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A GIS-based method to calculate flow accumulation by considering dams and their specific operation time☆

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Abstract

This paper presents a new approach to calculate flow accumulation with geographic information systems (GIS). It is based on the well-known D8 single-flow algorithm that is extended to consider the trap-efficiencies of dams and their specific operation time. This allows realistic calculations of flow accumulation for any time period. The new approach is not restricted to surface water runoff but can be applied to all kinds of mass fluxes like suspended or dissolved sediment load (weighted flow accumulation). To facilitate its use, two GIS extensions for ArcView and ArcGIS have been developed. This paper presents the principles of the new approach, the functionality of the extensions and gives some applications in the fields of hydrology and sedimentology.

Keywords: GIS; Flow accumulation; Algorithm; River basin; Sediment yield; Trap-efficiency

1. Introduction

Geographic information systems (GIS) play an important role in the analysis of hillslopes and large river basins. Typical applications are computations of flow directions, flow accumulation or simulations of soil erosion and sediment yield (Fernandez et al., 2003, van Rompaey et al., 2001). For this reason a variety of algorithms have been developed. The most popular is the D8 single-flow algorithm (O'Callaghan and Mark, 1984), which is implemented in a lot of GIS programs like ArcView, ArcGIS, IDRISI, GRASS or PCRaster. Other more sophisticated but less well-known routines are FD8 multiple-flow algorithms (Quinn et al., 1991; Freeman, 1991), stream-tube approaches (Costa-Cabral and Burges, 1994) or the Dinf algorithm (Tarboton, 1997). Although quite different in their conception, all of these algorithms share one common deficiency: they give no option to consider dams and their retention capabilities that are controlled by trap-efficiency (TE) and the length of influence (defined below). The consideration of dams and their retention capabilities, however, is of fundamental importance for hydrological and sedimentological analyses since dams considerably influence

☆Code available from server: 〈http://www.terracs.de/ArcView_3_x/AccumPlus/accumplus1.html〉.

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the dynamics in a river system (Vörösmarty et al., 2003; Meade and Parker, 1985). Depending on constructional and hydrological conditions a dam can trap up to 100% of the sediment load. This is referred to as TE (Morris and Fan, 1997; USACE, 1995; Heinemann, 1984). However, TE is insufficient to explain the true sediment retention of a dam. Just as important is the specific operation time (t_{op}) of a dam, which we define as the number of years of dam operation divided by the number of years of sediment observation. A dam that has been put into operation from the beginning of an observation period traps considerably more sediment than one that has been put into operation some years later, even if the TE is the same (Fig. 1).

During the 20th century the number of dams has tremendously increased. The World Commission of Dams (WCD) reports that at present more than 47,000 large dams and reservoirs are in operation (WCD, 2000); small impoundments not included (Fig. 2). This corresponds to a density of about 50 large dams per 100,000 km^2. Peak densities can be found in eastern Asia (e.g., China: 235 dams per 100,000 km^2; Japan: 747 dams per 100,000 km^2), medium densities in the USA, Germany or other mid-latitude countries (50–70 dams per 100,000 km^2) and low densities in countries with flat topography like Brazil and Canada (less than 10 dams per 100,000 km^2) (Schäuble, 2005). Apart from these regional differences, there is almost no river catchment left that is unaffected by large dams and their continuous or temporary influences on sediment yield. Hydrological and sedimentological studies, which refer to specific time periods (e.g., simulations of discharge or sediment yield in the 1970s, 1980s or 1990s, etc.), must therefore take into account temporal influences of dams as well, i.e., their operation time with respect to a specific observation period (specific operation time t_{op}). If this temporal aspect is neglected, the computed discharge or sediment fluxes will be misleading. Present flow-routing algorithms like D8, FD8, Dinf or stream-tubes do

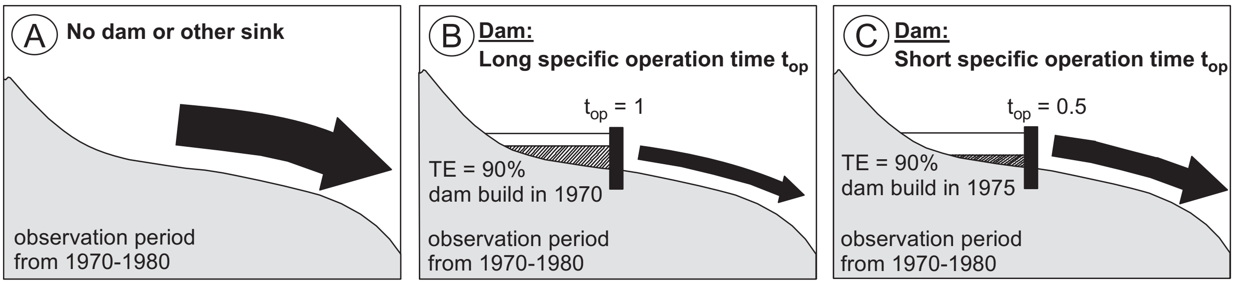

Fig. 1. Mean annual sediment yield (black arrow) due to different retention capabilities. TE: trap-efficiency of dam. t_{op}: specific operation time.

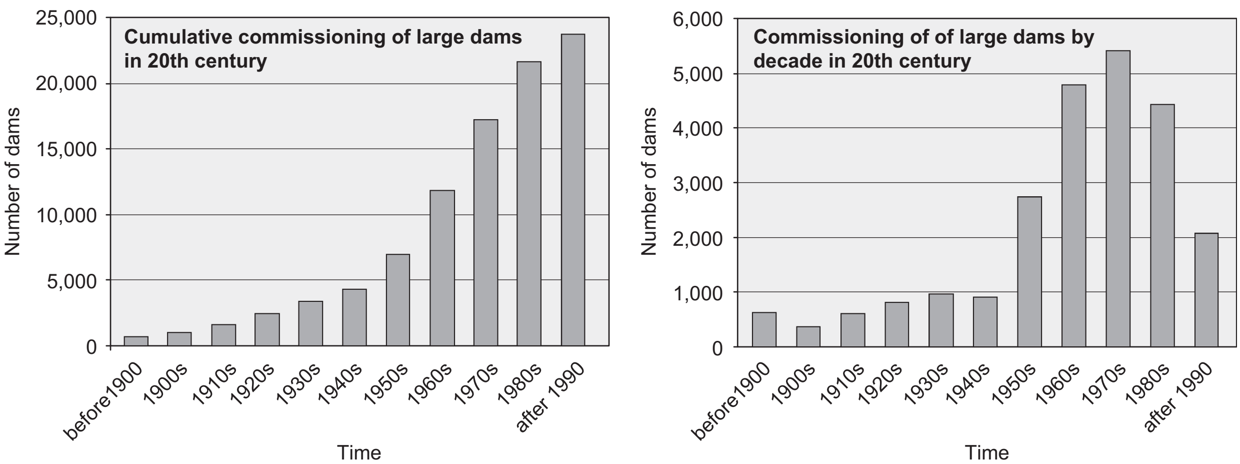

Fig. 2. Commissioning of large dams around the world in the 20th century. Data from ICOLD (2000) that cover only 2000 of all 25,000 Chinese dams.