HydroTrend v.3.0: A climate-driven hydrological transport model that simulates discharge and sediment load leaving a river system

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Abstract

HydroTrend v.3.0 is a climate-driven hydrological water balance and transport model that simulates water discharge and sediment load at a river outlet, by incorporating drainage basin properties (river networks, hypsometry, relief, reservoirs) together with biophysical parameters (temperature, precipitation, evapo-transpiration, and glacier characteristics). HydroTrend generates daily discharge values through: snow accumulation and melt, glacier growth and ablation, surface runoff, and groundwater evaporation, retention and recharge. The long-term sediment load is predicted either by the ART-QRT module based on drainage area, discharge, relief, and temperature, or the BQART module that also incorporates basin-average lithology and anthropogenic influences on soil erosion. Sediment trapping efficiency of reservoirs is based on reservoir location in the river network and its volume that determines the residence time of water within the reservoir. Glacial influence is based on the extent of ice cover, equilibrium altitude, and freezing line mobility. HydroTrend v.3.0 captures the inter- and intra-annual variability of sediment flux by using either high-resolution climate observations or a stochastic climate generator for simulations over longer geological intervals. A distributary channel module simulates the flow conditions and transport capacity across a multiple deltaic channel system. Simulations of the Metauro and the Po rivers, in Italy, are used as case studies to demonstrate the applicability of the new model.

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1. Introduction

Fluvial sediment supply directly influences coastal dynamics (Coltorti, 1997; Liquete et al., 2004; Ly, 1980; Summerhayes et al., 1978) and human habitats (Syvitski et al., 2005c). However, only 10–15% of the world’s rivers have been monitored for their supply of sediment to the coast, and most
of these rivers are no longer gauged (Syvitski et al., 2003). At longer time scales fluvial sediment supply is a dominant determinant of the stratigraphic architecture of basin fills, whereas the formation of storm beds is particularly important in defining reservoir properties (Fan et al., 2004).

**Symbole list**

- $A_g$: glacier area within a river basin (km²)
- $\bar{A}_g$: non-dimensionalized glacier area within a river basin (–)
- $A$: basin area (km²)
- $A_0$: basin area, equal to 1 (km²)
- $\bar{A}$: non-dimensionalized basin area (–)
- $C$: reservoir storage capacity (m³)
- $C_{(o)}$: the rating coefficient over a 1 year timestep (–)
- $C_s$: suspended sediment concentration (kg m⁻³)
- $D$: reservoir geometry (–)
- $E_h$: anthropogenic factor
- $E_v$: evapo-transpiration (m³ s⁻¹)
- $g$: acceleration due to gravity (m s⁻²)
- $k_1, k_2$: global climate zone-based coefficients (see Table 1)
- $L$: lithology factor (–)
- $m$: number of days
- $n$: number of years
- $n_e$: number of epochs
- $Q$: water discharge at the river mouth (m³ s⁻¹)
- $Q_0$: water discharge at the river mouth, equal to 1 (m³ s⁻¹)
- $Q$: non-dimensionalized water discharge (–)
- $Q_{bb}$: bedload (kg s⁻¹)
- $Q_{ew}$: water discharge loss by evapo-transpiration processes (m³ s⁻¹)
- $Q_{gg}$: water discharge generated by ground water (m³ s⁻¹)
- $Q_{gce}$: water discharge generated by glacier melt (m³ s⁻¹)
- $Q_n$: water discharge generated by nival melt (m³ s⁻¹)
- $Q_{pea}$: peak water discharge (m³ s⁻¹)
- $Q_r$: water discharge generated by rainfall (m³ s⁻¹)
- $Q_s$: long-term suspended sediment load (kg s⁻¹)
- $Q_{SG}$: long-term suspended sediment load derived of glacial processes (kg s⁻¹)
- $Q_{SG(o)}$: annual suspended sediment derived from glaciers (kg s⁻¹)
- $Q_{ST}$: total long-term average suspended sediment discharge (kg s⁻¹)
- $P$: total annual precipitation within the river basin (m y⁻¹)
- $P_g$: total annual precipitation restricted to glacier area (m y⁻¹)
- $R$: maximum relief of river drainage basin from sea level (m)
- $R_0$: maximum relief of drainage basin from sea level, equal to 1 (m)
- $\bar{R}$: non-dimensionalized maximum relief (–)
- $S$: slope of the riverbed (mm)
- $S_{r}$: water storage and release (m³ s⁻¹)
- $T$: basin wide average temperature (°C)
- $T_e$: sediment trapping efficiency of reservoirs/lakes (–)
- $u$: stream velocity (m s⁻¹)
- $u_{cr}$: critical stream velocity (m s⁻¹)
- $V_g$: glacier volume (km³)
- $V_{g(o)}$: annual added glacier volume (km³)
- $V_{i}^o$: operational volume of a reservoir (m³)
- $V_{g(o)}$: glacier water storage and release (m³ s⁻¹)
- $W$: drainage area above a reservoir (km²)
- $\alpha_3 - \alpha_6$: global climate zone-based coefficients (see Table 1) (kg s⁻¹ °C⁻¹)
- $\alpha_4, \alpha_5, \alpha_7, \alpha_8$: global climate zone-based coefficients (see Table 1) (–)
- $\beta$: bedload rating term (–)
- $f$: constant of proportionality (–)
- $k_1$: constant of proportionality (m³ s⁻¹)
- $k_2$: max flood constant (–)
- $\eta$: constant of proportionality (km³)
- $\lambda$: limiting angle of repose of sediment grains lying on the river bed
- $\rho$: fluid density (kg m⁻³)
- $\rho_s$: sand density (kg m⁻³)
- $\Delta T$: approximate residence time of a reservoir/lake (–)
- $\varpi$: coefficient of proportionality (kg s⁻¹ km⁻² °C⁻¹)
- $\psi$: rating parameter to capture inter-annual variability (–)
Because of scarcity of river sediment load observations, we present a significant upgrade to the model HydroTrend (Syvitski and Alcott, 1995; Syvitski et al., 1998). HydroTrend is a climate-driven hydrological transport model used to generate synthetic water discharge and sediment load records of multiple grain sizes at a river’s outlet, for time scales varying from $10^3$ to $10^7$ y. The model aims to reflect realistic water and sediment fluxes by capturing complex natural processes in relatively easy to obtain parameters. Model output is provided in such a way that it can directly be used as input for SedFlux (Hutton and Syvitski, this issue; Syvitski and Hutton, 2001), a basin fill simulation program. Key improvements to HydroTrend v.3.0 include:

1. New suspended sediment algorithms (Morehead et al., 2003; Syvitski and Milliman, 2007; Syvitski et al., 2003) to predict the long-term suspended sediment load and the instantaneous load of a river.

2. An improved routine to simulate the sediment delivery fluctuations from ice storage and release, based on changes in ice volume (Kettner and Syvitski, in press).

3. A sediment trapping routine to account for lakes or reservoirs in a river basin (Kettner and Syvitski, in press).

4. A new distributary channel routine to simulate the effect of sediment load entering the ocean through multiple outlets (Syvitski et al., 2005a).

5. The use of sequential climate observations as an alternative to the statistical generation of climate data from observed statistical variability, for more direct model comparison to observations (Syvitski et al., 2005b).

As climate and geomorphology data are available online, HydroTrend v.3.0 provides general use for the simulation of water and sediment discharge of the world’s ungauged rivers. An Internet web site for the model provides the possibility to upload input data and to run the model remotely. An email response alerts users when the simulation is completed. The website\(^1\) contains background information, example files and MATLAB routines to analyze and visualize the generated discharge and sediment load data.

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\(^1\)http://instaar.colorado.edu/deltaforce/models/hydrotrend.html.

2. Hydrological model

**HydroTrend** simulates mean daily water discharge ($Q$) at a river mouth based on the classic water balance model (Eq. (1)) of precipitation ($P$) per unit area ($A$) reduced by evaporation ($E_v$) and modified by water storage and release ($S_r$), through the simultaneous partitioning of five runoff processes on a daily ($i$) basis: rain ($Q_r$), snowmelt ($Q_s$), glacial melt ($Q_{lm}$), groundwater discharge ($Q_g$), and evaporation ($Q_{Ev}$) (Eq. (2))

\[
Q = A \sum_{i=1}^{ne} (P_i - E_{vi} \pm S_{ri})
\]

\[
Q = Q_r + Q_s + Q_{lm} - Q_{Ev} \pm Q_g
\]

The boundaries for the subcomponents are determined for every time-step. Precipitation is presumed to be equally distributed over the entire river basin. The right-hand terms of Eq. (2) are defined in detail elsewhere (Syvitski and Alcott, 1995; Syvitski et al., 1998). Basin climate (temperature and precipitation), and the lapse rate, which defines the temperature gradient with increasing elevation, determines the freeze line altitude (FLA), and the partition of precipitation into rain or snowfall. The time-varying FLA in combination with the basin hypsometry (the basin area per elevation class) determines the areas that are required by the snow and rain subcomponents. Similarly, glacier equilibrium line altitude (ELA) in combination with hypsometry determines the area of the basin covered by glaciers and thus the contribution of the ice melt component. Different climate scenarios can be simulated to hindcast or predict the influences of climate change on discharge and sediment load of a river during a particular climate interval or epoch ($ne$ in Eq. (1)).

The maximum possible discharge ($Q_{max\,\,flood}$) of a drainage basin is constrained by a power-law regression Eq. (3) after Matthai (1990). This empirical relation is initially developed for North American rivers ($r^2 > 0.99$) but appears to be also valid for rivers at other continents (Matthai, 1990).

\[
Q_{max\,\,flood} = k_1 \bar{A}^{k_2} \quad \text{for } A < 10^6 \, \text{km}^2
\]

where $\bar{A} = (A/A_0)$ is non-dimensionalized as $A_0$ is equal to 1 km$^2$, $k_1 = 8.037 \, \text{m}^3 \, \text{s}^{-1}$ and $k_1 = 0.725$. If on a certain day the peak discharge exceeds the maximum possible discharge for that basin, the program will sample a new set of statistical climate
values. After 10 attempts HydroTrend will add a flag to output file HYDRO.TRN2 file to notify the user and continues without consequences.

Geometry of the basin influences the delay in the contribution of the different hydrological subcomponents. HydroTrend takes the discharge delay and smoothing of the peak discharge by lakes and reservoirs as well as the length of the river into account while simulating discharges at the river mouth (Syvitski and Alcott, 1995). Large basins (A > 10^5 km^2) may be subdivided into several subunits using a standard lumped-model approach, with kinematic-wave routing between subunits.

The model employs the glacier ELA in combination with the hypsometry to determine the glacier area following Andrews (1975); assuming that 33% of the total glaciated area, the ablation zone is below the ELA and 66%, the accumulation zone, is above the ELA of a glacier in steady state. To simulate climate change, the model user specifies an annual trend in the ELA. Fluctuations in glacier area are driven by ELA change, the model user specifies an annual trend in the ELA of a glacier in steady state. To simulate climate scenarios in which precipitation changes may play a role (Kettner and Syvitski, in press). A more comprehensive global predictor of long-term sediment load (BQART) requires additional information about average basin lithology and human activity (Eqs. (8a) and (8b); Syvitski and Milliman, 2007), and is the recommended option. We choose to keep the ART and QRT models in HydroTrend v.3.0. as additional information required for the BQART model is not always available.

\[ Q_S = (1 - T_e)z_3 \overline{A}^{0.4} \overline{R}^{0.8} c^{k_1 T} \] the ART equation

\[ Q_S = (1 - T_e)z_6 \overline{Q}^{0.3} A^{0.5} R^{0.5} c^{k_1 T} \] the QRT equation

\[ Q_S = \omega BQ^{0.31} A^{0.5} R \] the BQART equation

\[ T < 2^\circ C \] for \( T \geq 2^\circ C \)

\[ Q_S = 2\omega BQ^{0.31} A^{0.5} R \] the BQART equation

Note that the parameters \( \overline{A}, \overline{R} \) and \( \overline{Q} \) in Eq. (6)-(8b) are, respectively non-dimensionalized: drainage basin area, maximum relief and long-term discharge; extracted, following similar reasoning as for Eq. (3). \( \omega \) is a coefficient of proportionality defined as \( \omega = 0.02 \text{ kg s}^{-1} \text{ km}^{-2} \text{ C}^{-1} \). \( T \) is basin average temperature, \( B = L(1 - T_e) E_{rh} \) is the trapping efficiency of a reservoir or lake, \( z_3 \) and \( z_6 \) are coefficients of proportionality, \( x_4, x_5, x_7, x_8, k_1 \) and \( k_2 \) are dimensionless coefficients, which depend on climatic zone based on the geographical location.

3. Sediment load model

3.1. Long-term sediment load

HydroTrend v.3.0 simulates two forms of sediment delivery using semi-empirical relationships: suspended sediment load and bedload. An empirical relationship between glacier extent and sediment production also adds to the suspended sediment supply. The total suspended sediment discharge, \( Q_{ST} \), is therefore defined as

\[ Q_{ST} = Q_s + Q_{sG} \]
of the drainage basin (Table 1). $L$ is the lithology factor, and $E_h$ is the anthropogenic factor.

It is assumed that $L = 0.5$ for basins comprised principally of hard, acid plutonic and/or high-grade metamorphic rocks. $L = 0.75$ for basins comprised of mixed, mostly hard lithology, sometimes including shield material. $L = 1.0$ for basins comprised of volcanic, mostly basaltic rocks, or carbonate outcrops, or mixture of hard and soft lithologies. $L = 1.5$ for basins characterized by a predominance of softer lithologies, but having a significant area of harder lithologies. $L = 2$ for fluvial systems draining a high proportion of sedimentary rocks, unconsolidated sedimentary cover, or alluvial deposits. $L = 3$ for basins having an abundance of exceptionally weak material, such as crushed rock, or loess deposits, or shifting sand dunes (Syvitski and Milliman, 2007).

A simple a priori method to define the $E_h$ factors around the world is based on population density (PD) and the Gross National Product (GNP) per capita (Syvitski and Milliman, 2007). $E_h = 0.3$ for basins with a high-density population $PD > 200 \text{ km}^{-2}$, and a GNP/capita $> \$15 \text{ K y}^{-1}$). $E_h = 1$ for basins with a low human footprint ($PD < 50 \text{ km}^{-2}$), or basins containing a mixture of the competing influences of soil erosion and conservation. $E_h = 2.0$ for basins where the population is high ($PD > 200 \text{ km}^{-2}$), but GNP/capita is low ($\leq \$1 \text{ K y}^{-1}$).

### 3.2. Reservoir retention

About 30% of the global sediment flux is trapped behind large reservoirs (Syvitski et al., 2005c; Vörösmarty et al., 2003). To incorporate this anthropogenic interaction, the model simulates trapping efficiency $Te$ depending on the reservoir volume either by the Brown Eq. (11), for reservoirs $<0.5 \text{ km}^3$ (Brown, 1943), or the modified Brune Eqs. (9) and (10) by Brune (1953) and Vörösmarty et al. (1997), for reservoirs $\geq 0.5 \text{ km}^3$ where $Te$ is the sum of trapping by each reservoir-regulated sub-basin $j$.

$$Te = \frac{1}{\pi} \left( 1 - \frac{0.05}{\sqrt{\Delta \tau_j}} \right) \quad V \geq 0.5 \text{ km}^3$$

Here $\Delta \tau_j$ is the approximated residence time per sub-basin $j$ and is estimated by

$$\Delta \tau_j = \frac{\sum_{i=1}^{m} V_i}{Q_j}$$

where $V_i$ is the operational volume of the reservoir $i$, $Q$ is the discharge at the mouth of each sub-basin $j$.

$$Te = 100 \left( 1 - \frac{1}{1 + 0.0021 D W} \right) \quad V < 0.5 \text{ km}^3$$

where $D$ reflects the reservoir geometry (0.046–1; mean = 0.1), $C$ is the reservoir storage capacity, and $W$ is the drainage area above the reservoir. For the sake of simplicity HydroTrend v.3.0 treats lakes equally as human-made reservoirs.

### 3.3. Glacial impact

Hallet et al. (1996) summarize studies by Guymon (1974) and Parks and Madison (1985), which indicate that sediment flux at the river mouth increases with glacier area in the basin. A numerical approach to incorporate annually derived sediment from glaciers is based on data presented by

### Table 1

Regression coefficients of long-term sediment Eq. (6) and (7) (after Syvitski et al., 2003)

<table>
<thead>
<tr>
<th>Global sector</th>
<th>Polar $(T \leq 0 \degree C)$</th>
<th>Temperate N (lat. $&gt; 30 \degree N; T &gt; 0 \degree C)$</th>
<th>Tropics N (lat. $0–30 \degree N$)</th>
<th>Tropics S (lat. $0–30 \degree S$)</th>
<th>Temperate S (lat. $&gt; 30 \degree S; T &gt; 0 \degree C$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_1$</td>
<td>$2.0 \times 10^{-5}$</td>
<td>$6.1 \times 10^{-5}$</td>
<td>$0.31$</td>
<td>$0.57$</td>
<td>$1.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>$z_4$</td>
<td>$0.5$</td>
<td>$0.55$</td>
<td>$0.4$</td>
<td>$0.5$</td>
<td>$0.43$</td>
</tr>
<tr>
<td>$z_5$</td>
<td>$1.5$</td>
<td>$1.12$</td>
<td>$0.66$</td>
<td>$0.37$</td>
<td>$0.96$</td>
</tr>
<tr>
<td>$z_6$</td>
<td>$1.3 \times 10^{-4}$</td>
<td>$1.1 \times 10^{-3}$</td>
<td>$2.0$</td>
<td>$162$</td>
<td>$1.1 \times 10^{-3a}$</td>
</tr>
<tr>
<td>$z_7$</td>
<td>$0.55$</td>
<td>$0.53$</td>
<td>$0.45$</td>
<td>$0.65$</td>
<td>$0.53$</td>
</tr>
<tr>
<td>$z_8$</td>
<td>$1.5$</td>
<td>$1.1$</td>
<td>$0.57$</td>
<td>$-0.05$</td>
<td>$1.1a$</td>
</tr>
<tr>
<td>$\xi_1$</td>
<td>$0.1$</td>
<td>$0.07$</td>
<td>$-0.1$</td>
<td>$-0.1$</td>
<td>$0$</td>
</tr>
<tr>
<td>$\xi_2$</td>
<td>$0.1$</td>
<td>$0.06$</td>
<td>$-0.09$</td>
<td>$-0.16$</td>
<td>$0.06a$</td>
</tr>
</tbody>
</table>

*Too few river data are available to extract QRT equation parameters for the Southern Temperate region. As an assumption, temperate Northern parameters are substituted here.*
Guymon (1974)

\[ Q_{S(G_{0})} = 1.93 \times 10^{-3} A(9.8)^b - Q_s \quad (r^2 = 0.74) \]

(12)

where \( Q_{S(G_{0})} \) is the annual average suspended sediment exclusively derived from glaciers, \( A \) is the drainage basin area, and \( b \) is the logarithm of percentage glacier cover of the basin. So, sediment production by a glacier is based on an empirical relationship between sediment flux and glacier area within a basin. Based on Eq. (12), the long-term suspended sediment exclusively derived by glaciers is

\[ Q_S = \left( 1 - \frac{V_S}{P_g} \right) \frac{\sum_{i=1}^{n} Q_{S(G_{0})}}{n} \]

(13)

where \( V_S \) is the annual water storage (rain and snow turned into ice) of the glacier, \( P_g \) is the total annual precipitation falling directly on the glacier, and \( n \) is the number of years of a simulated glacier in the drainage basin. No distinction is made between minimally erosive cold-based glaciers and warm-based (streaming faster) glaciers, which are more erosive.

3.4. Daily sediment distribution

A stochastic \( \Psi \) model of Morehead et al. (2003) is used to calculate the daily suspended sediment load fluxes (Eq. (14)). The model is derived from the commonly used empirical rating equation \( Q_s = aQ \). However, these rating equations do not incorporate the variability around the trend. The \( \Psi \) model captures the inter- and intra-annual variability of suspended sediment load of rivers.

\[ \frac{Q_{S[i]}}{Q_{S(T)}} = \psi[i] \left( \frac{Q_{S[i]}}{Q} \right) \quad \text{the } \Psi \text{ model} \]

(14)

where \( m \) is the total number of days being modeled within a climate interval or epoch. The following relationships define the inter- and intra-annual variability of the \( \Psi \) model (Morehead et al., 2003; Syvitski et al., 2005b):

\[ E(\psi) = 1 \]

(15)

\[ \sigma(\psi) = 0.763(0.99995)^{Q} \]

(16)

\[ E(C) = 1.4 - 0.025T + 0.00013R + 0.145 \ln(Q_{S(T)}) \]

(17)

\[ \sigma(C) = 0.17 + 0.0000183Q \]

(18)

In these equations, \( E \) and \( \sigma \) denote subsequently the mean and standard deviation of a random variable. The rating coefficient \( C \) varies over a time step of 1 y and is taken to have a normal distribution with standard deviation that depends on the mean discharge. In this way, small low discharge rivers tend to have less annual variation around the mean value of \( C \). Large rivers with high discharges have greater values of \( \sigma(C) \), depending on the importance of their various tributaries to the overall discharge within a given year. The random variable \( \psi \) varies on a daily time step and has a log-normal distribution. Also for this parameter the standard deviation (and variance) depends on the mean discharge, but now in a power relation. In this way flood dynamics are captured: small rivers have a larger variance in \( \psi \), while larger rivers have a smaller variance. Notice that for short simulations (years to decades), the mean of all the daily suspended sediment loads \( (Q_{S[i]}) \) derived from the \( \Psi \) model (Eq. (14)) might not match the long-term sediment load \( (Q_{S(T)}) \) provided by Eqs. (6–8b), because of the nature of the incorporated variability. However, for long-term simulations the mean of all the daily suspended sediment loads \( (Q_{S[i]}) \) will be similar to the long-term sediment load \( (Q_{S(T)}) \).

3.5. Bedload

The daily bedload \( (Q_{b[i]}) \) is simulated depending on the delta plain slope \( (S) \) and the daily mean water discharge \( (Q_{i}) \) after the modified Bagnold (1966) equation

\[ Q_{b[i]} = \left( \frac{\rho_s}{\rho_s - \rho} \right) \frac{\rho g Q_{i}^2 S e_b}{g \tan \lambda} \quad \text{when } u \geq u_{cr} \]

(19)

where \( \rho_s \) is sand density, \( \rho \) is fluid density, \( e_b \) is the bedload efficiency, \( \beta \) is a dimensionless bedload rating term, \( \lambda \) is the limiting angle of repose of sediment grains lying on the river bed, \( u \) is stream velocity, and \( u_{cr} \) is the critical velocity needed to initiate bedload transport.

3.6. Distributary channels

Distributary channels strongly impact sediment delivery to the ocean. The discharge velocity, channel width and depth, as well as the sediment load all change when a river reaches the ocean by multiple outlets, influencing the resulting river plume into the marine basin. Furthermore, sediment
load per outlet branch tend to vary more largely than for the water discharge in a multiple outlet river system (Syvitski et al., 2005a). These changes are important as input to stratigraphic models like SedFlux (Hutton and Syvitski, this issue; Syvitski and Hutton, 2001) as they will affect river plume width and distance out off the coast as well as plume concentration, which determines e.g. if the river plume will become hyperpycnal or hypopycnal. Thereby multiple outlets are less energetic, generating more diffusive plumes into the ocean than single outlet systems. So, multiple outlet diffusive plumes distributing sediments closer to the coast than single jet-like plume rivers.

An adapted $\Psi$ model (Eq. (20)) presented by Syvitski et al. (2005a) is incorporated in HydroTrend v.3.0 to simulate distributary channel sediment load based on the fraction of discharge per channel.

$$Q_{S_{[p]}} = \psi_{[p]}/E \left( \frac{Q_{[p]}}{Q_{S_T}} \right)^{C_{(a)}} \left( \frac{Q_{[p]}}{Q_{[p]}} \right)^{C_{(a)}}$$

where

$$\sum_{p=1}^{k} (Q_{[p]})^2 = Q$$

$p$ indicates the distributary branch of the river being modelled, $k$ is the total number of branches, $i$ is the daily time step, $E$ is the rate of sediment trapped by the subareal delta which is defined by the user and $f$ is a constant of proportionality such that:

$$f = \frac{\left( \sum_{p=1}^{k} \sum_{i=1}^{n} Q_{S_{[p]}} \right)/m}{Q_S}$$

By using the same rating coefficient $C_{(a)}$ for each distributary channel, for each year, the delta behaves as a coherent unit driven by the flux of water and sediment coming down the hinterland river. $E$ equals 1.0 as no sediment is trapped on the delta.

### 4. Program notes and structure

#### 4.1. Model input

Appendix A illustrates the 3 ASCII input files of HydroTrend v.3.0. HYDRO.IN, the main input file, contains: project title, input–output directory, simulation length, yearly and monthly climate statistics, glacier parameters, groundwater parameters and parameters that describe the possible river distributaries. A new epoch can be started after line 44, by leaving one blank line and repeating the input lines from line 5 onwards. The HYDRO.HYPS file contains the hypsometric data of the river basin. The hypsometry can be obtained by GIS analysis of a Digital Elevation Model (DEM) of the basin. These two input files (HYDRO.IN and HYDRO.HYPS) are required to run HydroTrend v.3.0. The third file, HYDRO.CLIMATE, allows the user to run HydroTrend v.3.0 with sequential climate input instead of the statistical realizations of the climate otherwise defined in HYDRO.IN. The sequential climate input minimum–maximum time step ranges from 1h to 1 day. A line-by-line description of the input files can be found on the web.

#### 4.2. Model structure

HydroTrend v.3.0, written in ANSI C is platform independent. Compilation for multiple platforms is made possible by the automake command and the makefile.am file. A README file with compile notes is added to the source files. The code has been optimized to simulate long time scales ($10^3$–$10^5$ y) and simulation run time should not exceed a few minutes. The program consists of 35 *.c files and 10 *.h files. All program files start with the extension hydro, directly followed by a logical short name for each subroutine. Hydrotrend.c is the backbone of the program and calls the subroutines (Fig. 1). Subroutine files contain a header describing briefly the routine and the local parameters.

HydroTrend v.3.0 is set up to simulate processes at a daily time scale, with a minimum simulation time of 1 y. The program can postprocess the time scale to monthly, seasonally or yearly output as specified by the user. The model contains two main loops (Fig. 1); one to correct if the maximum possible flood is reached (See Eq. (3)), and the other loop is a combination of simulation time (climate epochs, multiple years) versus model time scale (days simulated on a yearly bases) and to determine mean parameters like $Q_{S_T}$ and $Q$.

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1. [http://instaar.colorado.edu/deltaforce/models/hydrotrend.html](http://instaar.colorado.edu/deltaforce/models/hydrotrend.html)
Fig. 1. Schematic overview of program structure.
4.3. Model output

HydroTrend v.3.0 generates 12 output files, of which five ASCII files are optional. All ASCII files start with a header containing output parameters and units.

4.4. ASCII output

HYDRO.LOG lists information about the simulation process: possible warnings, simulation time and a brief overview per epoch of the main model controls and output. HYDRO.STAT includes more detailed statistics of the simulation per epoch. The file lists the parameters used to determine the mean long-term sediment load, the influence of possible glacier melt on suspended sediment load, the mean long-term discharge, and the statistics of the Psi model (Eq. (14)).

Three files (HYDRO.TRN1, HYDRO.TRN2, HYDRO.TRN3) include mean annual model results. The TRN1 file describes mean annual simulated climate: temperature, precipitation, ELA, potential glacier area, glacier area, exceeded flood flag, base flow and the glacier volume. The TRN2 file lists the mean annual simulated hydrological balance components: total discharge based on its components rainfall, glacier melt, snow melt, surface runoff, baseflow, water exceeding groundwater and water lost to the groundwater pool. In addition it tracks the yearly peak discharge. The TRN3 file describes the annual sediment load results: suspended sediment load, bedload, drainage area and the sediment yield of the basin.

The optional ASCII output files all have a file name including HYDROASCII. Results will be given in the time step determined in the HYDRO.IN file. The extension of the file name describes which results are reflected. The CS file lists suspended sediment concentration per grain size. The Q file includes water discharge, the QB file reflects the bedload and the QS file includes the suspended sediment load. The VWD file reflects, respectively the simulated discharge velocity, width and depth at the river mouth.

4.5. Binary output

Two binary output files, HYDRO.DIS, HYDRO.CONVDIS are created by HydroTrend v.3.0. The files serve as input files for stratigraphic models such as SedFlux (Hutton and Syvitski, this issue; Syvitski and Hutton, 2001), or shelf sediment-transport models (Sherwood et al., 2004). The two binary output files contain exactly the same results, they only differ in format. The binary CONVDIS file can be used on a UNIX platform once HydroTrend simulations are done on a Windows platform and visa versa. The binary file contains for each time step: water discharge, discharge velocity, width and depth at the river mouth, bedload and the suspended sediment concentrations for each grain size.

5. Examples of model simulations

5.1. Glacier routine

The Po River of northern Italy provides an opportunity to study the impact of climate change and sea-level rise on sediment supply to continental margins (Kettner and Syvitski, in press). The Po River with a PD length of 650 km is bordered by the Alps in the North and West, and the Apennines in the South, and drains an area of 74,500 km$^2$. During the significantly colder Last Glacial Maximum (LGM) (21 kyr BP), the Alps were covered by the late-Würmian ice sheet (Hinderer, 2001).

The present-day climate and its associated variability is reconstructed using 20 climate stations distributed throughout the basin, which were made available by National Oceanic and Atmospheric Administration (NOAA) (Vose et al., 1992). The hypsometry of the basin is based on the GTOPO30 DEM. The LGM climate and its variability, is based on output of a 10-y simulation of the Community Climate Model (CCM1) at LGM conditions (Kutzbach et al., 1998). To generate a continuous climate time serie over 21 kyr, the CCM1 LGM data and the PD climate data are interpolated using a normalized $\delta^{18}$O GRIP curve as forcing factor array, presuming that the Po Basin tracks the Northern Hemisphere climate. The forcing curve is also used for the glacier ELA time series (Kettner and Syvitski, in press).

Studies in the Alpine region indicate that glaciers reached their maximum extent during the LGM and were approximately at their present position at the start of the Holocene (Hinderer, 2001). HydroTrend v.3.0 simulations reflect this trend. Fig. 2A shows 3
years of daily discharge simulations. The first and the third year both represent typical melt events during, respectively, the late-Würmian and the Younger Dryas. Meltwater, dominant during the summer months, has significant impact on the total discharge leaving the river. The Younger Dryas melt events have the larger impact, 23% of the total discharge originates from meltwater, compared with late Würmian at 8%. The second selected year (16,380 y BP in Fig. 2A), represents a hydrograph typical for a hinterland with growing glaciers. In this case, hardly any glacier melt is generated over the summer, and much of the precipitation falls as snow and contributes to the glacier growth.

Fig. 2. Influence of glacier ablation on water discharge (A) and sediment concentration (B) according to HydroTrend v.3.0 simulation. (A) Dotted line represents daily discharge (m³·s⁻¹) from all water sources. Solid line represents daily discharge from glacier ablation. (B) Daily suspended sediment load increases significantly during glacier ablation (modified after Kettner and Syvitski, in press).
Fig. 2B shows the simulated daily sediment yield for the 3 selected years. The yield during the late-Würmian period is three times higher than for present-day glacier melt, as late-Würmian glaciers cover a more significant proportion of the drainage basin. The influence of glacier coverage on water discharge is even more evident during the Younger Dryas period, although less sediment in total is produced during the Younger Dryas as the glacial areas in the drainage basin are already much smaller (Fig. 2, and Eq. (12)). The second panel in Fig. 2 represents a typical glacier growth year. Although there are still glaciers in the Po drainage basin, little sediment is derived from this growing ice sheet, reflected by the lower sediment yield values.

5.2. Reservoir model

Reservoirs can significantly reduce the contribution of hyperpycnal flows (sediment concentrations >40 kg m\(^{-3}\) at the river mouth) and the transfer of sediment to the Adriatic margin. In this example, we apply HydroTrend v.3.0 to the Metauro River, a small mountainous (1570 m) basin of the Apennines, Italy. Given the size of the Metauro basin (1440 km\(^2\)) and the small amount of precipitation that falls as snow, water discharge follows rainfall patterns very closely in a pre-anthropogenic natural environment (Fig. 3A). However high demands for water by hydroelectric power, tourism and irrigation in a relative dry area (mean annual precipitation is \(~0.62\) m y\(^{-1}\)) changed the natural water flux dynamics. Water discharge of 1971 shows systematic releases of water exactly 1 month apart (Fig. 3B). Peak discharges are almost non-existent. In addition, monthly reductions in discharge occur to recharge the reservoirs, which thus control the ambient flow conditions.

HydroTrend v.3.0 simulations over 100 y are applied to generate water and sediment fluxes for

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**Fig. 3.** (A) Daily observed water discharge for the Metauro River at Acqualagna (half drainage area is contributing at this point; 617 km\(^2\)) for 1959 when river is relatively undisturbed by humans. River might get hyperpycnal as a 100-y simulation of HydroTrend v.3.0 indicates. (B) Daily observed water discharge at Acqualagna for same river in 1971. Hydrograph now is controlled by reservoirs. Metauro River does not become hyperpycnal anymore according to simulations.
the Metauro River, first under natural conditions; secondly as a river that is regulated by reservoirs. Climate data are obtained from the online NOAA database (Vose et al., 1992). Table 2 shows that the estimated trapping efficiency of the Metauro River is 32%, well within the observed values (20–50%) of the Apennine rivers (Macinelli, 2000). The water routing delay due to reservoir operations suppressed peak discharges \( Q_{peak} \) as is shown in Fig. 3A versus 3B. Hyperpycnal events lasting greater than 24 h do not occur after reservoirs are in place (Syvitski and Kettner, 2007).

5.3. Distributary channels

The flux of sediment into the coastal ocean is controlled by the number of distributary channels. Deltas with many distributary channels produce hypopycnal (surface) plumes rather than a single momentum possible hyperpycnal (plunging)-driven jet. This results in a reduction of transport capacity, reflected by sedimentation closer to the coastal line. The Po Delta, Italy, offers an ideal environment to model the effect of distributary channels as it is probably one of the best-documented delta. Presently, the Po Delta consists of 5 main distributaries: Maestra, Pila, Tolle, Gnocca and Goro, with respectively, discharge proportions of: 3%, 61%, 12%, 16% and 8% (Canali, 1959, 1961; Visentini, 1940). The present-day climate and basin morphology dataset described in the Glacier routine example are also applied to this experiment.

Table 3 shows that \( \text{HydroTrend} \) v.3.0 is able to simulate the sediment load carried by each of the distributaries within 1–2%. Comparing monthly observations with simulations (Fig. 4), \( \text{HydroTrend} \) v.3.0 provides estimates of both mean conditions and variability to realistically simulate the fluxes of sediment discharged out of each individual distributary channel.

![Fig. 4. Comparison of monthly observed and simulated sediment load versus water discharge of five main distributaries of the Po River (modified after Syvitski et al., 2005a).](image)

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Present day ( \text{HydroTrend} ) v.3.0 simulation applied to Metauro River</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q ) &amp; 22.0 &amp; 22.0</td>
<td></td>
</tr>
<tr>
<td>( Q_{peak} ) &amp; 1349 &amp; 414</td>
<td></td>
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<tr>
<td>( C_{S} ) &amp; 2.4 &amp; 1.6</td>
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<tr>
<td>( Q_{S0} ) &amp; 25.7 &amp; 17.4</td>
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<tr>
<td>( Q_{Savg} ) &amp; 3.8 &amp; 2.7</td>
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<tr>
<td>No. of hyperpycnal events &amp; 2 &amp; 0</td>
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<tr>
<td>( &gt;24 \text{ h} ) &amp;</td>
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<tr>
<th>Table 3</th>
<th>Distributary channel: ( \text{HydroTrend} ) v.3.0 simulations and field observations for Po Delta (after Syvitski et al., 2005a)</th>
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</thead>
<tbody>
<tr>
<td>Maestra &amp; Pila &amp; Tolle &amp; Gnocca &amp; Goro</td>
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<tr>
<td>( \text{HydroTrend} Q ) (%) &amp; 3.0 &amp; 61.0 &amp; 12.0 &amp; 16.0 &amp; 8.0</td>
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<tr>
<td>( Q ) observations 1926–1939 (%) &amp; 2.1 &amp; 62.7 &amp; 15.8 &amp; 12.6 &amp; 6.8</td>
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</tr>
<tr>
<td>( Q ) observations 1958–1959 (%) &amp; 3.4 &amp; 60.6 &amp; 12.1 &amp; 16.3 &amp; 7.6</td>
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<tr>
<td>( \text{HydroTrend} Q_{S} ) (kg s(^{-1})) &amp; 8.4 &amp; 411 &amp; 46 &amp; 66 &amp; 6.6</td>
<td></td>
</tr>
<tr>
<td>( \text{HydroTrend} Q_{S} ) (%) &amp; 1.5 &amp; 73.4 &amp; 8.1 &amp; 11.8 &amp; 4.9</td>
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<tr>
<td>( Q_{S} ) observations (kg s(^{-1})) 1932–1937 &amp; 10 &amp; 329 &amp; 69 &amp; 72 &amp; 42</td>
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<tr>
<td>( Q_{S} ) observations (%) 1932–1937 &amp; 2.0 &amp; 63.0 &amp; 13.2 &amp; 13.7 &amp; 8.1</td>
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<tr>
<td>( Q_{S} ) observations (%) 1958–1959 &amp; 1.2 &amp; 73.6 &amp; 6.6 &amp; 10.5 &amp; 8.2</td>
<td></td>
</tr>
<tr>
<td>Flow velocity ( \text{HydroTrend} ) versus observed (m s(^{-1})) &amp; 0.7 &amp; 0.6 &amp; 1.0 &amp; 0.9 &amp; 0.8</td>
<td></td>
</tr>
<tr>
<td>Flow width ( \text{HydroTrend} ) versus observed (m) &amp; 36 &amp; 32 &amp; 163 &amp; 363 &amp; 72</td>
<td></td>
</tr>
<tr>
<td>Flow depth ( \text{HydroTrend} ) versus observed (m) &amp; 1.9 &amp; 2.6 &amp; 6.5 &amp; 5.0 &amp; 3.4</td>
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</table>
6. Summary

HydroTrend v.3.0 provides a powerful tool to simulate sediment supply to the ocean. Daily synthetic water discharge and sediment load can be generated for $10^5$–$10^8$ y including possible impact of climate change scenarios. Previously developed routines (Syvitski and Alcott, 1995), such as snow accumulation and melt, groundwater recharging and discharging, rainfall generation and evaporation routines, have been shown to capture water discharge patterns at river mouths, given accurate input parameters. HydroTrend v.3.0 adds more advanced sediment delivery routines to calculate: (1) the long-term sediment load of river systems and (2) the short-term variability of the daily and annual sediment load. The approach predicts the flux of sediment of any basin in the world to within the uncertainties associated with global observations (Syvitski, 2003). The short-term sediment equations reflect the temporal variability of transported sediment load caused by locally varying water sources through a season (rainfall, snow melt, glacier melt), hysteresis effects and variability in erosional processes.

Climate change and the effect of glacier processes on sediment flux have been analyzed for the Po River, since the LGM (Kettner and Syvitski, in press). Based on climate interpolations and the change in ELA over time HydroTrend v.3.0 was able to capture: (1) glacier ablation and growth; (2) increased water discharge and sediment flux due to glacier melt; and (3) decreased importance of glacier sediment contribution to the total sediment budget as glaciers withdraw and/or nearly disappear.

The Po Delta, Italy was studied to illustrate how the flux of sediment into the coastal ocean is controlled by the number of distributary channels. Five dominant distributary channels divide the discharge of the Po River to the Adriatic Sea. The multiple channel routine in HydroTrend v.3.0 tends to capture the mean (within 1–2%) and range of sediment flux per channel (Syvitski et al., 2005a).

The impact of reservoirs on the sediment flux has been tested for the Metauro River, Italy. Simulated peak discharges are suppressed nowadays as is shown in modern measurement records. HydroTrend v.3.0 predicts that hyperpycnal flows lasting longer than 24 h, which form an important mechanism to transport sediment into the marine basin, do not occur anymore. ~32% of the sediment is trapped in reservoirs (Syvitski and Kettner, 2007).

HydroTrend v.3.0 is a fast and platform-independent model. Example files, background information, detailed description of the input files and the possibility to remotely run the model online (http://instaar.colorado.edu/deltaforce/models/hydrotrend.html) make the model easily accessible for students, geoscientists, engineers and policy makers alike.

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Appendix A. Supplementary materials

The online version of this article contains additional supplementary data. Please visit doi:10.1016/j.cageo.2008.02.008

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