tracked over time in order to describe their consequences on the physical habitat.

Accounting for sediment dynamics has proven to be a significant improvement in stream habitat assessment. Several cases of ecological response have shown to be mainly controlled by sediment dynamics.

Keywords: *Physical habitat model (PHABSIM), sediment transport, ecological response model.*

1. INTRODUCTION

In the last decades the increasing socioeconomic water demand has shed light onto the importance of ecological quality of streams, raising the question of how much the stream ecology would be sacrificed due to different water management policies. The highly degraded situation of many streams has driven costly restoration works and exposed the need for reliable methods to quantify the amount of ecological improvement. The immediate consequence was the development of different methodologies of ecological response assessment.

The Physical Habitat Simulation System (PHABSIM, Milhous, 1989) is one of the most widely used tools to assess the ecosystem response to flow regime changes. It analyses physical habitat quality and quantity by identifying levels of habitat suitability. The analysis is based on the preference of target species and life stages for flow conditions (e.g. velocity and depth) as well as substrate composition. Habitat variability can be represented as habitat time series, providing valuable information to assess issues related with species life cycles. Hydraulic variables used in PHABSIM simulations are usually obtained by the application of hydraulic models. These models rely on the assumption that both the shape of the channel and the substrate composition do not substantially change in time over the range of flows simulated. In practice, there are many cases where these assumptions do not hold true and considerable changes in bed shape or substrate may take place due to sediment dynamics. This is of particular importance when sediment supply is significantly changed due to e.g. flow regime, land use and river training alterations.

The impacts of substrate characteristics on ecosystem quality have been reported by several researchers (e.g. Kondolf, 2000; Julien and Bergeron, 2006; Shirazi and Seim, 1981). Milhous (2004) observed that significant differences in bed shape and substrate composition for three different field surveys produced considerable differences in physical habitat versus discharge relation. The author also identified that no direct relation between discharge and bed shape can be established (such as low bed levels during high flow due to erosion and higher levels during low discharges) as the latter is intimately associated with the previous history of discharges and sediment inputs. These observations highlight the importance of tracking both stream shape and bed composition changes in time by taking into account the complex time-dependent dynamics of sediment transport.

This paper firstly presents a numerical model that combines hydraulic, sediment transport and physical habitat models for predicting stream ecological response. Secondly the results of a conceptual simulation are presented to depict the general capabilities of the model to qualitatively predict morphological and substrate composition changes, as well as the consequent habitat changes. Physical habitat characteristics furnished by the model are then compared with those provided when sediment dynamics is not taken into account.

2. MODEL DESCRIPTION

The model is comprised by five main components which are solved consecutively (uncoupled) for each time step. The following sections describe each component in details.

2.1. Hydraulic model

The hydraulic model solves the Saint Venant one-dimensional unsteady flow equations (Liggett and Cunge, 1975):

$$\frac{\partial y}{\partial t}+\frac{1}{B}\frac{\partial Q}{\partial x}=0 \qquad ; \qquad \frac{\partial}{\partial t}\left(\frac{Q}{A}\right)+\frac{\partial}{\partial x}\left(\frac{\alpha Q^2}{2A^2}\right)+g\frac{\partial y}{\partial x}+g\frac{Q|Q|}{K^2}=0 \qquad (1)\ ;\ (2)$$

where t=time; x=streamwise coordinate; y=water surface elevation; g =gravitational acceleration; U= cross-section averaged streamwise flow velocity; Q= flow discharge; A= flow area; α= non-uniform velocity distribution coefficient; K= conveyance. The cross section is divided into vertical strips (see sediment transport model) and the conveyance K *is* obtained by the sum over all vertical strips :

$$K=\sum_{m=1}^{M}\frac{1}{n}A_m R_{hm}^{2/3} \qquad (3)$$

where n=manning roughness coefficient; A_m= flow area of vertical strip m; R_{hm}= hydraulic radio of vertical strip m; M= number of vertical strips;

The equations are solved by using a generalized form of the Preissmann (1961) four-point implicit finite difference scheme. In this scheme a continuous function f (i.e., y and Q) and its time and space derivatives area replaced by:

$$f = \theta\left[\psi f_{j+1}^{n+1} + (1-\psi) f_j^{n+1}\right] + (1-\theta)\left[\psi f_{j+1}^{n} + (1-\psi) f_j^{n}\right] \tag{4}$$

$$\frac{\partial f}{\partial t} = \psi \frac{f_{j+1}^{n+1} - f_{j+1}^{n}}{\Delta t} + (1-\psi)\frac{f_j^{n+1} - f_j^{n}}{\Delta t} \quad ; \quad \frac{\partial f}{\partial x} = \theta \frac{f_{j+1}^{n+1} - f_j^{n+1}}{\Delta x} + (1-\theta)\frac{f_{j+1}^{n} - f_j^{n}}{\Delta x} \qquad (5)\ ;\ (6)$$

where θ and ψ are time and space weighting coefficients; n is the number of time steps; j is the number of space steps; Δt= time step; Δx= space step.

2.2. Sediment transport model

Wilcock (2003) transport model is used in this study for estimating fractional transport rates for mixed sand/gravel sediment. The transport function is defined as

$$W_i^* = \begin{cases} 0.002\phi^{7.5} & \phi < 1.35 \\ 14\left(\dfrac{1-0.894}{\phi^{0.5}}\right)^{4.5} & \phi \geq 1.35 \end{cases} \tag{7}$$

where W_i* is a parameter representing the rate of transport for size i, and ϕ is the relationship between bed shear stress τ and a reference value of shear stress τ_{ri}, i..e.,

$$W_i^* = \frac{(s-1)gq_{si}}{F_i u_*^3} \quad ; \quad \phi = \frac{\tau}{\tau_{ri}} \qquad (8)\ ;\ (9)$$

In (8) s is the ratio of sediment to water density, g the gravity, q_{si} the volumetric transport rate of size i per unit width, F_i is the fraction of size i in the bed surface and u_* is the shear velocity. Reference shear stress τ_{ri} may be regarded as the critical shear stress. The value of τ_{ri} for each individual grainsize is given by:

$$\frac{\tau_{ri}}{\tau_{rsm}} = \left(\frac{D_i}{D_{sm}}\right)^b \tag{10}$$

where τ_{rsm} is the value of τ_{ri} that corresponds to the mean size of bed surface D_{sm}, and b is given by:

$$b = \begin{cases} 0.12 & \dfrac{D_i}{D_{sm}} < 1 \\ \dfrac{0.67}{1+\exp\left(1.5 - \dfrac{D_i}{D_{sm}}\right)} & \dfrac{D_i}{D_{sm}} \geq 1 \end{cases} \tag{11}$$

The reference shear stress for mean grainsize is observed to depend on the full particles size distribution in the bed, and can be modeled as a function of the sand fraction in the mixture:

$$\tau_{rm} = (s-1)\rho g D_{sm}\left[0.021 + 0.015\exp(-20F_s)\right] \tag{12}$$

where F_s is the fraction of sand in the surface size distribution.

In one-dimensional models the use of cross-sectional average shear stress may give rise to significant underestimations of sediment transport rate. In order to have a better estimation of total sediment transport rate, in this work the cross section is subdivided into vertical strips and the transport formula is applied individually. The cross section transport rate of grainsize i is the sum of transport rate in each strip. Shear stress in each strip is estimated using hydrodynamic information as $\tau_m = \gamma R_{hm} S_f$, where R_{hm} is the hydraulic radio of the individual vertical strip m and $S_f=(Q/K)^2$ is the energy slope.

2.3. Morphological model

Bed level changes are solved in two steps. First the one-dimensional sediment continuity equation (Exner equation)

$$\frac{\partial Q_s}{\partial x} + (1-\lambda) B \frac{\partial z}{\partial t} = 0 \tag{13}$$

is solved providing the cross-section averaged values of erosion (or sedimentation) ΔZ. In (14) Q_s is the bedload transport and λ is the porosity of the bed material. The equation is solved using the following finite difference approximation:

$$(1-\lambda)\left\{\theta\left[\psi B_j^{n+1} + (1-\psi) B_{j-1}^{n+1}\right] + (1-\theta)\left[\psi B_j^{n} + (1-\psi) B_{j-1}^{n}\right]\right\}\frac{\Delta z_j}{\Delta t} + \theta\left(\frac{Qs_j^{n+1} - Qs_{j-1}^{n+1}}{\Delta x_{j-1}}\right) + (1-\theta)\left(\frac{Qs_j^{n} - Qs_{j-1}^{n}}{\Delta x_{j-1}}\right) = 0 \tag{14}$$

The second step consists in distributing ΔZ over the cross section. This is done by weighting local ΔZ values as a function of the transport rate in each point on the bed:

$$\Delta z_p = C q_{sp} \tag{15}$$

where subscript p represents a point in the bed surface (see.Figure 1). The coefficient C is obtained by imposing that the total eroded area be equal to that given by Exner equation, that is:

$$\Delta Z B = \sum_{p=1}^{P-1} \frac{\left(\Delta z_p + \Delta z_{p+1}\right)}{2} b_m \tag{16}$$

where b_m is the width of the strip between points p and $p+1$.

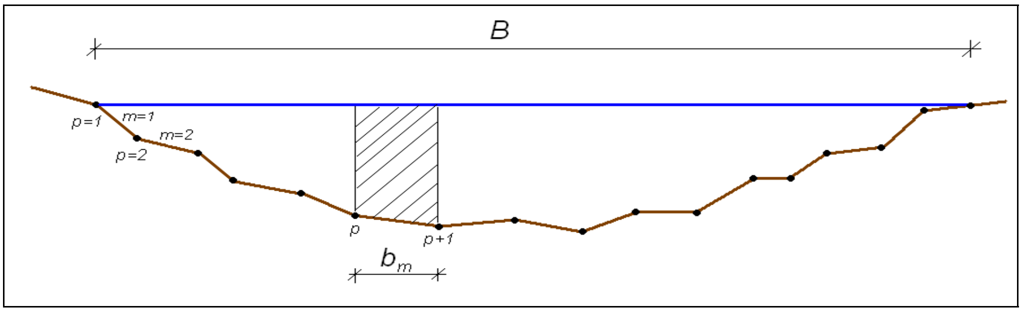

Figure 1: Cross-section sketch showing the vertical strip used to distribute sediment transport transversely.

2.4. Grain sorting model

The grain sorting model is based on the mass conservation in a thin layer of thickness L_a on the bed surface (active layer):

$$(1-\lambda)\left[f_i \frac{\partial z}{\partial t} + \frac{\partial}{\partial t}(F_i L_a)\right] = -\frac{1}{B}\frac{\partial}{\partial x}(Qs_i) \tag{17}$$

where F_i is the fraction of sediment size i in the active layer. This equation has the same form as that used by Hirano (1971), Ribberink (1987), Parker and Sutherland (1990) and Parker (1991). f_i is defined differently whether erosion or deposition occurs. If erosion takes place, the active layer is displaced downwards incorporating the material of the layer immediately below and f_i takes the value of the fraction of sediment size i in the latter layer. In the case of aggradation, the control volume of the active layer loses particles as it is displaced upwards so that f_i is equal to the fraction of sediment size i in the active layer. The vertical substrate profile is divided into layers which store a particular grainsize distribution. Several layers are necessary to record the history of successive erosion/sedimentation episodes.

2.5. Physical habitat model

The physical habitat used is based on PHABSIM (USGS, 2001) Weighted Usable Area (WUA). Here WUA is defined for one cross section (instead of a reach) by summing up the width of the vertical strips in the bed weighted by an index that represents the habitat suitability.

$$WUA = \sum B_m C_m \tag{18}$$

where C_m the combined suitability of strip m. C_m is defined as the product of the three habitat suitability coefficients being considered here:

$$C_m = HSC_v \times HSC_d \times HSC_s \quad (19)$$

where HSC_v, HSC_d and HSC_s are respectively suitability coefficients for velocity, depth, and substrate composition which values are between 0 (unsuitable) and 1 (fully suitable). These coefficients are obtained by the habitat suitability curves for a particular species and life stage. More information on habitat suitability criteria may be found in USGS (2001). In this paper HSC_s is defined as a function of sediment median diameter D_{50}. Depending on the specific analysis carried out, other variables related to sediment size distribution can also be used (e.g. percentage of fines).

3. MODEL APPLICATION

A conceptual simulation was carried out over a 3Km long reach with 0.001 slope and trapezoidal cross-sections 7m-wide (base width) and bank slopes 2V:7H (Figure 2). A one-year discharge time series was introduced as the upstream boundary condition for the hydraulic model (Figure 3a) and a fixed water level was established as the downstream boundary condition. This level was chosen in order to produce a M1 backwater curve. No overbank flow occurred during the simulation. This situation corresponds to a hydrological year without discharge peaks greater than approximately 1 or 2 years return period. The initial sediment grainsize distribution presented in Figure 4 was used all over the reach, including bed surface (active layer) as well as all layers underneath the active layer. Zero sediment inflow and fixed bed level were used as upstream boundary conditions in Exner equation. Time steps used were considerably small (less than 1 minute) and Δx=100m throughout the reach.

Figure 3 presents time-series of WUA for two cross-sections. The first section (Figure 3b) is located 100m downstream from the upstream boundary, where erosion is expected to take place due to the lack of sediment supply. The second cross-section is the downstream boundary condition. An erosion of 15cm has occurred upstream while a sedimentation of the same order has been observed at the downstream cross-section (Figure 2). The deposition of material downstream is explained by the velocity reduction due to the fixed water boundary condition at a high level. Figure 3d shows the time evolution of D_{50} in both cross-sections.

The relation between WUA and Q for the sections analyzed here are clearly different. In the upstream cross-section an increase in flow discharge induces a loss of physical habitat. Lowest discharges of the order of 5m^3/s are associated with suitability coefficients for velocity and depth very close to the optimum value so that any increase in Q results in habitat deterioration. Downstream flow depths are completely controlled by the boundary condition so that depths do not change over time. In this case, the high water level induces small velocities and any increment on discharge considerably increases the velocity suitability coefficient.

To complete the analysis, the effects of bed shape and sediment size changes on physical habitat must be investigated. Bed incision (e.g. observed in the upstream section) is accompanied by a reduction of wet width, which represents a loss of total available habitat. Conversely, at the downstream cross-section, the sedimentation induces the increase of flow velocity and consequently of HSC_v. The effect of sediment size is straightforward: since initially D_{50}=6mm, any increment on median grainsize represents an improvement of habitat conditions (see Figure 5). The differences observed between WUA furnished using *i*) the model proposed in this paper and *ii*) a physical habitat model which neglects sediment dynamics must be interpreted in light of the combination of the above-mentioned effects. Both upstream and downstream changes in bed shape and sediment size induce changes in different directions in WUA: the erosion upstream deteriorates the habitat while sediment coarsening improves it; sedimentation downstream improves velocity suitability while sediment fining reduces habitat quality. The analysis of Figure 3b and c indicates that sediment size changes produce the most significant habitat modifications in both instances. This dependence is more obvious in Figure 3c, where the two time series deviate from one another after the highest flow peak induced a more significant change in sediment size.

4. CONCLUSIONS

A numerical model combining hydraulic, sediment transport and physical habitat models to assess stream ecological response was presented. Results of a conceptual simulation have illustrated the general capabilities of the model and also have highlighted the importance of sediment dynamics on the definition of the physical habitat.

The distributed approach taken here for hydraulics makes the model more flexible providing an easier treatment of details of the longitudinal characteristics of the stream, as many cross-sections may be easily added without the need of exhaustive field measurement (velocities, etc). Furthermore, the computational performance of the one-dimensional approach opens new pathways for the analysis of long term transformations of the physical environment. Time-series of physical habitat generated by the model has proven to be a powerful tool to assess issues related with species life cycles.

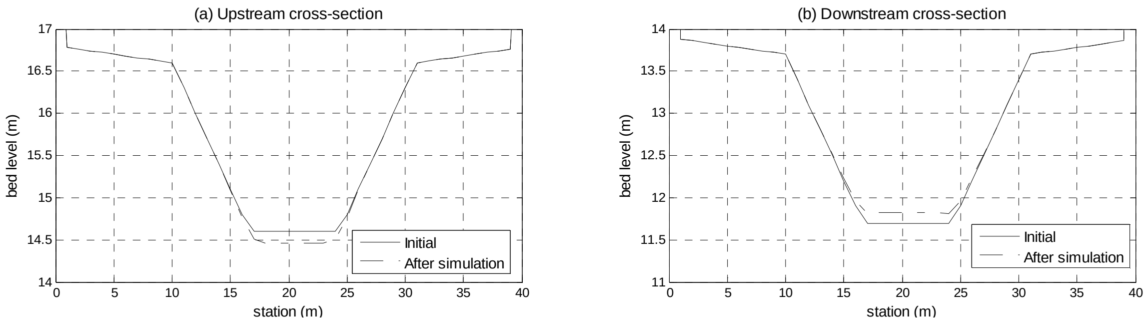

Figure 2. Initial cross-sections and the corresponding ones after simulations. (a) erosion takes place in the upstream cross-section; (b) sedimentation takes place downstream.

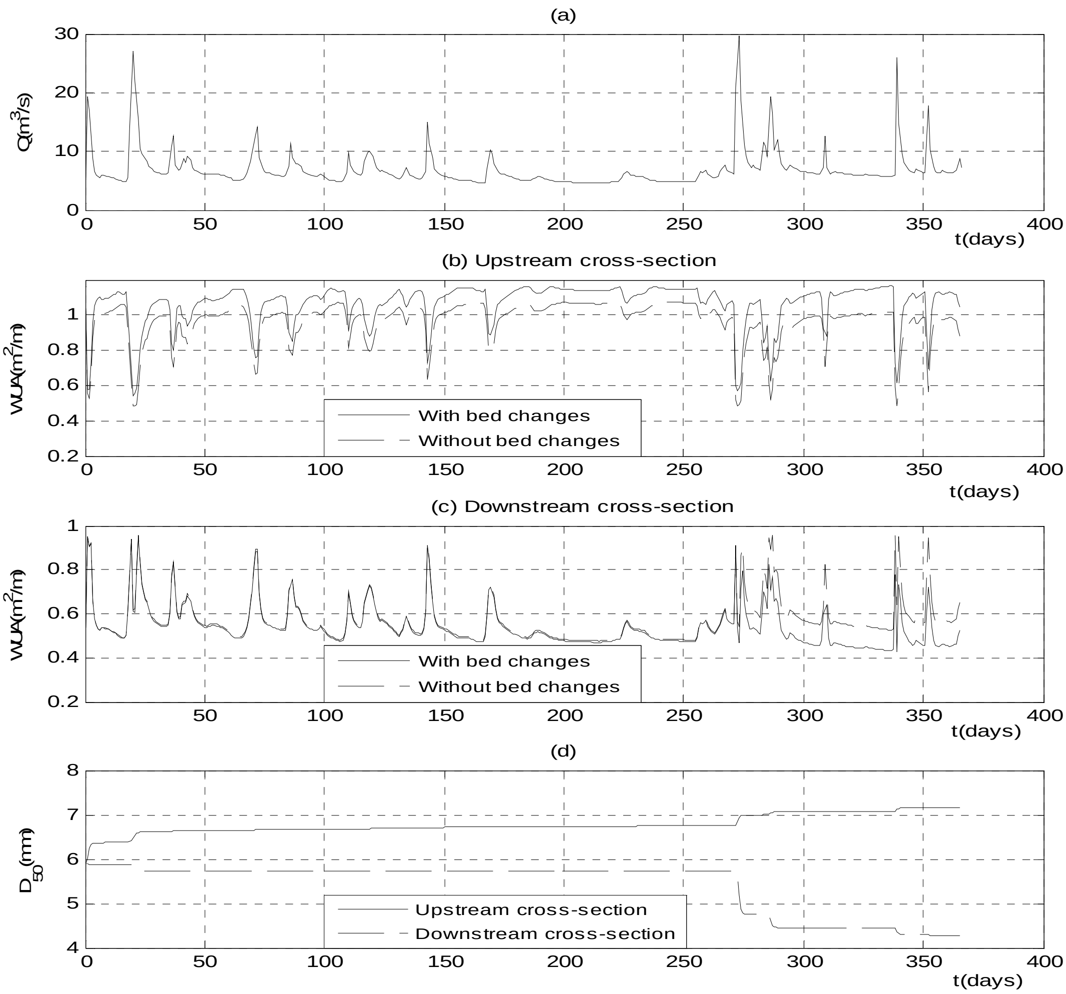

Figure 3. (a) Discharge time series used in the simulation; (b) time series of weighted usable area (WUA) for a cross-section located in the upstream part of the reach (100m downstream the boundary); (c) WUA time series for the downstream cross-section;(d) D_{50} time series for both cross-sections;

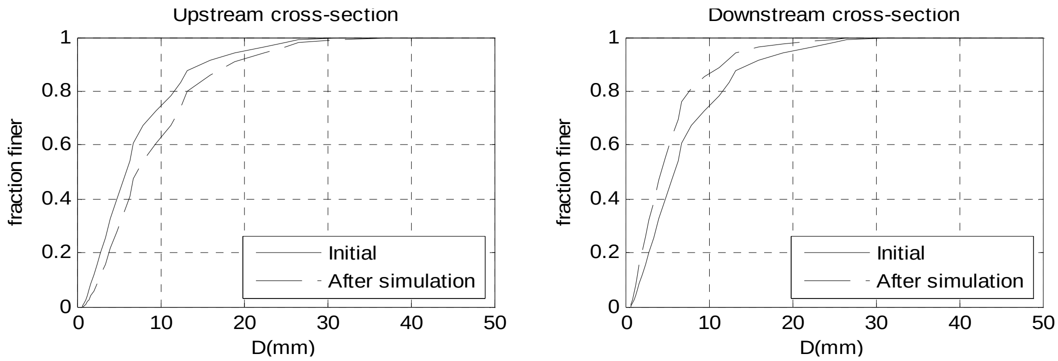

Figure 4. Grainsize distributions. Dashed lines represent the distribution after one year of flow.

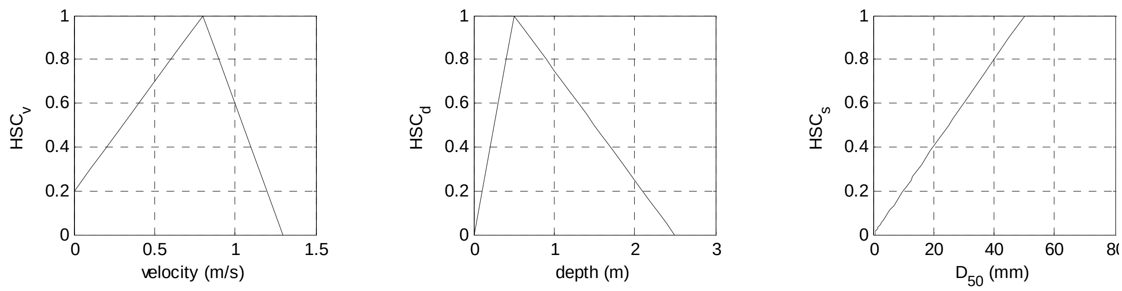

Figure 5. Habitat suitability curves used in the simulation.

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