A GIS-based method to correct sediment yield gauges in large river basins by considering dams and time

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Abstract: A new GIS-based algorithm is introduced by which flow accumulation can be computed. In contrast to existing algorithms sinks and their time-dependent retention behavior can be considered. This is of fundamental importance as sediment fluxes in large river basins are not only reduced by the trap-efficiency of sinks but also on their time of influence. The poster introduces the GIS-software AccumPlus for ArcView, where the new algorithm is implemented (circle), the important role of dams and time (1), the fundamentals of the algorithm (2) and some examples which show its importance for large-scale modelers (3 and 4). Up to now sediment yields in large river basins are considered by far too low. The new algorithm allows to correct sediment yield data of large dam-dominated river basins in order to get more reliable values.

1 Dams, sediment gauges and time

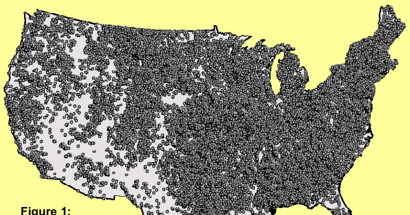


Figure 1: Dams and reservoirs in the USA. Source: National Inventory of Dams Database.

Large river basins are dominated by the construction of dams which do reduce sediment yield to a considerable extent. According to WCD (2000) more than 47.000 large dams are reported on global scale. This is equalent to an average density of 50 dams per 100,000 km². Sediment yield gauges are therefore extremely affected by dams. Controlling factors of sediment production in the river basins like relief, climate, soils and vegetation cover are only of minor importance. Large-scale denudation models like those of Syvitski et al. (2005, 2003), Harrison (2000), Hovius (1998) or Ludwig & Probst (1998) are thus not as reliable as they can be as long as they were calibrated against data which was affected by dams.

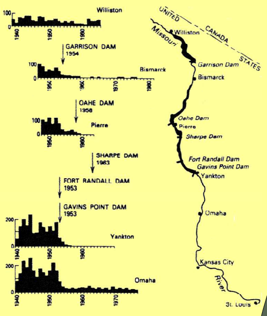


Figure 2: Sediment yield gauges and the construction of dams in the Mississippi river basin. Black arrows depict the rapid decline of sediment fluxes after the construction of a dam. Source: Meade & Parker (1984).

2 Correcting sediment yield datasets

Sinks like dams and natural lakes reduce sediment fluxes and their contributing areas as well. Both can be evaluated by the new time-based D8t algorithm. This algorithm computes flow accumulation in a time-weighted manner by reducing the trap-efficiencies of sinks according to their time of influence. The basic principles are depicted in fig.3a-c. A detailed description is given in Schäuble et al. (submitted). Raster datasets of flow accumulation computed by the new D8t algorithm can be used to correct existing sediment yield datasets. An example to do so is shown in fig.4

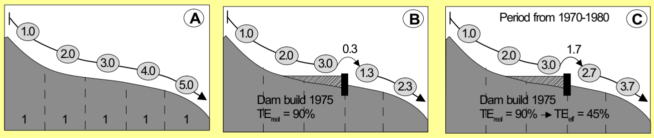
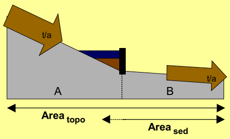


Figure 3: Fundamentals of the new D8t-flow routing algorithm which is implemented in AccumPlus. *Left:* Accumulation without any sinks. Each pixel has a value of 1. *Middle:* Accumulation considering the trap-efficiency of a sink but not time (dam with a real trap-efficiency of TE_{real} = 90%). *Right:* Accumulation with consideration of time: a period from 1970-1980 is assumed in this case. In contrast to fig. 3b the dam is just in action half the time. Thus the retention capacity is reduced from TE_{real} = 90% to an effective value of TE_{eff} = 45% for that time period.

Figure 4: Correction of sediment data by the influence of sinks and time. *Top:* Reduction of sediment yield. l/a = load in t/yr. $Area_{topo}$ = catchment size derived from maps or with standard GIS-proceedures (= flow accumulation). $Area_{sed}$ = true contributing area derived with the new GIS-based D8t-algorithm of Accum Plus. *Bottom:* Formulas to correct existing sediment yield data. SSL = load in t/yr. SSY_{orig} = suspended sediment yield from databases in t/km²/a.



1. $SSY_{orig} = SSL / Area_{topo}$
2. $C_{area} = Area_{topo} / Area_{sed}$
3. $SSY_{korr} = SSY_{orig} * C_{area}$

AccumPlus and the new time-variable flow-routing algorithm (D8t)

The new D8t flow routing algoritm which is implemeted in AccumPlus considers trap-efficiency and time of influence as well. A given trap-efficiency from 0 to 100% can be modified by the time of influence. In case of a long lasting influence (= dam is in action during the total gauging period) the effective trap-efficiency is equalent to the nominal trap-efficiency which can be calculated by formulas given in USACE (1995) or Brune (1953). In case of a short lasting influence (= dam is in action just a little part of the total gauging period) the effective trap-efficiency is reduced according to the time of influence. Fig. 3a-c shows the fundamental principles, fig. 5a-c the results of a GIS-based analysis with AccumPlus in a small river catchment. In case of missing sinks (fig. 5a) flow accumulation is calculated without any reductions. In case of permanent sinks flow accumulation is decreased considerably: about 90% after having passed the dams B and C (fig. 5b). After a certain distance flow accumulation 're-covers' and the river courses can be seen again (fig. 5b near point A). In contrast to that the temporary influences of dams result in a quite different behaviour (fig. 5c). The two dams D and E (same trap-efficiency as B and C) have been constructed during the gauging period of station A, in that case in the middle of the gauging period. Thus their effective trap-efficiencies have been decreased and the flow accumulation is reduced less. A similar but quite more complicated situation can be observed in all large river catchments like the Amazon, the Danube or the Mississipi (fig. 7). In all cases flow accumulation is controlled by a big quantity of dams with quite different effective trap-efficiencies which vary from one gauging period to the other.

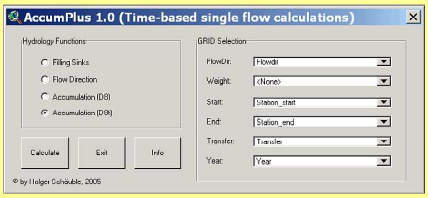
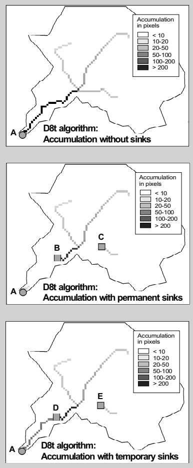


Figure 6 Screenshot of AccumPlus for ArcView. GIS-based software written in Avenue and C/C++ which contains the new D8t algorithm and is able to consider sinks and time. 5 separate Raster datasets are needed at least: a flowdirection grid, grids with the begin and the end of a gauging period and grids which give information about the trap-efficiencies of the dams and their year of contruction. Additional weighting is possible as well, e.g. for simulation sediment fluxes and not only catchment sizes (weighted versus unweighted flow accumulation). More detailed informations are are given in Schäuble et al. (submitted).



no sinks considered

permanent sinks assumed

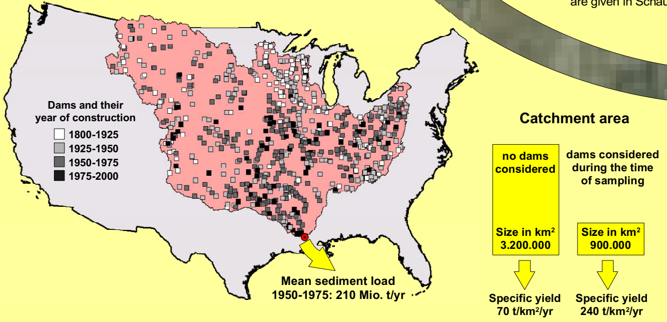
temporary active sinks

Figure 5: Flow accumulation, sinks and their different different retention behaviour with respect of time. A = gauging station. B, C, D, E = dams with a trap-efficiency of 90% D, E = dams active in half of the gauging period

Figure 7: Specific sediment yield of the Mississippi river with and without considering large dams and their year of construction.

Left: Dams and their year of construction in the Mississippi river basin upstream of Tarbert gauging station (USGS river sampling station no. 07373291, Online source: http://webserver.cr.usgs.gov/sediment).

Right: Specific sediment yield in t/km²/yr derived from a mean value of 210 Mio. t/yr (measured between 1950 and 1975 at Tarbert sediment gauging station). Left column = specific sediment yield considering the absolute catchment area which can be calculated by traditional flow routing algorithms like D8, FD8, Dinf or Stream-tube approaches (Gallant & Wilson, 2000). Right column = specific sediment yield considering the real contributing area which can be calculated by the new time-based D8t flow routing algorithm (fig.3a-c, fig.5a-c).



3 Example 1: Mississippi basin

Figure 8: Development of major US-dams during the 20th century. Only dams with a volume > 1 Mio. m³ and a catchment > 300 km² are considered.

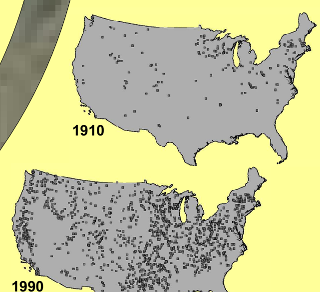
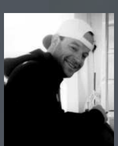


Table 1: Sediment samplings in the most large US-river basins and how they have to be corrected. Period: Period of sampling. SSL: Mean daily suspended sediment load in tons. Area_D8: Catchment area in km2, calculated with a traditional D8-algorithm without considering sinks and time. Area_D8t: Catchment area in km2, calculated with the new B8t-algorithm of AccumPlus by considering sinks and time. SSY_D8, SSY_D8t: Mean suspended sediment yield in tons/km²/year, derived from Area_D8 or Area_D8t respectively.

Station	Period	SSL (t/d)	Area_D8	Area_D8t	SSY_D8	SSY_D8t
Mississippi River at Tarbert	1950-1975	570,000	3,150,000	880,000	70	240
Missouri River at Bismark	1972-1981	15,000	450,000	20,000	10	260
Ohio River at Louisville	1980-1983	60,000	230,000	20,000	100	1050
Atchafalaya River at Simmesport	1973-1989	230,000	230,000	50,000	360	1650
Yellowstone River at Sidney	1972-1995	26,000	180,000	125,000	55	75
Red River at Alexandria	1973-1982	115,000	175,000	45,000	240	950
Kansas River at Wamego	1957-1975	20,000	140,000	45,000	50	170
Tennesse River at Paducah	1935-1942	15,000	105,000	25,000	60	230

Example 2: Large US-river basins 4



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