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ETA (Erosion Transport Accumulation) systems, their classification, mapping and management

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Abstract A regional, distributed systems approach for the transport of sediment in basins is presented, based on the causal relationships and patterns in the chain Erosion-Transport-Accumulation. Thus ETA systems can be defined, mapped and documented on the basis of their transporting agents: wind, water, snow, ice, gravity and man. ETA systems have an inherent logic in space and time, following sediment from source areas to its temporary or final accumulation areas, differentiated according to scale and the practical problems to be solved. The methodology is applicable at any scale of time and space. The systems can be: (a) inactive fossil systems, called paleo-ETA systems; (b) active, recent systems, called actuo-ETA systems; (c) to-be-active, future systems, called futuro-ETA systems. ETA processes result in associated erosion, transport and accumulation features to be observed and measured in field surveys and by remote sensing. A stepwise procedure for the strategy to manage the ETA systems of an area can be based on ETA systems maps. Examples based on detailed field surveys are given for the alpine basin of the Upper Boite River (±200 km^2) in the Ampezzan Dolomites in northern Italy.

Systèmes d'érosion, de transport et de l'accumulation (ETA), leur classification, cartographie et gestion

Résumé Une méthode régionale par les systèmes distribués pour l'étude des transports de sédiments des bassins fluviaux fondée sur les causalités des relations et des processus des modèles dans la chaîne Erosion-Transport-Accumulation est présentée dans cette communication. On peut définir, relever et documenter des systèmes ETA selon les agents de transport: le vent, l'eau, la neige, la glace, la gravité et l'action de l'homme. Les systèmes ETA possèdent une structure logique propre dans l'espace et le temps. Les particules solides sont suivies depuis les zones de départ jusqu'aux régions de sédimentation temporaires ou permanentes. La méthode est applicable à chaque échelle d'espace où de temps. Les systèmes ETA peuvent être: (a) des systèmes inactifs, fossilisés, appelés paléo-systèmes ETA; (b) des systèmes actifs, actuels, appelés actuo-systèmes ETA; (c) des systèmes pas encore actifs, futurs, appelés futuro-systèmes ETA. Les processus ETA sont en rapport avec des phénomènes d'érosion, de transport et d'accumulation (sédimentation) que l'on peut observer et mesurer sur le terrain ou par télédétection. Un procédé progressif pour la stratégie de gestion des systèmes ETA d'une région a comme point de départ les cartes des systèmes ETA. Quelques exemples basés sur les relevés detaillés de terrain sont présenté pour le bassin fluvial de la Boite supérieure (±200 km^2) dans les Dolomites Ampezzanes en Italie.

INTRODUCTION

Within the framework of a cooperation agreement between the Experimental Centre for Avalanches and Hydrogeological Protection of the Department of Forestry of the Regional Council of the Regione del Veneto (northern Italy) at Arabba (Belluno) and the Department of Hydrogeology and Geographical Hydrology of the Faculty of Earth Sciences of the Vrije Universiteit at Amsterdam (The Netherlands) a methodological and applied study on erosion and sediment transport problems in alpine areas was undertaken. The fieldwork in the area of investigation, the basin of the Boite River upstream from Cortina d'Ampezzo with an area of ±200 km^2, was undertaken in the summer periods of 1985, 1986 and 1987 by scientific staff and graduate students from the Vrije Universiteit with partial financial contribution from the Italian counterpart (Engelen & Venneker, 1987; Engelen *et al.*, 1987). This report elaborates on the concept of erosion-transport-accumulation (ETA) systems and their mapping and management.

OUTLINE OF THE METHODOLOGY

Management of drainage basins requires a good understanding of the role of sediment transport for many practical applications such as optimization of land use, design of roads, culverts, water courses, ski-runs, control of reservoir silting etc. The necessary collection, representation and interpretation of data on sediment transport can be optimized by applying the concepts of regional analysis, as elaborated previously for hydrological purposes (Engelen & Jones, 1986). The systems approach is based on the fundamental causal relationships in the chain Erosion-Transport-Accumulation. Thus Erosion-Transport-Accumulation systems can be defined, mapped and documented. These will be abbreviated as ETA systems. ETA systems have an inherent logic in their cause/effect relations in space and time, following the transport of the sediment from its detachment at source areas to its accumulation in temporary or final accumulation areas. ETA systems can be differentiated according to scale, depending upon the desired applications and the availability of data and funds for additional research. The systems methodology in itself is a procedure which is independent of scale.

ETA systems can be studied within different time horizons; the systems

can be:
(a) inactive, fossil systems, called paleo-ETA systems;
(b) active, recent systems, called actuo-ETA systems;
(c) to-be-active, future systems, called futuro-ETA systems.
Each ETA system acts on source systems for sediment, consisting of consolidated or unconsolidated rock systems or combinations of these. It contains erosion, transport and accumulation processes which in turn result in erosion, transport and accumulation features or phenomena. These features or phenomena can be observed and measured in field surveys, and by remote sensing methods. A general classification of these processes and the resulting features/phenomena forms the basis for the transformation of the observed data into ETA system maps. These maps can portray paleo- or actuo-ETA systems or indicate possible futuro-ETA systems under different management scenarios of a watershed or area.

CLASSIFICATION OF ETA SYSTEMS ACCORDING TO MAIN PROCESSES

The denudation/erosion component of the causal chain of an ETA system can be classified most efficiently according to a division into the main transporting agents and it can subsequently be subdivided hierarchically according to mappable features.

The principal transporting agents for sediment in a drainage basin are:
(a) snow/ice,
(b) flowing water,
(c) gravity,
(d) flowing air,
(e) man.
These transporting agents result in the following main ETA systems:
(a) nival ETA systems,
(b) glacial ETA systems,
(c) fluviatile ETA systems,
(d) limnic ETA systems,
(e) marine ETA systems,
(f) subsurface water ETA systems (including karst),
(g) gravitational ETA systems,
(h) aeolian ETA systems,
(i) manmade ETA systems.

CHAINS AND PATTERNS OF ETA SYSTEMS

The main ETA systems can be developed separately and completely from their denudational/erosional components down to the final accumulation components. It is, however, also possible, and in most cases more common, that the systems are linked and have developed partially. In some examples the fate of a few sediment particles eroded from the top of a glacierized mountain and passing through the following ETA systems and system components is described briefly (see Figs. 1 and 2, an example of an actual situation is given in Fig. 3):

Gravitational ETA system
Start by detachment from rock scarp above cirque by frost shatter and gravitational transport with temporary deposition/accumulation on surface of cirque glacier; transition into:
Niveo/glacial ETA system
Transport to meltwater creek at the glacier tongue; transition into:
Fluviatile ETA system
Transport to delta in downstream lake; transition to:
Limnic ETA system
Transport by turbidity current to temporary accumulation in lake bed; transition into:
Manmade ETA system
Dredging of lake bottom and disposal in downstream river bed; transition into:
Fluviatile ETA system
Transport to the sea; transition into:
Marine ETA system
Transport by coastal current to edge of continental shelf, transport by turbidity current to deep sea floor and final deposition/accumulation in turbidite series.

The sequence of events shows how this particular sediment particle passed through different systems at different rates of movement with temporary, intermediate periods of accumulation. On its travel from source to sink it was joined by particles with different histories. Some of these travelled along all the time, others were diverted into other ETA systems or became retarded in other temporary accumulation areas.

Maps of ETA systems can be produced now as composite maps, showing all ETA systems and their components as actually present in a given area. Another option is to show a map sequence as a time series of past, present and possible future ETA systems (see Figs 4 and 5). It is equally possible to extract from the data base only those data pertaining to a specific type of ETA system, e.g. a map of man-made ETA systems in an area. The systematic analysis of an area with the concept of ETA systems can provide a powerful tool for mapping, documenting, planning and managing the flow of sediment through an area.

CLASSIFICATION/LEGEND FOR ETA SYSTEMS

Table 1 lists a classification/legend for ETA systems in alpine environments. The marine and aeolian ETA systems are not relevant in the Upper Boite basin and will not be discussed further within this context. The ETA systems analysis can be executed for any degree of detail as required by the scientific

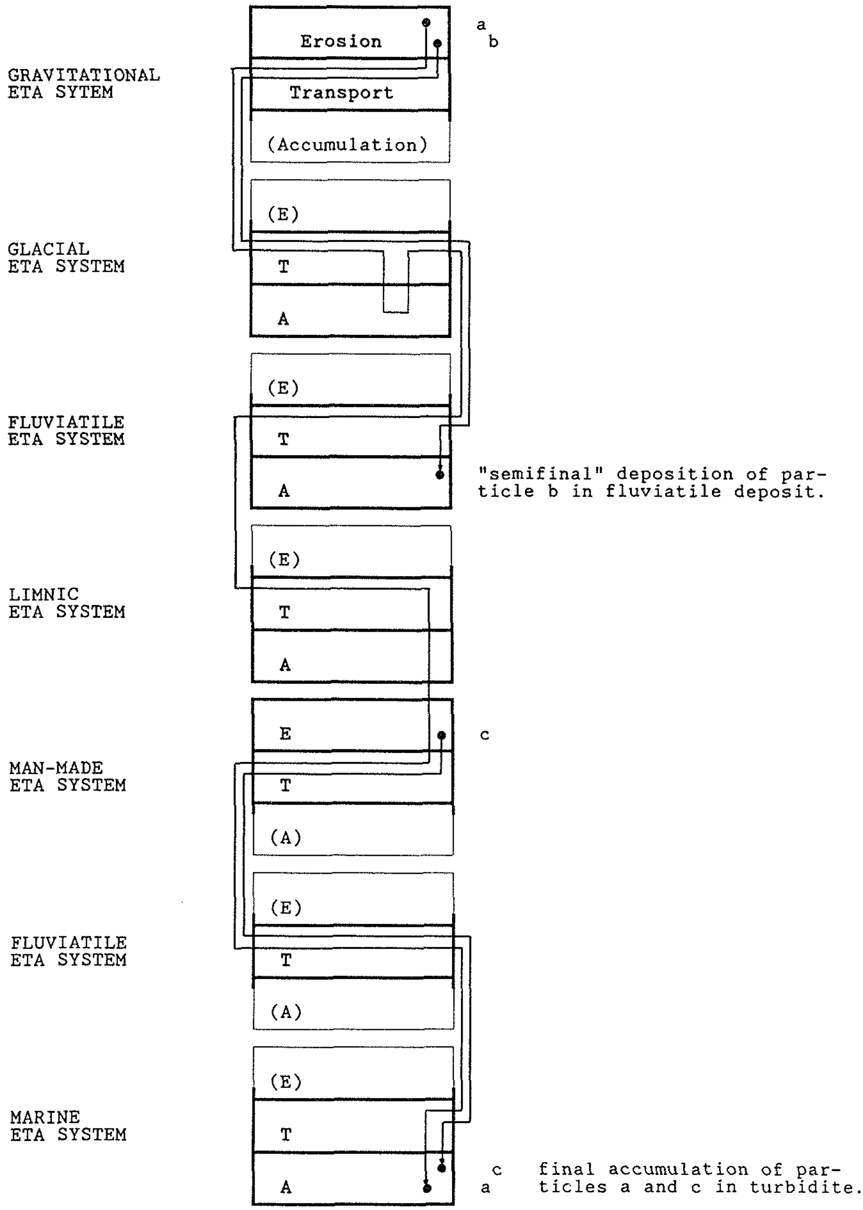

Fig. 1 Hypothetical, schematic flowpaths of some sediment particles through a single chain of connected ETA systems between mountain top and ocean floor. Particles a and b have the same origin at the mountain top but different destinations. Particle c starts halfway by excavation by man and ends up at the ocean floor together with particle a.

or applied problem, given the constraints of available data and available time and funds. The level of detail in the legends used is dictated by the

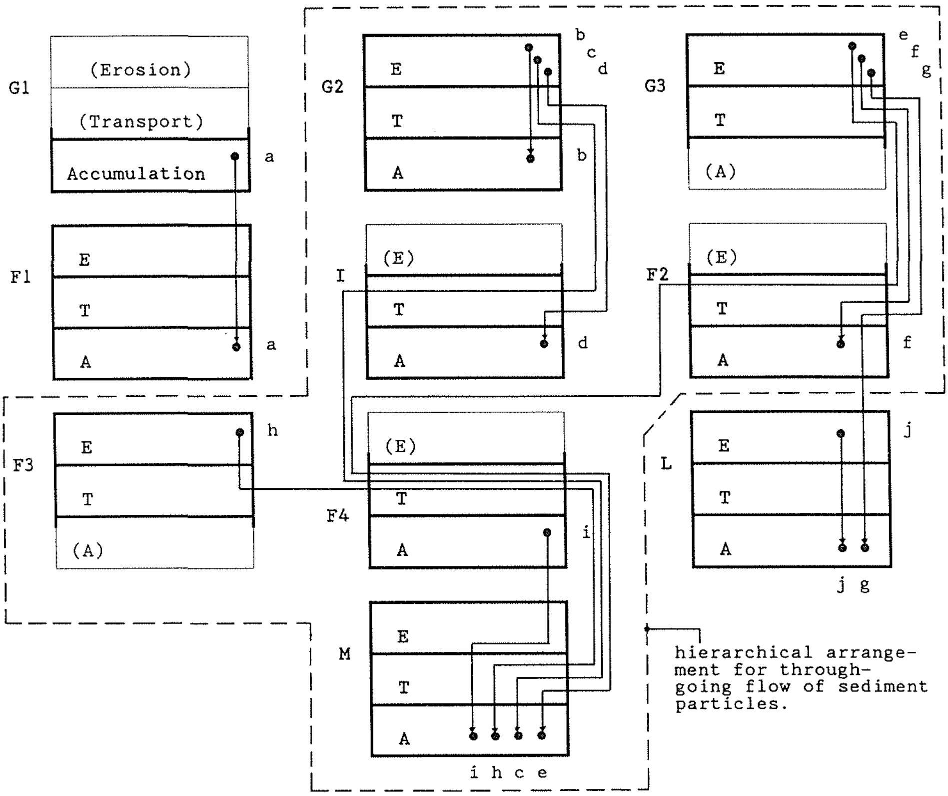

Fig. 2 Hypothetical, schematic flowpaths of some sediment particles of different origins through a regional pattern of partly hierarchically connected, partly disconnected ETA systems. The ETA systems pattern consists of three gravitational (G), one glacial (I), four fluviatile (F), one limnic (L) and one marine (M) ETA systems. Different flowpaths may converge, diverge, run parallel and start and end at different points. The end of a flowpath may be in a "dead end" storage of the connected ETA systems network, in a final storage at the bottom of the chain or in the accumulation part of a separate, disconnected ETA system. The final or temporary character of the accumulation in a storage depends on the time scale under consideration. In time the maturity of the network may increase, e.g. when fluviatile ETA system F3 links up with fluviatile ETA system F1 and gravitational ETA system G1 by means of headward erosion.

intended use of the analysis and it can be accommodated by using the higher or lower levels of hierarchy in the legend structure. An appropriate representation of the results of an ETA systems analysis of an area will require at least a series of maps if only black and white reproduction facilities are available. The use of coloured maps is recommended, however, for simultaneous representation of ETA systems of different age or of different type.

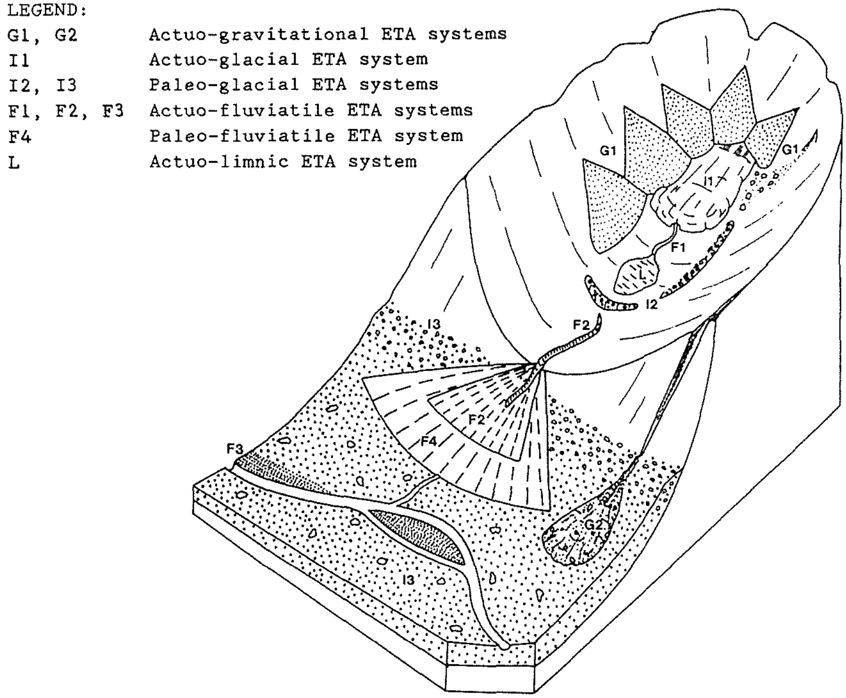

Fig. 3 Representation of several ETA systems and their linkage pattern in an alpine environment. Actuo-ETA systems appear as an overprint on relics of paleo (fluvio-)glacial and fluviatile ETA systems that were responsible for the morphology of the area.

INTRODUCTION OF THE REGIONAL PLANNING AND MANAGEMENT OF ETA SYSTEMS

Regional planning and management of ETA Systems deals with the following aspects of erosion and accumulation problems:

(a) mapping, description and quantification of ETA systems;
(b) mapping, description and risk evaluation of objects, structures, population centres etc., liable to erosion and/or accumulation;
(c) development of a cost-effective strategy to prevent, alleviate and combat erosion/accumulation problems on regional and local scales
(d) execution of an actual programme of optimal measures to minimize the risk and damage due to erosion and accumulation processes.

The natural processes of erosion and sedimentation/accumulation by weathering and transport by gravity, wind, water and ice have different rates depending upon the climate, the given geological environment and the impact of man. In most cases the natural processes cannot be stopped completely and neither is this necessary. Zones with high natural or man-induced rates of erosion and accumulation, however, deserve special attention. Once the inventory and mapping phases of ETA systems and endangered areas and objects have been completed, both data sets can be compared to design a strategy for preventative and curative action.

SOME GENERAL RULES

Maturity of the ETA systems network

The linking of different ETA systems into a larger network for the transfer of material makes the situation potentially more dangerous. Thus it will be advantageous to try to isolate different ETA systems from each other on purpose or to prevent isolated ones from becoming connected. This fits in with the aim of trying to contain ETA systems within their existing boundaries or even to reduce their sphere of influence. The degree of interconnectedness of different ETA systems in a region or in other words the degree of maturity of the ETA systems network, is an important factor to consider and to manipulate.

ETA systems and threshold values

The behaviour of a system may change drastically in character and/or in

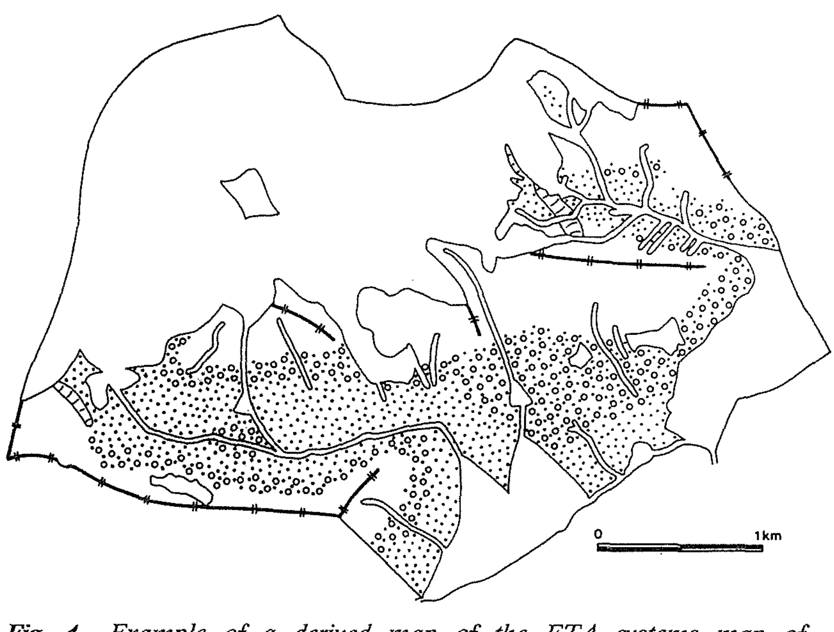

Fig. 4 Example of a derived map of the ETA systems map of the upper Boite basin. In this derived map the paleo-ETA systems of a small part of the Upper Boite basin have been singled out. For legend see Fig. 5.

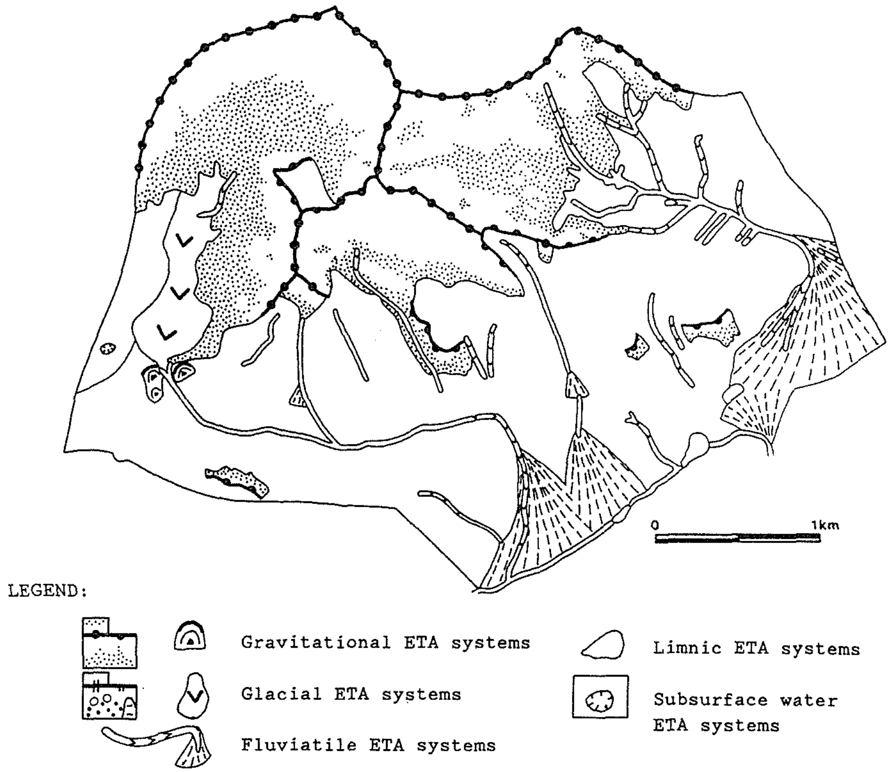

Fig. 5 Example of a derived map from the ETA systems map of the Upper Boite basin. In this derived map the actuo-ETA systems of the same area as shown in Fig. 4 have been singled out. Note that the combination of the derived maps of Fig. 4 and 5 yields the composite ETA systems map.

intensity once a crucial threshold barrier has been exceeded. It is thus of utmost importance to understand the behaviour of the ETA systems instead of considering and treating them like black box systems. A search for the weak spots in the behaviour of the systems and of the networks of systems is appropriate. Thresholds may be exceeded occasionally by natural factors with long return periods such as excessive high-intensity storms or by manmade changes in the environment such as a systematic change in land use and resulting hydrological characteristics. Short term climatic variations may push a system across a threshold barrier as well. In many cases it would have been relatively easy and cheap to prevent a system from passing a threshold value in its behaviour had it been known in time. However the system behaviour may have changed so drastically and almost irreversibly after passing a critical threshold value that remedial action becomes much more difficult and expensive or even impossible.

Table 1 Classification/legend for ETA systems in alpine environments

NIVAL ETA SYSTEMS Denudation/erosion features:	Transport features:	Accumulation features:
snow-carved hollows. scooped depressions.	sliding over snow surface. avalanches.	low curved stone ridges. irregular mounds.
GLACIAL ETA SYSTEMS Denudation/erosion features:	Transport features:	Accumulation features:
Cirques. U-shaped valleys. Confluence basins.	cirque glacier. valley glacier. coalescing glaciers.	diverse moraines. diverse moraines. diverse fills.
FLUVIATILE ETA SYSTEMS Denudation/erosion features:	Transport features:	Accumulation features:
pediments. gullies. V-shaped valleys. broad valleys or plains. broad valleys or plains.	sheetwash. creeks (episodic). rivers (active incision). meandering rivers. braiding rivers (lateral erosion).	gravel sheets. cones of debris. fluviatile cones. channel deposits, levee deposits, backswamp deposits, crevasse deposits. braided deposits.
LIMNIC ETA SYSTEMS Denudation/erosion features:	Transport features:	Accumulation features:
cliffs, platforms.	waves, currents.	deltas, lake bed deposits.
SUBSURFACE WATER ETA SYSTEMS Denudation/erosion features:	Transport features:	Accumulation features:
leached and eluviated soils. karst phenomena: clints, sink holes, poljes, grottoes.	soil water movements. soil- and groundwater.	hardpans, illuvial horizons. travertine deposits, speleothemes.
GRAVITATIONAL ETA SYSTEMS Denudation/erosion features:	Transport features:	Accumulation features:
microtopographic relief. slump topography of various types. earth glacier valleys. bare rock slopes. major rock fall scars.	creep tilted trees. slow sliding. slow/rapid sliding. rapid falling. rapid falling.	slope parallel ridges. irregular bulges and ridges. glacierlike forms and outwash plain. angular debris cones at base. toma landscape.
MAN-MADE ETA SYSTEMS Denudation/erosion features:	Transport features:	Accumulation features:
levelled areas for roads, construction sites, ski facilities etc. quarries.	artificial by truck, cable or pipeline. see above.	soil dumps and fills. spoil dumps.

THE QUATERNARY HISTORY OF THE ALPINE ENVIRONMENT AND ITS INFLUENCE ON ETA SYSTEMS

The alpine environment is characterised by two major points affecting the present-day ETA situation ;

(a) The alpine area is characterized by a strong and continuing geological uplift. This creates the necessary gravitational energy anomaly to drive the transport of matter by gravity, water and ice from the topographic high areas to the surrounding lowlands in chains of ETA systems. This natural process cannot be stopped and can be influenced only partly in its effects. The best man can achieve on his time scale is to adapt to it and modify its effects locally in critical areas. Natural process rates are high in these areas.

(b) The effects of the Pleistocene climatic history of the alpine areas with their heavy impact of the glaciations are still particularly strong. The glaciations have caused a tremendous inequilibrium by creating huge masses of easily transportable debris, which are prone to subsequent transport and accumulation by gravitational and fluviatile ETA systems. In other areas without these stores of accumulation materials from the glacial paleo-ETA systems actuo-ETA systems can be much less active.

A STEP-WISE PROCEDURE FOR A STRATEGY TO MANAGE ETA SYSTEMS

(a) Locate the most urgent locations for action by comparing the ETA systems data base with the data base of endangered areas/objects.

(b) Try to stop extension of existing ETA systems by preventing headward extension of their erosional parts.

(c) Try to stop downstream extension by containing their downstream accumulation parts.

(d) Try to break chains of connected ETA systems by inserting artificial breaks between them.

(e) Consider in decreasing order of importance for remedial action:

- (i) areas with important storages of transportable material from paleo- or actuo-ETA systems in direct connection with active transport pathways of recent ETA systems;
- (ii) areas without important storages of removable material but with easily erodible bedrock in the reach of actuo-ETA systems with high process rates (zones of rapid mass wasting and sliding, soft types of bedrock, tectonized zones in hard bedrock, etc.);
- (iii) areas without important storages of removable material and with rather erosion-resistant bedrock and low process rates.

(f) Focus for prevention and remedial action on the most sensitive component of a given ETA system in its internal chain of causes and effects and pay special attention to the role of threshold values in these systems.

(g) Several lines of approach are open to manage ETA systems:

- (i) isolation of systems from each other;
- (ii) containment of individual systems within fixed limits;
- (iii) retardation of sediment and water fluxes by inserting temporary storages and increase of internal roughness of the systems;
- (iv) reduction of sediment and water fluxes, e.g. by diversion,

increase of threshold values for erosion, changes in land use with consequent changes in water balances and process rates;

(v) immobilization of complete ETA systems.

CHRONOLOGY OF THE ETA SYSTEMS IN THE UPPER BOITE BASIN

An overview of the chronological sequence of the ETA systems shown in decreasing order of age and proceeding from the remnants of paleo-ETA systems to the actuo-ETA systems is listed below (cf. Figs 6–9).

(a) remnants of a possibly Middle Tertiary fluviatile paleo-ETA system(s);

(b) remants of a fluviatile erosional topography and of fluviatile deposits of a Late Tertiary paleo-ETA system at altitudes around 2000-2200 m;

(c) a widespread coverage of the area by the paleo-ETA system of glacial origin from the Pleistocene epoch, ranging in altitude from the highest summits to the lowest parts of the area;

(d) a fairly extensive zone in the northern part of the Upper Boite basin represented by the actuo-ETA system of subsurface water, dissolving the limestones and to some minor degree the dolomites of the area;

(e) a set of fluviatile actuo-ETA systems, from which the hierarchically arranged Boite River system is the main one;

(f) a set of gravitational actuo-ETA systems:

  (i) active scree slopes below rock slopes with actual forest weathering;

  (ii) zones with intensive slumping in marly volcanic tuffs;

(g) a small number of minor lakes of glacial or gravitational origin form limnic actuo-ETA systems;

(h) a number of manmade actuo-ETA systems occurs in the area: road systems, ski areas, airport, urban centres.

THE NETWORK STRUCTURE OF THE ETA SYSTEMS IN THE UPPER BOITE BASIN

Although the number of active or actuo-ETA systems is quite high in the area, not all of them are connected in continuous pathways for sediment transport. This is due to the activity of the glacial ETA system in the recent past. The recent fluviatile ETA systems have not had sufficient time as yet to link up with each other and to remove the large storages of glacial accumulation material. The latter can be considered on a longer time scale as being only in transient storage in the area, awaiting further transport by actuo-ETA systems.

SEDIMENT SOURCE AREAS FOR THE UPPER BOITE RIVER

The original, detailed ETA systems map at scale 1:25000 of the Upper Boite

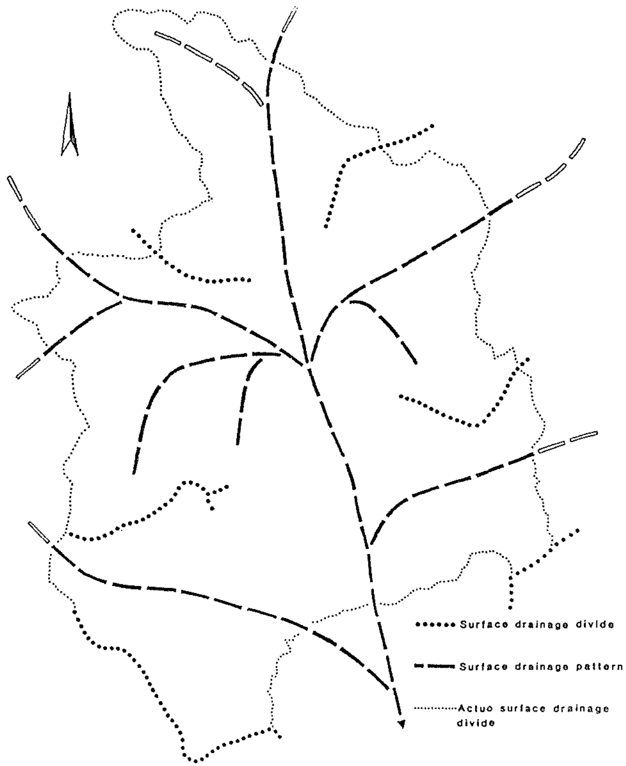

Fig. 6 *Approximate drainage pattern of the paleo-fluviatile ETA system of the Upper Boite basin during the Upper Tertiary. Note the piracy and diversion in the former headwater areas due to headward erosion from the north.*

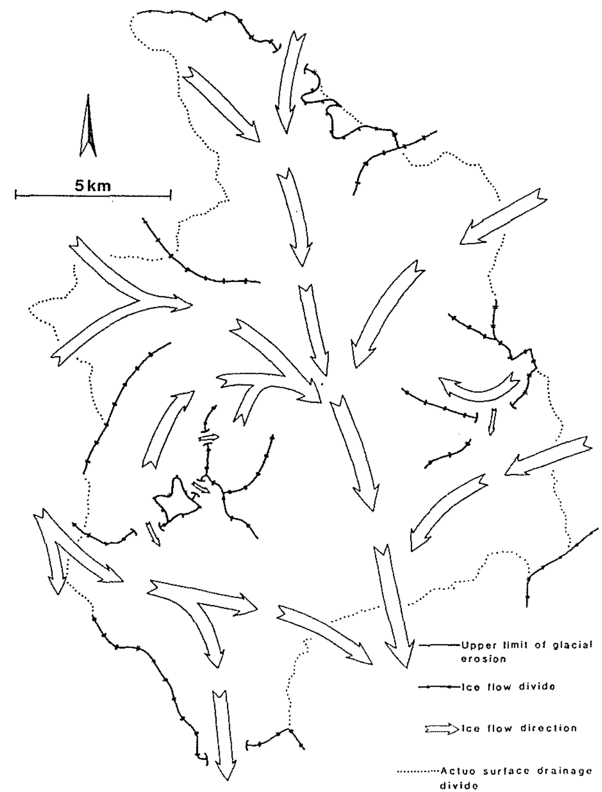

Fig. 7 *Approximate ice flow pattern of the paleo-glacial ETA system with transfluence of central-alpine glaciers from the north through the former decapitated Upper Tertiary fluviatile valley system during the Middle Pleistocene.*

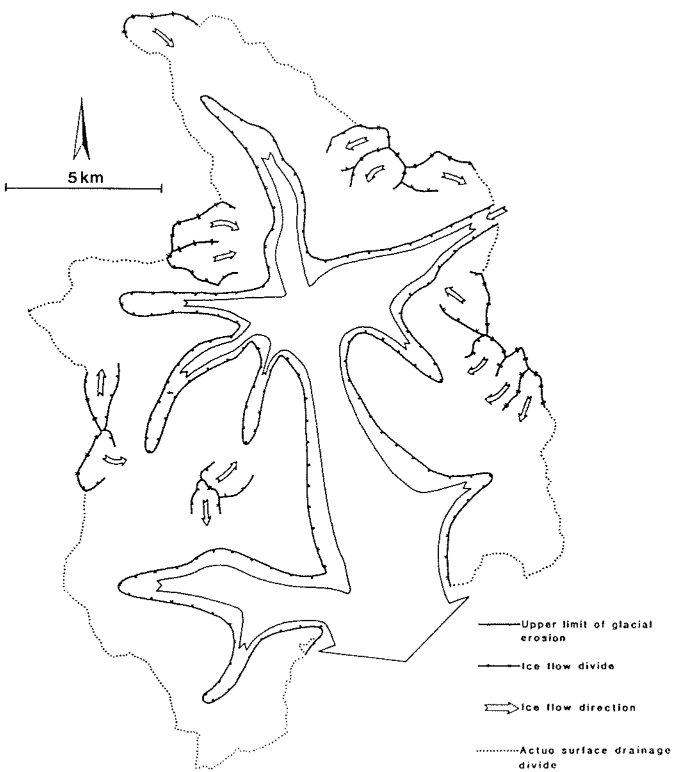

Fig. 8 Approximate ice flow pattern of the paleo-glacial valley- and cirque- glacier ETA systems during the Upper Pleistocene.

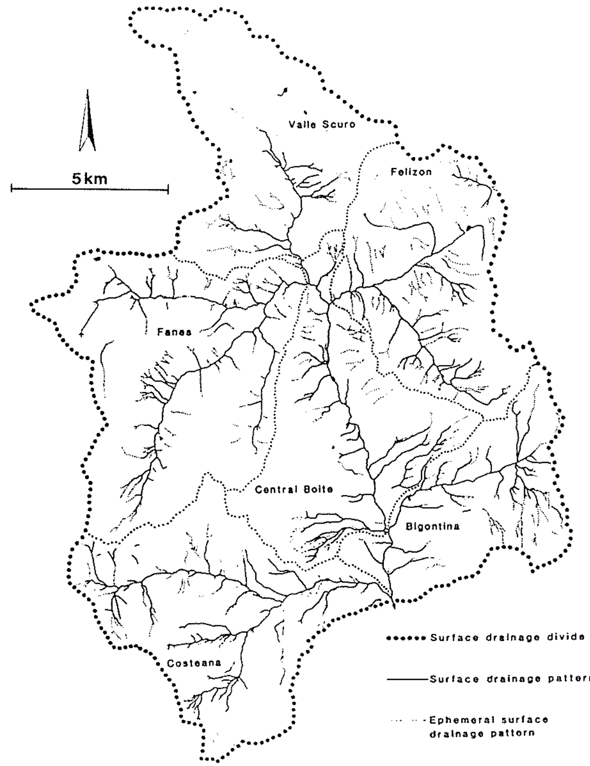

Fig. 9 Recent drainage pattern of the actuo-fluviatile ETA system of the Upper Boite basin.

basin could be used to compile a map of the actual, present source areas of sediment for the Upper Boite River. Many of the active scree slopes in the higher parts of the area are not yet tapped by the river network. For large areas with moraines the same holds true. In other areas temporary

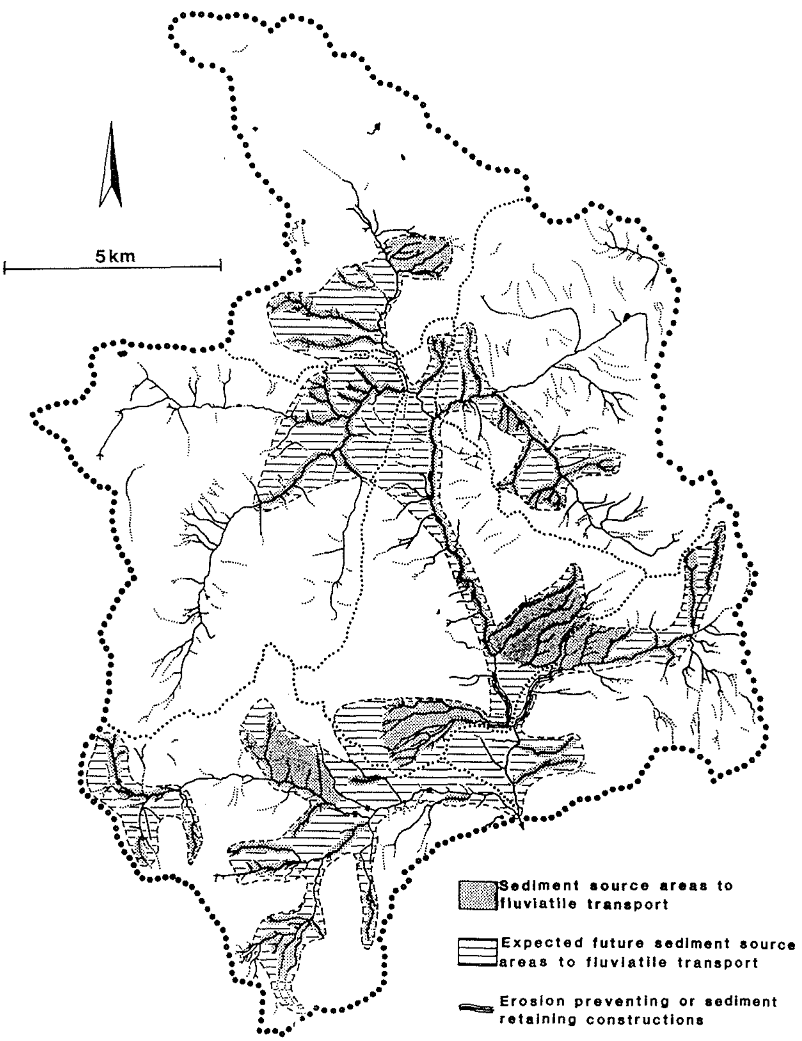

Fig. 10 Recent drainage pattern of the actuo-fluviatile ETA system of the Upper Boite River with perennial and episodic/periodic water courses. Present sources for fluviatile transport occupy only a minor part of the basin. Possible future sediment source areas for ongoing transport in the Boite system indicate zones for preferential planning of prevention measures against erosion and sediment transport. Present erosion prevention or sediment retaining measures consist of drop structures in the river beds and bank protection works.

accumulative storages on fluviatile cones intercept the sediment flow. Such areas may show locally strong erosion and transport, but most or all of the sediment is redistributed and redeposited within that particular zone without reaching the downstream part of the main river (see Fig. 10). The result is that less than a quarter of the total area of the Boite basin presently delivers sediment to the river. Furthermore, a zone can be indicated which in the future may contribute sediment to the river. It contains loose or easily erodible materials which are within reach of a possible future headward erosion of nearby surface water channels of the present fluviatile actuo-ETA system of the Boite River. It is also possible to use the ETA systems map of the Upper Boite basin to indicate critical positions in the surface water network, where headward erosion should be stopped or prevented by the construction of drop structures in the channels. In this way the fluviatile system is prevented from tapping these sediment stores and from passing critical thresholds in erosion and sediment transport. Figure 10 shows relevant sediment source areas falling into five groups:

(a) active gravitational ETA systems (recent scree slopes) in the higher zones;
(b) accumulations of moraines from glacial paleo-ETA systems in the lower parts;
(c) large outcrops of slumped Triassic marly, volcanic tuffs;
(d) scattered smaller outcrops of Triassic marls;
(e) an outcrop of Cretaceous marls.

A map could be drawn indicating the specific sites recommended for action to serve as a basis for a protection scheme for the Upper Boite against excessive sediment transport.

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