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A REVIEW OF TWO STRONGLY CONTRASTING GEOMORPHOLOGICAL SYSTEMS WITHIN THE CONTEXT OF SCALE

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ABSTRACT

Scale issues are often addressed in contemporary geo-ecological studies and form one of the major challenges in the fields of physical geography, hydrology and ecology. In this paper the application of hierarchy theory and response units is proposed as an approach towards scale-transcending environmental studies on degradation and geomorphological development.

Goals of the research were to establish which processes are important at what spatio-temporal scale, how hydro-geomorphological response is influenced by biological processes and whether hierarchy theory and the response unit approach can be used as an up-scaling methodology.

Results from two climatologically and geomorphological different regions are discussed, one dominated by water shortage (SE Spain) and the other by water surplus (Luxembourg). In both cases detailed process research was carried out at scales ranging from the micro-plot to the catchment. Process research was concentrated on understanding and quantifying sediment and water transfer through the geo-ecosystems studied.

Outcomes showed that in both cases the role of biological processes was important in the hydrological and degradation response of both areas. This was not only true for the finest scale levels but also had its impact on the emerging properties and response at the hillslope and catchment level.

Connectivity of runoff-generating and runoff-absorbing areas was important on all scale levels. Connectivity is dominated by both the rainfall magnitude–frequency–duration characteristics and physically and biologically controlled thresholds, which range from initial soil moisture contents, vegetation patterns or soil biological activity, to the presence of water harvesting structures.

The complex interrelationships of the processes involved showed that linear up-scaling from fine to broad scale is impossible, as many thresholds and non-linear processes are involved at specific scales. The identified response units are used to integrate these complex relationships in a relatively manageable way, and may provide a useful framework for up-scaling, and for understanding catchment hydro-geomorphological response and development. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: biological activity; runoff; up-scaling; connectivity; response units; degradation

INTRODUCTION AND OBJECTIVES

Scale issues are increasingly mentioned in current environmental studies and form one of the major challenges in the fields of physical geography, hydrology and ecology. The reason for this interest is not only concerned with learning how systems operate across scale boundaries, but is also related to our needs to deal with regional or global environmental problems. In this paper the application of hierarchy theory (O'Neill *et al.*, 1986) is used as a possible approach towards scale-transcending environmental studies on degradation and geomorphological development.

The main objective of this study is to present some concerns on scale, exemplified by a review of a method for up-scaling applied in two contrasting areas. The first describes a semi-arid system in SE Spain, where water limitation is a driving factor in geo-ecosystem pattern development, and the second discusses a humid temperate system, where water surplus determines the spatial organization of the geo-ecosystem. The goals

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of the research presented are (1) to understand which processes are important at what spatio-temporal scale, (2) to determine how hydro-geomorphological response is influenced by biological processes, and (3) to find out whether the response unit methodology can be used as an up-scaling methodology.

BACKGROUND

Nowadays many models or frameworks exist connecting fine-scale processes to regional or even global processes such as SWAT and hydrological models (Feddes, 1995; Diekkrüger *et al.*, 1999), global change models (Roswall *et al.*, 1988) or erosion models (Kirkby *et al.*, 1996).

In general we can distinguish several approaches to scale-related geomorphological issues or scaling of processes. One of these is extrapolation, often used to scale up point measurements to larger areas with grids of several square kilometres, under the assumption that spatial variability or heterogeneity can be neglected, and that broad-scale spatial patterns are static. It does not incorporate dynamic processes that generate new patterns and it furthermore overlooks the fact that pattern-generating processes have specific spatio-temporal domains (Bergkamp, 1998).

Another approach is the application of scaling theory, based on the similar media concept (Warrick and Nielsen, 1980; Sharma and Luxmoore, 1979), which is often applied in soil-hydrological studies. Some of the disadvantages mentioned above apply here as well.

More recent work is done on down-scaling but it remains problematical to parameterize finer-scale heterogeneity in broader-scale spatial and temporal resolutions (Schulze, 2000).

Ecologists have adopted hierarchy theory for scaling issues (O'Neill *et al.*, 1986; Turner *et al.* 1991), and this has since been adopted by geomorphologists also (De Boer, 1992; Bergkamp, 1998). Applying this approach, a specific scale of study is selected, and finer-scale processes are incorporated at this central level of scale, enabling the emergence of patterns derived from the finer-scale processes. In turn, the processes and consequent pattern development on this scale are constrained by the broadest level of scale with dictating boundary conditions. It seems likely that these complex interactions across scales are highly non-linear.

Several key-questions on scale can be formulated.

(1) Are processes related to patterns? It is generally accepted in geomorphology and geo-ecology that processes acting on a landscape, over time will lead to the development of patterns in a landscape such as erosional or depositional landforms, associated soils and vegetation communities. However, observed patterns may not be related to present-day processes but might be created under past conditions.
(2) How do we deal with homogeneity or heterogeneity? Local point measurements are often used for extrapolation to (far) larger areas. When there are clear spatial relationships geo-statistical techniques like kriging can be used. This may, however, be difficult or impossible, when finer-scale spatial heterogeneity is involved. It may well be that geomorphological and hydrological response of an area is determined by the spatial distribution of maxima or minima and not by an average value. The hydrological response of a sparsely vegetated slope, for instance, may be determined by the spatial distribution of local sinks and sources of water, and this fine-scale heterogeneity may determine the response on broader scales. Wood *et al.* (1986) consider such heterogeneities as important factors in the effect of scale. Another approach would be to collect data on a scale fine enough to cover all variation, but extending this approach to far broader scales is not feasible in practice.
(3) How important is connectivity between landscape units? Spatial heterogeneity becomes even more important when scaling up, and a part of the non-linear geomorphological response is related to (dis)connectivity of the incorporated processes when transferring these to broader scales. Aspects of event-related magnitude frequency thresholds are extremely important to understand connectivity. Connectivity does not only determine the intrinsic response of the land unit itself but also the flux of water and material between units.

Present-day processes are superimposed on a landscape which has a long history of different climatological and ecological impacts on a geological timescale, as well as influences from land use regimes with respect to more recent periods. Hence inherited properties may be hidden in the present-day geomorphological system

(De Boer, 1992). It may therefore seem useful to define landscape units with more or less comparable internal characteristics, including these inherited properties, but also including spatially homogeneous present-day processes. These are here called response units.

The importance of scale is often expressed in the hydrological or geomorphological response of catchments. Runoff is highly scale dependent and many studies have shown that unit runoff is decreasing with increasing sizes of catchments as a result of local infiltration and storage. The actual connection of hydrological processes over different scales has been studied by several authors and both hierarchical (Flügel, 1993) and other methods have been applied. The same is valid for erosion, looking at the sediment delivery ratio. Only a fraction of the material eroded in the catchment headlands actually reaches the basin outlet (Schumm, 1977; Trimble, 1983; Duysings, 1987). This is because of the local deposition of sediment within the catchment itself either as colluvium on lower hillslopes, or as alluvial material in the channel itself. A third important aspect in relation to the response of catchments is the incorporation of thresholds in hydrological and geomorphological processes (Schumm, 1977; Wolman and Gerson, 1978; Imeson, 1983; Faulkner, 1994; Ritter *et al.*, 1999). This aspect, although studied for a long time, is still an underrated aspect in hydrological and geomorphological studies, but is essential for understanding catchment response and how processes are spatially and temporally connected.

APPROACH

Are response units the solution to up-scaling? The idea of response units and its application in watershed studies was described in 1970 by England and Stephenson.

Also the partial area concept of Betson (1964) can be perceived as an early application of the response unit concept. The work of Hewlett and Hibbert (1967) on the variable source area concept incorporated a dynamic component to the partial area concept of Betson and this is now a widely accepted theory for soil moisture dynamics related to topography.

Spatial heterogeneity imposes large problems on process-based modelling of hydrology and erosion, and although encouraging results have been obtained so far, they are far from perfect (Beven, 1996; Favis-Mortlock *et al.*, 1996). Physically based distributed modelling approaches, such as that applied by Calver and Cammeraat (1993) for one of the study areas, may incorporate spatial heterogeneity and even dynamic soil parameters, but require large amounts of parameters, which are often not available for larger areas.

The development of GIS and dynamic GIS approaches offer the possibility to overcome parts of the problems mentioned before, combining both process response modelling, spatial heterogeneity, and landscape characteristics. However, it is still necessary to include a translation of the intrinsic finer-scale properties of landscape parts into a broader-scale framework. This may be done by defining distinctive units with specific process responses, representative for the unit classified.

Busch *et al.* (1999) used hydrological response units to regionalize hydrological response by aggregation methods. Becker and Braun (1999) also proposed a methodology where the landscape is disintegrated into hydrological response units with quasi-homogeneous behaviour and where internally heterogeneities are dealt with in a statistical way. Schulze (2000) followed this approach and defined homogeneous landscape response units. Response units are also used in desertification research (Imeson *et al.*, 1995) and more or less the same approach is followed in this study.

The principle of response units can be explained as follows: a watershed is built of several land units that have a characteristic response with respect to hydrological and geomorphological processes. Each response unit should be identifiable in a proper and preferably easy way. This identification can be done by selecting key indicators that reflect dominant processes within a response unit. This could be vegetation structure or spatial pattern in biological activity, differences in soil characteristics, or others, depending on the geo-ecosystem (Imeson and Cammeraat, 2000) or depending on the landscape processes to be analysed.

Several points should be kept in mind when applying the response unit approach:

(1) How can we classify response units in a useful and clear way? This means that we need easy-to-determine indicators and that these should be distinctive for each response unit.
(2) How do we handle uncertainty in the classification and the relation between process, pattern and response?

(3) Another key question is the quantification of process rates and fluxes of water and matter in and between different response units.
4) A last point for attention is the link or connection between the different response units with respect to flows of water and matter.

FIELD SITES AND MEASUREMENT METHODS

The scale relationships are demonstrated for two contrasting field sites. One site in semi-arid Spain, is dominated in its functioning by water shortages whereas the other site, in temperate Luxemburg, is dominated by water surplus related processes. In both cases the role of biological processes is crucial in the spatio-temporal aspects of the hydro-geomorphological response of the areas.

The first site is situated in SE Spain, in the Guadalentín catchment in the Province of Murcia (see Figure 1). The field site covers a second-order catchment of about 12 km^2 covering the Barranco de Casa Panes, an ephemeral channel leading directly towards the Puentes Reservoir. It has a semi-arid climate (precipitation = 270 mm a^{-1}; potential evapotranspiration = 950 mm a^{-1}; Navarro-Hervás, 1991) and runoff events are scarce, especially on broader scales (first-order catchments and larger; De Wit (2001); Cammeraat, in press). The geology is dominated by small hills built of Eocene to Miocene limestones and valley systems

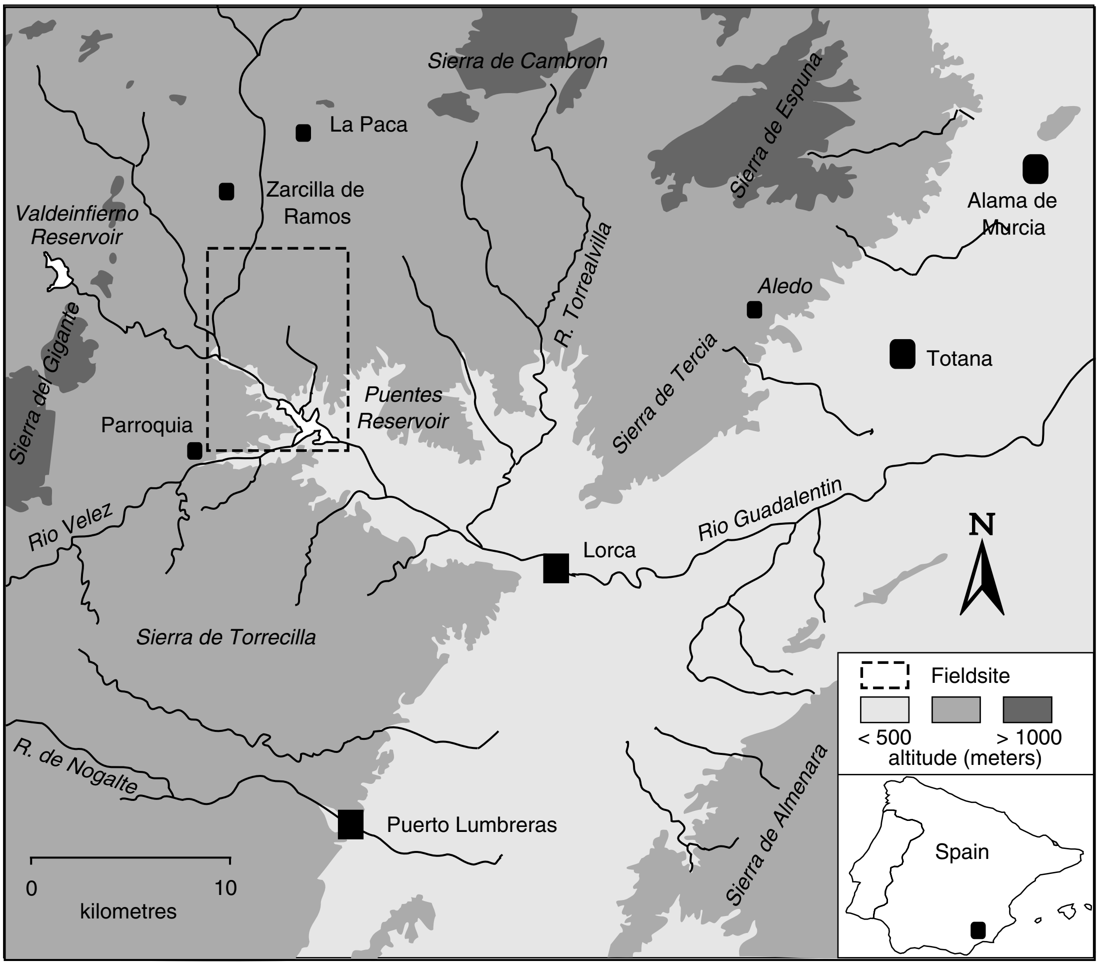

Figure 1. Location map of the catchment of the Barranco de Cases de Panes in the Guadalentín area in SE Spain. The dotted square gives the outline of Figure 2

which are developed in less resistant marly strata ranging in age from Cenomanian to Miocene, often covered with Quaternary slope and alluvial deposits (IGME, 1977, 1981). However, the geology and geomorphology are strongly influenced by complicated fold and fault structures. The geomorphological setting is dominated by rounded limestone hills, with several levels of pediments attached. The high neo tectonic activity in the area causes strong valley rejuvenation and active gullying. Soils are generally very shallow or eroded, with low organic matter contents and low aggregate stability (Cammeraat and Imeson, 1998). Pediment surfaces are often underlain by (partly eroded) calcretes.

Vegetation belongs to the meso-mediterranean zone (Murcian thermofile facies of *Rhamno lycioidi–Querceto coccifero sigmetum*) and is dominated by an open cover of *Stipa tenacissima* tussocks on most of the hills, which are used as rangelands. North-exposed hillsides are covered with open *Pinus halepensis* forests and dense undergrowth of various bushes and grasses. Most of the lower pediments and valley bottoms are used for rain-fed agriculture, such as cereals, olives and almond groves, although irrigated agriculture is increasing.

The experimental set-up of the field site has a nested hierarchical design, with monitored open plots at the finest scale, micro-catchments covering small rills, sub-catchments, first-order channels and a second-order valley system (Figure 2). The runoff of the open plots, micro-catchments and sub-catchments is continuously measured over V-notches, equipped with pressure transducers (Figure 3). The first-order and second-order catchments are monitored on an event base, looking at flood marks and erosion features. Sediment is collected only for the finest-scale level and broadest scale using collection systems and measuring field damage by erosion and displacement of material through bench terrace breaching throughout and at the outlet of the catchment.

The second, contrasting site is located in the centre of Luxembourg (Figure 4) in the upper watershed of the Schrondweilerbaach, a tributary of the Alzette river. The catchment has a size of 1·2 km^2 and has a small, partly intermittent and partly permanent stream. It has a humid temperate climate (precipitation of 788 mm a^{-1}, and an actual evapotranspiration of 220–280 mm a^{-1}; Cammeraat, 1992). Runoff is continuous below the seepage zones and peak flows occur directly after larger rainfall events.

The area has a rolling topography, developed in the dominant, very slightly dipping layered variegated marls of the Triassic Keuper deposits. Thin beds of conglomerates and sandstones occur, which act as limited aquifers in between the marl-dominated formations. The stream divides are broad and slightly convex and the gentle hillslopes have slope angles of up to 8° at most. The channels have steep walls and show signs of active incision and erosion (Duysings, 1987). The heavy soils are generally characterized by an abrupt

Figure 2. View of pediment with open *Stipa* vegetation (response unit 6) and runoff plots near Lomo de Alquería (Campo de Panes catchment, SE Spain)

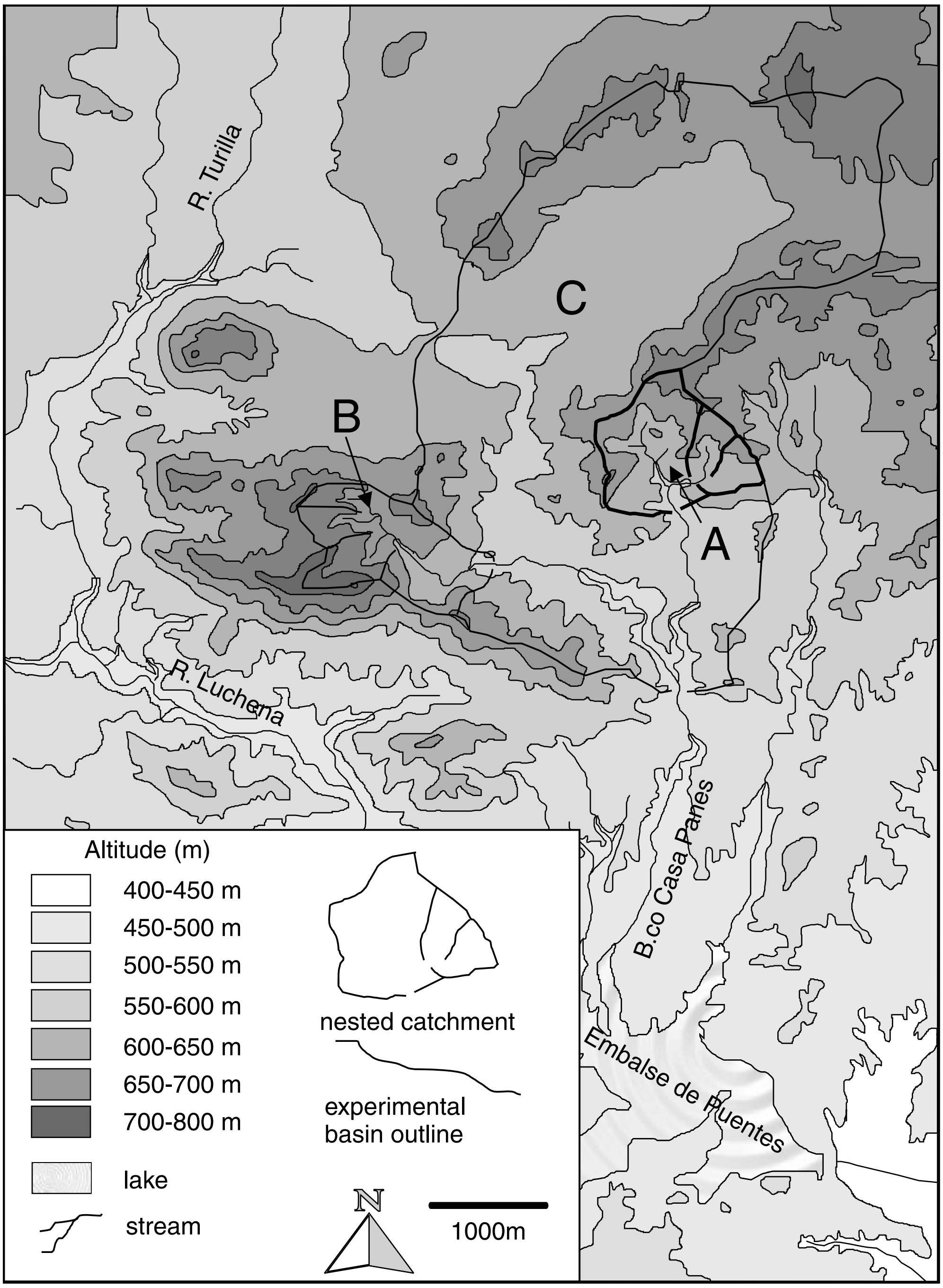

Figure 3. Outline of the Spanish catchment area with measurement set-up. A = Alquería experimental catchments; B = Ponce/Buittre experimental catchments; C = Barranco de la Casa de Panes catchment

textural contrast at a depth of 10–30 cm, implying seasonal perched water tables on the dense Bwg horizon (>50 per cent clay) (van den Broek, 1989) and lateral subsurface flow. The topsoil (upper 10–30 cm; AEh and EAh horizons) has a clay content of only 15–20 per cent as most clay has been laterally removed by lateral subsurface erosion over the dense Bgw horizon.

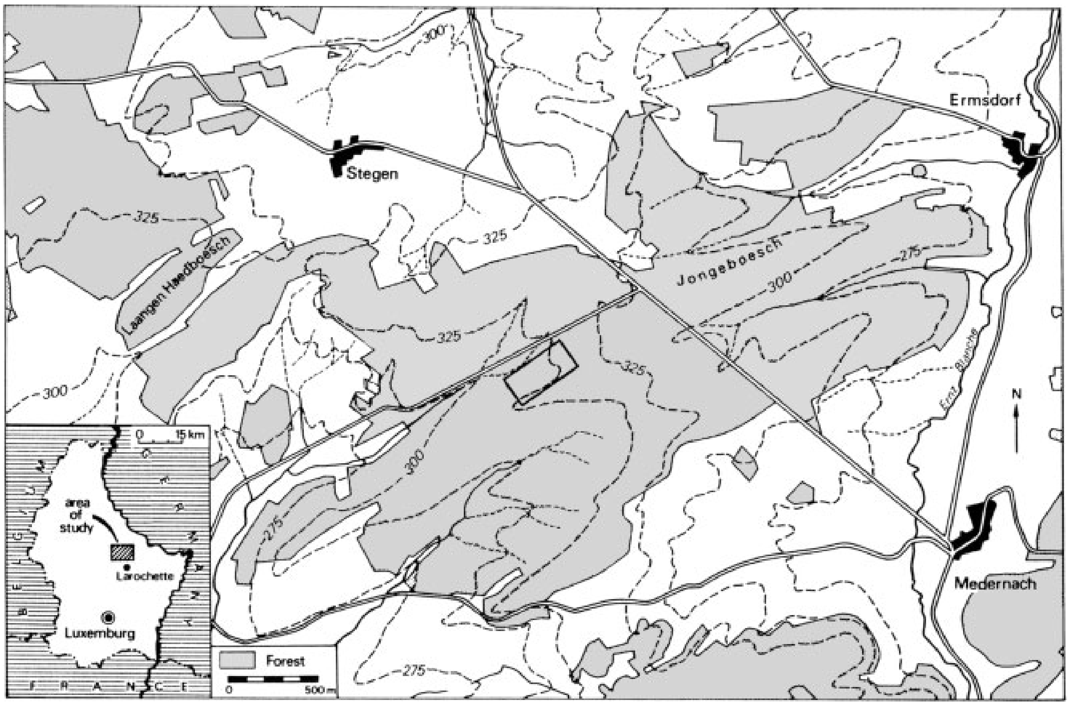

Figure 4. Location map of the Schrondweilerbaach catchment in Luxembourg

Figure 5. View of the valley bottom of the Schrondweilerbaach catchment

The dominant vegetation is a semi-natural oak (*Quercus robur*)–hornbeam (*Carpinus betulus*)–beech (*Fagus sylvatica*) forest, with locally shrubby undergrowth of mainly hawthorn (*Crataegus leavigata*) and ash (*Fraxinus excelsior*)) (Figure 5). Hornbeam is found at wetter locations (Stellario-Carpinetum (R.Tüxen 1937 pp.) Oberdorfer 1957), whereas the dryer parts are dominated by beech (Milio-Fagetum Hesmer et Schroeder 1962 non Frehner, 1963; or Melico-Fagetum Lohmeyer et Seibert 1954). Natural channels have been extended with ditches to improve drainage of the forests. Small parts of the catchment are covered by meadow for grazing purposes.

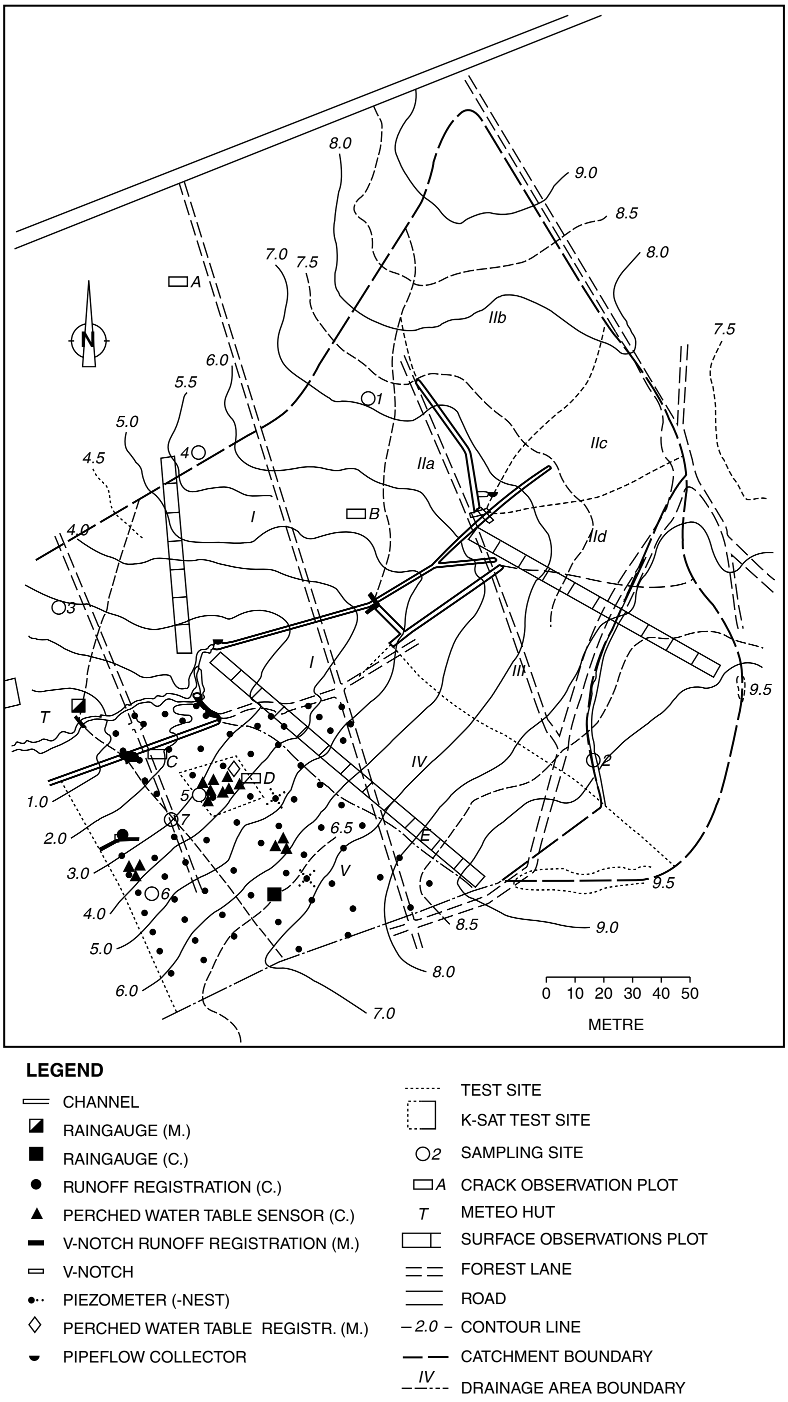

Figure 6. Set-up of one of the instrumented sub-catchments of the Schrondweilerbaach

The experimental field site has a nested design of several continuously monitored micro- and sub-catchments within a larger catchment, as well as a 100 × 100 m test hillslope where lateral throughflow and pipeflow are measured. The perched water table was monitored both manually (100 piezometers) and automatically (14 piezometers) on this test slope (Figure 6).

The areas are chosen as examples to study across-scale processes and their interaction. The Spanish situation is representative for areas with moderate slopes and with open grass tussock vegetation, which is found throughout semi-arid SE Spain. This type of environmental condition is regularly found also in semi-arid northern Africa.

The Luxembourg site is specifically related to a special type of substrate, having clays that are easily dispersible, shallow permeable topsoils, gentle hillslopes, a water surplus and a deciduous forest cover. These locations may occur scattered in the outer zones of the Paris Basin, where Triassic Keuper deposits crop out and comparable geo-ecosystems are expected to occur in parts of Belgium, France, Germany and England.

SCALE, RUNOFF, DEGRADATION AND THRESHOLDS

Spain

Critical conditions affecting runoff generation at the finest temporal and spatial scales (runoff plot) are rainfall intensity, antecedent moisture content, soil depth (Cammeraat and Imeson, 1999a; Cammeraat, in press) and soil surface properties including vegetation distribution. The infiltration of the bare crusted areas in between the plants is smaller than in vegetated areas, due to higher roughness and higher infiltration rates. Vegetation clumps have favourable infiltration characteristics due to higher biological activity in the shaded area, higher organic matter contents, and better soil structure, as also found by other authors (Cerdà, 1997; Bochet *et al.*, 1999; Puigdefabregas *et al.*, 1999). This mechanism can be perceived as a self-reinforcing system, allocating all resources to the vegetated areas (Imeson *et al.*, 1995; Puigdefabregas *et al.*, 1999).

Figure 7 shows the spatial distribution of vegetation (*Stipa tenacissima* tussocks) as well as the measurement set-up. Once individual bare patches produce more runoff than can be absorbed by vegetation clumps lower on the hydrological pathway, runoff will concentrate and initiate rills, as commonly found in semi-arid and Mediterranean shrublands (Lavee *et al.*, 1998; Valentin and Poesen, 1999). When the vegetation pattern becomes too dense or is organized in dense bands, this creates important thresholds in runoff generation on hillslope scales, as it forms an important infiltration zone for water (Cammeraat and Imeson, 1999b; Cammeraat, in press). This is reflected in the runoff response of the area in Figure 7 where upslope areas respond in a similar way to downslope areas, but the upslope water never reaches the downslope area unless the rainfall intensity and amount surpasses a critical threshold. Therefore physical properties such as soil type and depth, slope angle and slopelength as well as roughness are important, but so too are vegetation density and pattern. Using these biotic and abiotic parameters, the catchment area has been divided into different response units, which are clearly different and also show different hydrological and erosion response (Cammeraat *et al.*, 2002). Figure 8 shows a part of the catchment with response unit zonations. These as well as vegetation patterns can be classified using high-resolution images, such as described by Prinsen and Imeson (in press).

Puigdefabregas *et al.* (1999) discussed the role of runoff generation and sediment distribution and dynamics on comparable *Stipa t.* covered hillslopes at various scales ranging from plot to hillslope scale on meta-schists and sandy-gravelly sediments derived from this substrate. They stress the dynamic interaction causing positive feedbacks between plant growth and spatial pattern, and water and sediment redistribution, strongly influencing the heterogeneity of hillslope characteristics. They concluded that most water did not reach the lower hillslope due to local sinks of water in the vegetated areas, and that only rarely were the rainfall conditions such that overland flow could be generated on broader scales. This is only partly the case for the area of the Campo de Panes discussed here, as the critical threshold for runoff generation on all scales is much lower, caused by a difference in substrate which has a much finer texture. Runoff is more frequently generated at finer scales than at broader scales. It was observed that overland flow starts to occur above threshold rainfall amounts of 5–8 mm with intensities above a certain threshold, also depending on the soil moisture level. In winter runoff is already observed at the finest scale (bare patch and plot scale) at rainfall intensities at 1·6–1·8 mm per 10 min. In dry summer periods, however, runoff does not occur until intensities reach a higher level than 3·2–3·6 mm in 10 min (Cammeraat, in press).

At the hillslope and sub-catchment scale, runoff is studied for different response units and aggregated response units, with increasing area of the catchment. At all scales the runoff response is extremely flashy

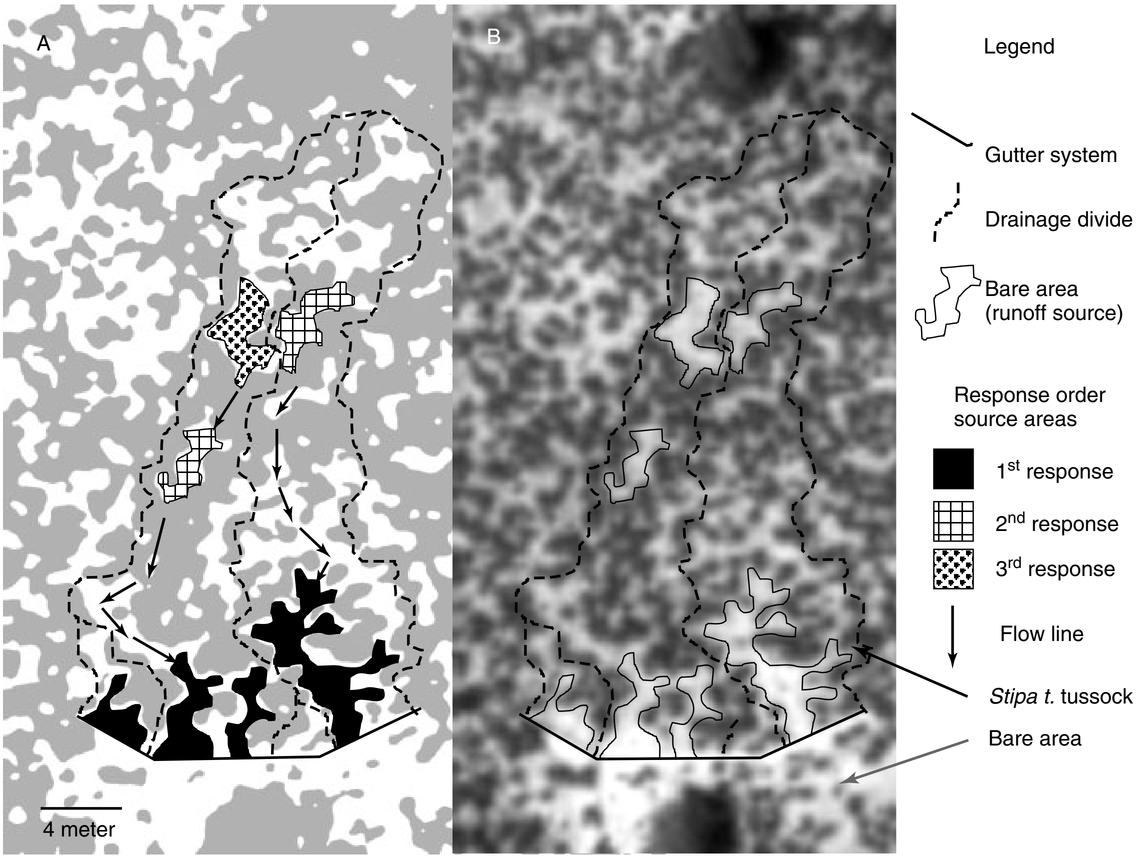

Figure 7. Hillslope section with open plot installation in the catchment of the Barranco de Cases de Panes. (A) Filtered presence of vegetation cover (grey) and bare areas; (B) the same area, but with unprocessed digital aerial photo background, giving a more natural picture of the hillslope. Runoff is generated in the larger bare areas indicated by the different order response areas (A). Depending on the intensity and duration of the rainfall, different hillslope zones will contribute to the runoff at the hillslope base. Measured runoff comes first from the first response area but with increasing rainfall intensity and duration the second and third response areas will start to contribute to the lower hillslope, when the buffer capacity of the vegetated zone below the second and third response areas are no longer sufficient

(Figure 9) and the lag time between the mass of precipitation and the runoff increases with the size of the runoff-producing area. Both the rising and falling limbs of the hydrographs are very steep, indicating fast response, relatively short travel distances, and flow concentration in rills under Hortonian-type conditions.

At the catchment scale runoff events becomes scarcer. De Wit (2001) found, after statistical analysis for five sub-catchments of various sizes (9·2–110·6 ha) and land use within the area of study, that runoff levels were all within the same order of magnitude. However, micro-catchments clearly showed more frequent runoff, and both runoff and peak discharge for all measured catchments were decreasing with increasing size of the catchment.

The spatial and temporal variation in runoff response on rainfall is strongly related to the recurrence period of the rainfall events. At the finest scale more runoff events are generated than at the broadest scale. An overview of spatial and temporal scale–runoff relations is shown in Figure 10, combining frequency of runoff occurrence at the different scale levels, type of threshold involved and rainfall characteristics. It shows that runoff is generated for different rainfall depth thresholds that increase with the size of the catchment. Standard errors are considerable and decrease with increasing rainfall depths. Large standard errors for the finer-scale response are related to storms that lasted a long time but had only low rainfall intensities and complete water infiltration on the finest scales. Looking at maximum rainfall intensity alone, it seems that

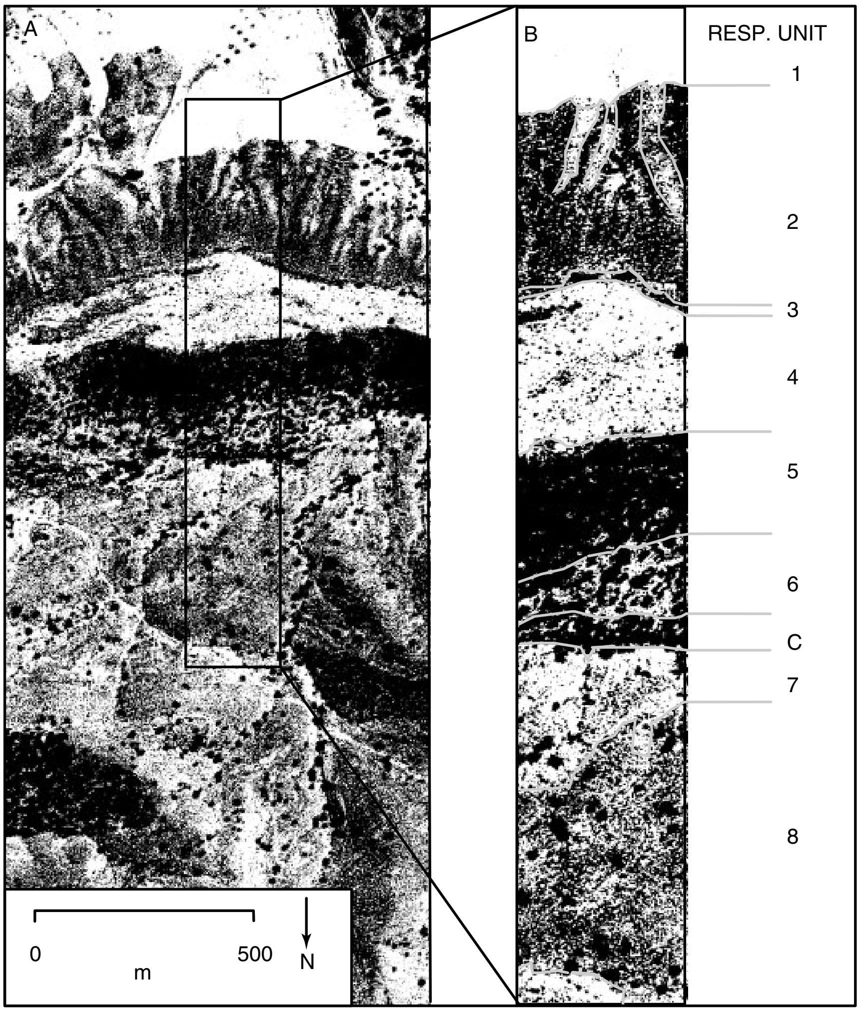

Figure 8. Response unit zonation for a part of the Campo de Panes catchment (Lomo de Alquería). Processed photo-mosaic of high-resolution digital images made in April 1997. The darker the area, the more vegetation is present. Small dots indicate *Stipa* tussocks, larger ones pine trees. Eight response units are indicated as well as the channel, all having differences in vegetation density and pattern, substrate and surface processes. Response unit 1 (RU1) = agricultural area; RU2 = *Stipa*-covered hillslope on marls, with shallow gulleis; RU3 = small zone with shrubs and trees; RU4 = bare limestone slope; RU5 = open pine forest; RU6 = degraded open pine forest; RU7 = degraded pediment with *Stipa* tussocks; RU8 = limestone hillslope with *Stipa* vegetation. C = channel (barranco)

there are three scale groups of responses: the finest scale (frequent occurrence; bare area–vegetation tussock), the intermediate scale (intermediate occurrence; hillslope to catchment scale) and the broadest scale (second-order catchment) where runoff is generated only very rarely (less than once in three years), as water harvest structures effectively buffer runoff. At the catchment scale the connection between the different response units becomes important, as the response unit may receive water from adjacent units on the upper slope. The response of the ephemeral channel network on the catchment scale is only occurring at rainfall intensities over a minimum threshold of 4·2 mm in 10 min with large amounts of rainfall (>30 mm) or less rainfall but under very high intensities. Thresholds are again higher due to losses related to longer flow paths on hillslopes and channel losses, especially where the channel is developed in limestone bedrock or in ploughed valley bottoms.

Rates of degradation show that at finer scales erosion rates are relatively small on the semi-natural pine and *Stipa* tussock-covered rangelands. Erosion rates per event are in the order of 0·08 t ha^{-1}. Even under

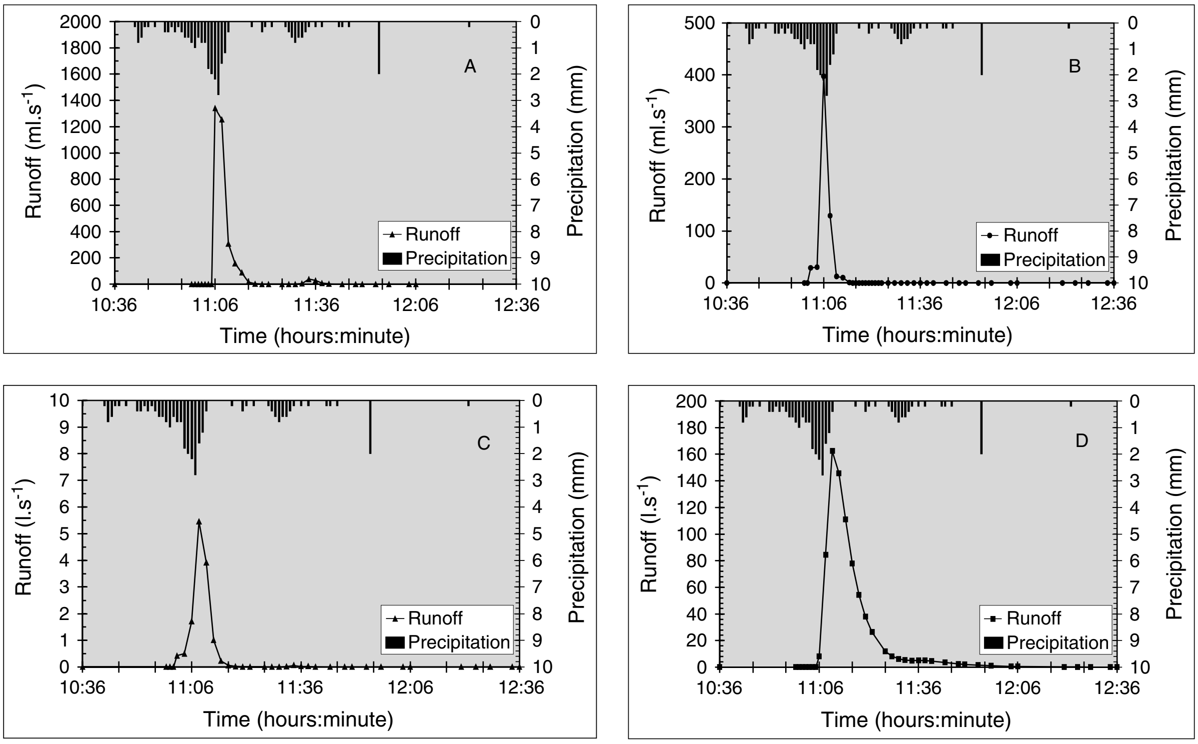

Figure 9. Runoff response from different response units and different scales, for an event of 27·4 mm with a peak intensity of 168 mm hr^{-1} for 1 min on 29 September 1997. (A) Open runoff plot on degraded pediments with *Stipa* cover (response unit 7). (B) Runoff plot on degraded forest (response unit 6). (C) Micro-catchment (2500 m^2) in degraded and open forest (response unit 6 + 5). (D) Sub-catchment (0·12 km^2) covering response units 5, 6, 7 and 8

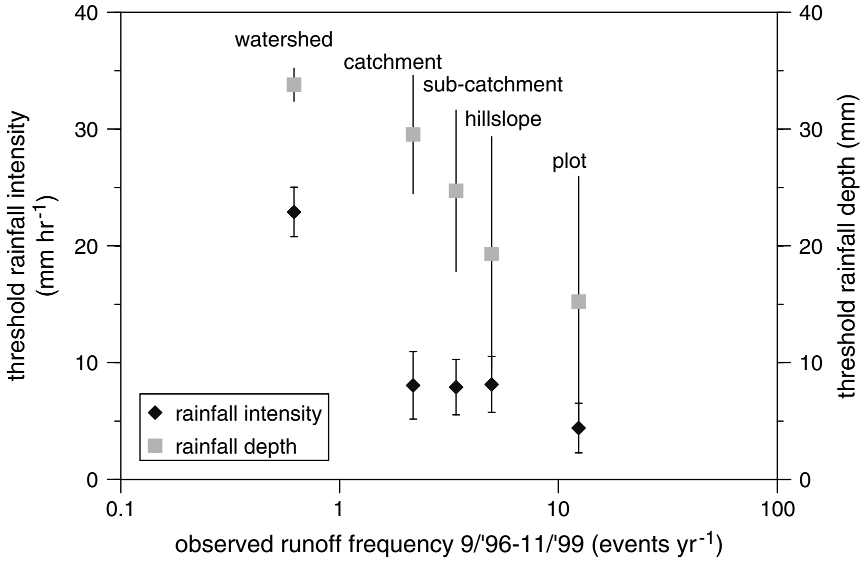

Figure 10. Threshold rainfall intensity and depth required to generate runoff at different scales within the Campo the Panes catchment for a three-year period. Vertical lines indicate standard errors around the mean. The number of observations of runoff varied per scale level, decreasing from the plot to the second-order catchment scale ($n = 37$, 18, 11, 8, 3 for plot, micro-catchment, sub-catchment, first-order catchment and second-order catchment respectively)

high-intensity, low-frequency storms these values remain in this order of magnitude (Cammeraat, in press); however, they occur frequently. For recently (1980s) reforested hillslopes values are much higher, as the soil surface is disturbed and bench terracing is applied. These terraces are imperfectly maintained resulting in extensive gullying and high erosion rates. These can be a magnitude of two larger than undisturbed semi-natural hillslopes (De Wit and Brouwer, 1998).

Looking at broader scales, such as the valley bottom areas where marls are predominating, far larger degradation rates are encountered for the low-frequency events, ranging to values >30 t ha^{-1} (Cammeraat, in press). Here water-harvesting measures using small water-retaining earth dams are used. Once waterflow exceeds the local infiltration rate and the storage capacity of the depressions between two dams, the dams are washed away, together with the ploughed topsoil, moving vast amounts of sediment (Figure 11).

From these figures one can conclude that all events contribute to the erosion of the vegetation-covered hillslopes at relatively low rates. However, due to the presence of the water-retaining walls, sediment also accumulates during these events. Only during high-intensity events during which the terrace walls are disturbed, is sediment moved downslope at high rates. So erosion rates are highly heterogeneously distributed over the area and strongly related to (a) the connectivity of the hydrological system, involving various roughness-related thresholds, such as vegetation density and pattern, micro-topography, channel linkage and water-retaining structures, (b) the intensity and duration of the rainstorm and (c) the influence of man (agriculture and land management practices, reforestation and grazing).

As rainfall is highly variable in this semi-arid climate, longer time periods of study are necessary to evaluate representative degradation rates. This is not feasible from erosion measurements alone as in most cases monitoring is not possible for periods longer than 10 years. To uncover these characteristics indirect measurements derived from sediment accumulations in small lakes and depressions could be evaluated and coupled to current measured events, to establish longer records of deposition and erosion to cover broader temporal scales. This can be extended to even longer periods by evaluating the catchment geomorphology, such as valley fills and erosion in barrancos and the truncation of pediments with calcrete profiles within the catchment.

Luxembourg

Critical conditions affecting runoff generation at the finest scales (runoff test site) are rainfall intensity, antecedent moisture content, soil depth, the presence of semi-permanent pipe systems and soil biological activity via the presence of earthworms (*Lumbricus terrestris*) and moles (*Talpa europea*) (Cammeraat, 1992; Calver and Cammeraat, 1993; Hendriks, 1993).

Figure 11. Runoff at highest level of scale on 29 September 1997, in the upper Cañada de Hermosa valley bottom, the upper source area of the Campo de Panes catchment. All water-retention dams are breached by continuous accumulation of overland flow

Runoff is mainly produced in partial areas (approximately 50 × 50 m), which form very shallow depressions with very dynamic hydrological behaviour (Bonell *et al*., 1984). Figure 12 shows the spatial extension of the perched water table in a partial area that is drained by semi-permanent pipe systems. However, runoff is fed not only by concentrated flow in pipe systems, but also via matrix throughflow. This second contribution to runoff is dominant in the parts of the hillslopes surrounding the partial areas. Water is flowing through pipes from the upper hillslopes to a central depression, forming the partial area. Here water is accumulating and a perched water table is building up over the dense Bwg horizon, leading locally to ponding and saturation excess overland flow. Slightly lower on the slope, overland flow is again infiltrating through pipes and draining directly to the channel, lowering the perched water considerately.

Key parameters behind this hydrological behaviour are the interaction between biological activity and soil properties in the forested part of the catchment. The presence of earthworms in the partial areas, which remove and digest freshly fallen surface litter from the soil surface (Hazelhoff *et al*., 1981), increases the organic matter content of the soil, which in turn increases the shrinkage and swelling properties of the topsoil. The topsoil has, despite its lower clay percentage, similar shrinkage properties when compared to material from the Bwg horizon. This is probably related to the presence of organo-mineral-clay complexes, which are susceptible to swelling upon wetting, whereas topsoil material without organic matter has no swelling properties (Cammeraat, 1992). As a result, the topsoils (only Aeh and Eah horizons) in the partial areas have extensive shrinkage-crack polygons in summer and autumn and consequently hydraulic conductivity is high in the two top horizons and drainage is dominated by preferential flow. This leads to rapid drainage and fast hydrological response in the channels. In this period the occurrence of the perched water table on the dense non-cracked Bwg horizon is rare, but can build up in the topographical depressions of the partial area under very wet circumstances. In late winter to early spring, however, the situation is reversed and shrinkage cracks of the Aeh and Eah horizon are closed and hydraulic conductivity is much lower, as matrix flow is dominant over preferential flow. Infiltration is still high as the topsoil is very porous. The slower drainage leads to a more regular occurrence of a perched water table in the shallow depressions of the partial areas, even more so as evapotranspiration rates are very low in this period. In very wet periods this leads to saturation excess overland flow (Figure 13a). With the lack of macro-pores, the drawdown of the perched water table takes more time and the recession factor of peak runoff is also reduced, and baseflow is enhanced.

The hillslopes in between the partial areas do not show high densities of macro-pore systems, show less biotic activity and have litter-covered surfaces. Here, drainage is matrix throughflow-dominated (Figure 13b). All matrix throughflow moving downslope over the dense Bgw horizon is eluviating the fine clays from the top of the Bwg horizon (van den Broek, 1989) enhancing the abrupt textural change at the Eah–Bwg horizon. This process is responsible for the formation of the specific type of soil in this area. As a result all streams draining these areas show high suspended loads, giving the water a milky colour (Duysings, 1987; van den Broek, 1989).

Hence runoff at the hillslope scale is not only primarily determined by the response of partial areas, but is also determined by the seasonal variation in hydraulic properties of the soil. The first spatial factor can be easily characterized by mapping the activity of the earthworms just in early autumn (Figure 14); the second factor is dependent on seasonal variation of the water budget of the topsoil. Under grass the response is quite different as concentrated lateral throughflow is less extensive and semi-permanent pipe systems are less dominant.

On the catchment scale these effects are still noticeable, but the runoff also becomes influenced by baseflow delivered from the thin underlying sandstone and conglomerates. Baseflow levels are in the order of 30 mm a^{-1}, calculated from the total surface covered and the discharge of the baseflow. This is less than 10 per cent of the 316–343 mm a^{-1} of rain, which is discharged through runoff in the measurement period (Cammeraat, 1992).

The area can be divided into forested areas, with partial areas and dry areas, such as given in Figure 14 and the grasslands, which are considered as one response unit. Connection between the different response units takes place via the drainage channels and pipe systems in the topsoil or by saturation excess overland flow in very wet periods. As in winter, the preferential flow paths in the topsoil do not operate and matrix flow is more common, and runoff response is slower, if compared to the summer–late autumn period, when pipe

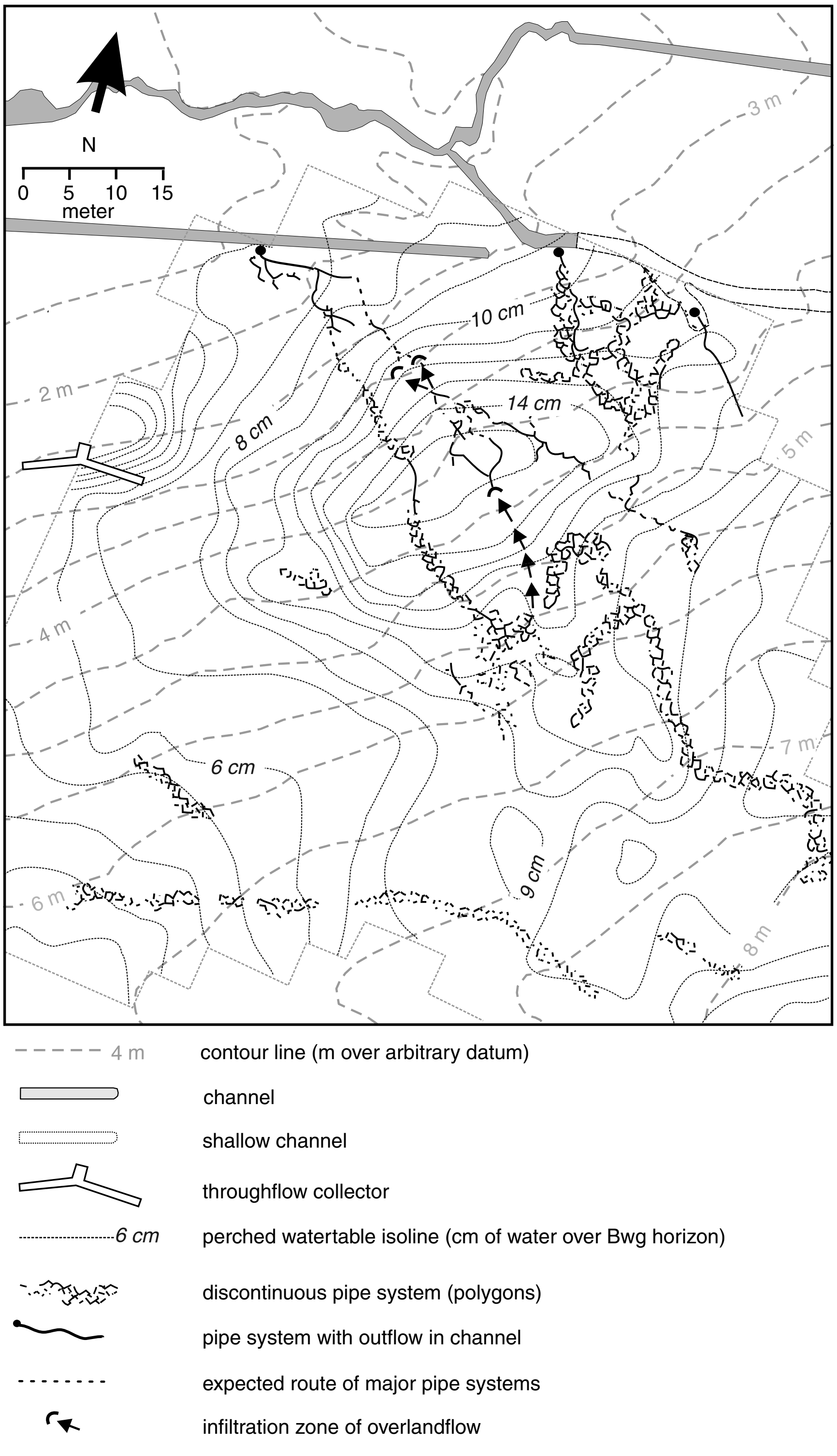

Figure 12. Spatial distribution of perched water table in the instrumented partial area of the Schrondweilerbaach catchment. Note the saturation excess overland flow paths as well as the crack polygons

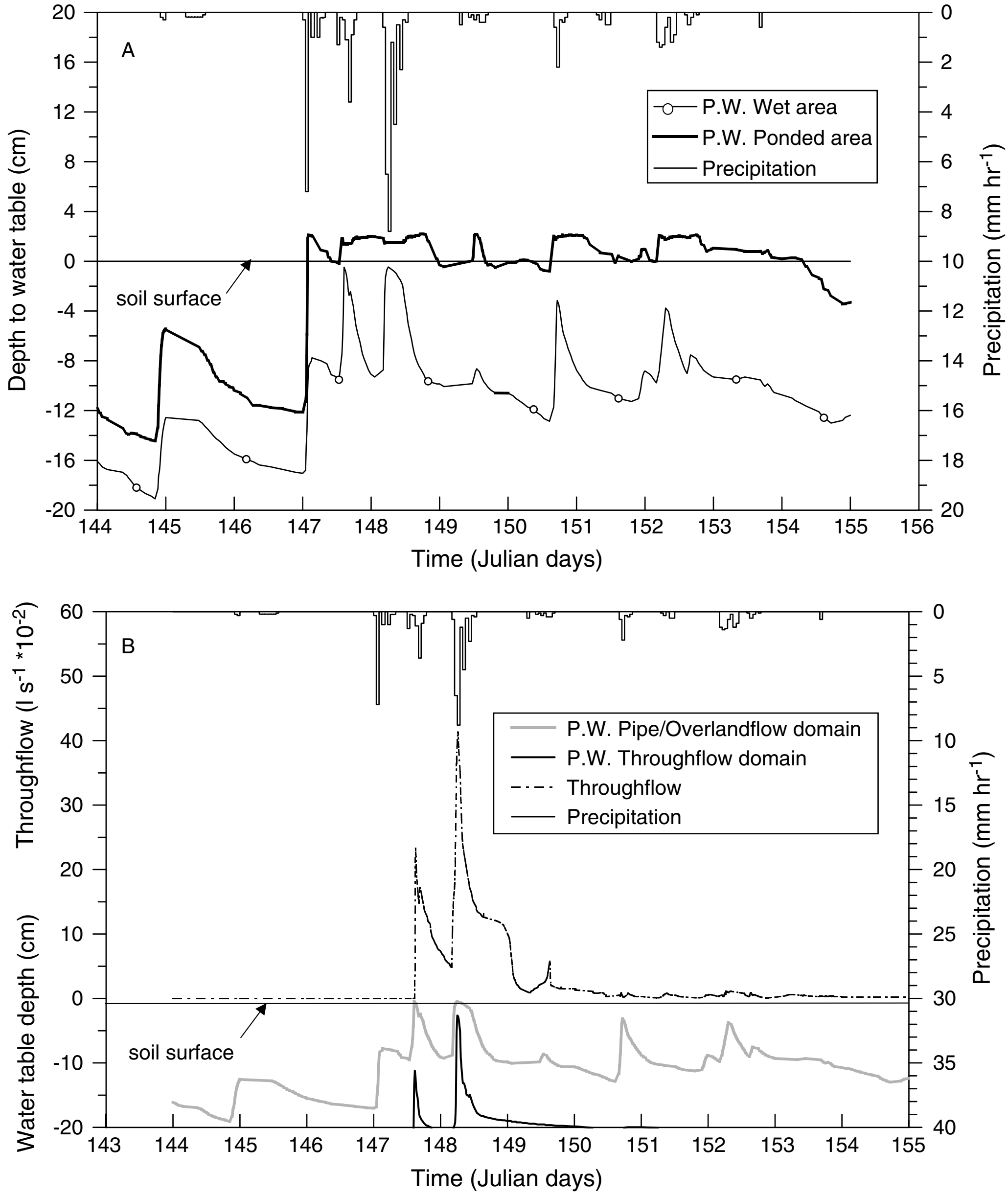

Figure 13. (a) Perched water table dynamics during an extreme wet period, for a partial area (centre of Figure 12), showing a ponded area with saturation excess overland flow and a less wet area in the same partial area. (P.W. = perched water table). (b) Spatial distribution of perched water table in the instrumented partial area and surrounding dry slopes of the Schrondweilerbaach catchment. The partial area (pipeflow and overland flow domain; centre of Figure 9) shows long periods with a perched water table. The dry hillslopes show only very short periods of matrix throughflow, reflected both in the level of the perched water table but also in the discharge of the throughflow collector (indicated on left side of Figure 12)

flow is very important. In grasslands this difference was not observed. Therefore catchment-scale peak runoff is higher in summer and late autumn for the forested catchments when compared to grassland-dominated catchments. In late winter and early spring the reverse can be observed (Figure 15; Imeson, 1986).

Erosion and sediment levels are runoff-dependent for the larger catchments (Duysings, 1986, 1987) and the well-documented sediment budget is dominated by the dispersed clay derived from the lateral erosion of the Bwg horizon (Duysings, 1987). However, looking at finer spatio-temporal scales, there is no relation between

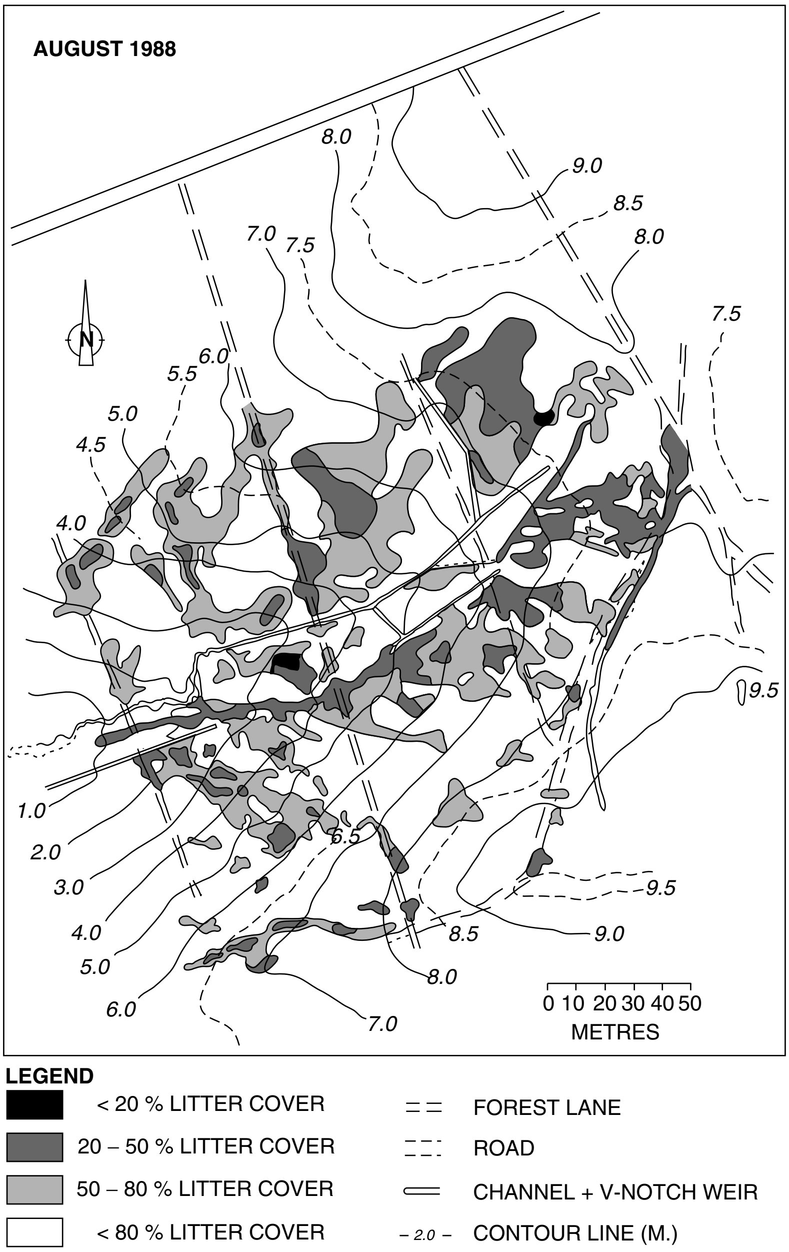

Figure 14. Spatial distribution of partial areas as reflected by earthworm activity in autumn. The degree of litter-free area is indicative of worm activity and the presence of more moist conditions in shallow depressions. The same pattern was observed for three consecutive years

runoff and sediment load. In autumn splash erosion-delivered sediment is transported to the tributaries, as partial areas are free of litter cover due to earthworm activity. This imposes a seasonal variation in sediment levels and composition (Duysings, 1986). Local digging and browsing by wild boar may also strongly influence sediment contributions to small tributaries (Cammeraat, 1992). At broader spatio-temporal scales the experimental evidence and the morphology suggest that partial areas are most active and erosion rates are largest in these areas. Van den Broek (1989) also calculated the minimum age of soil development from lateral eluviation rates of the soil, coming to a conservative age of about 3500 years.

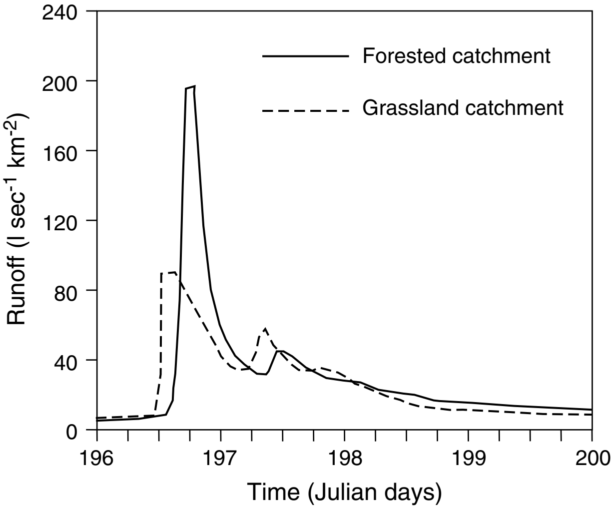

Figure 15. Runoff peaks for two neighbouring streams in the Luxembourg study area in July. Both areas are similar in size, exposition and lithology, only land use is different (Keiwelsbaach and Mosergriecht). Note the high response of the forested catchment as a result of macropore-flow drainage. Modified from Imeson (1986), reproduced by permission of Gebrüder Borntraeger Verlagsbuchhandlung

FINAL DISCUSSION AND CONCLUSIONS

In Figure 16 a spatio-temporal framework is given for both areas showing dominant processes and geo-ecosystem properties at different scale levels. Geo-ecosystem properties (all square boxes) are displayed a three scale levels: (i) the plot scale with individual plants or micro-topographical depressions, covering property changes mainly at event and seasonal temporal scales; (ii) the hillslope scale (response units), covering 'human' time scales; and (iii) the catchment scale, covering geomorphological landscape development time scales. Round boxes indicate dominant processes, which operate at and between the different scales. The arrows indicate process connections between individual properties. A distinction is made between two different domains within each geo-ecosystem. The domains can be separated in areas with relatively high (vegetated or wet areas; white boxes in Figure 16) and low biological activities (bare and relatively dry areas; shaded boxes in Figure 16). The figures show connections of processes between different scales, leading to emergent properties at higher scale levels. At the lower scales positive feedback relationships exist, which strengthen the development of spatial heterogeneity within one scale level. In both diagrams the role of biological processes is important at the lower levels, as these processes are related to the finest temporal scales, whereas the abiotic processes start to become more dominant at the highest levels presented, irrespective of the system. The figure illustrates the connections between properties at different scales and illustrates that sub-response unit processes and properties are highly complex, and non-linear. The evolution of the system is highly dependent on the interactions and feedback-dominated processes at the fine and intermediate scale.

From the previous discussion it may be clear that the impact of scale is important in hydro-geomorphological studies. It implies that the measurement strategy is dependent on the scale of interest and the spatio-temporal domains of the processes involved. It is also clear that a linear up-scaling from fine to broad scale is impossible, as many thresholds and non-linear processes are involved at specific scales but also at the connection between scales.

Biotic impact on hydro-geomorphological processes is often ignored but in the two examples discussed the interaction and feedback between biological and abiotic processes are clearly demonstrated. At the Spanish site the role of vegetation pattern and the positive feedback between plant growth and accumulation of water, sediments and nutrients play an important role in the spatial configuration of vegetation on the finer scales, as also found in other studies. On hillslope and catchment scales the results show

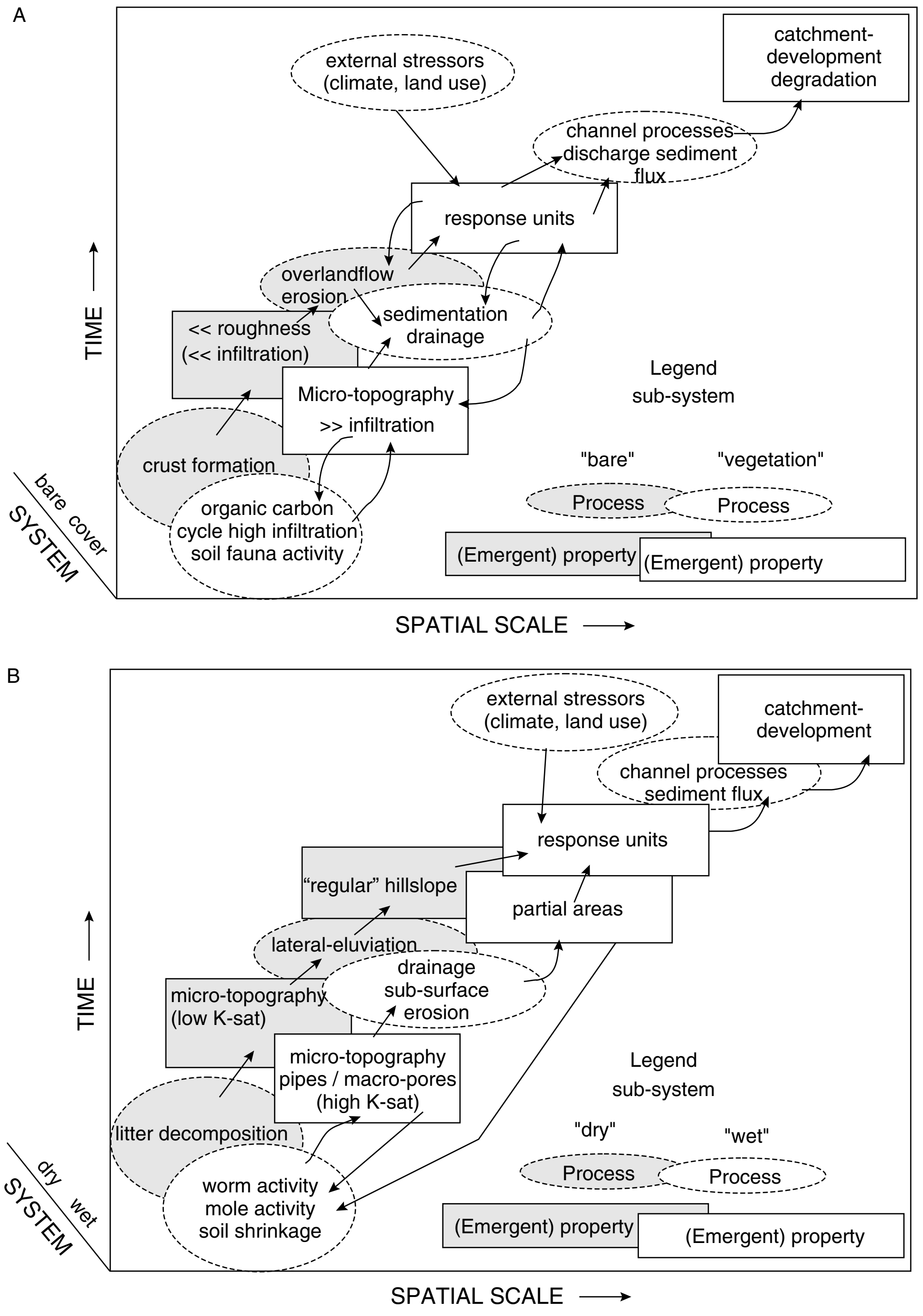

Figure 16. Conceptual framework showing process relationships between different scales for the Campo de Panes area (A) and the Schrondweilerbaach area (B)

that different spatial configurations of vegetation patterns determine hillslope runoff, which can be used to characterize hydrological or degradation responses of land units. For the Luxembourg situation a similarity exists in that soil faunal activity strongly influences local soil surface and sub-surface conditions, affecting both the spatial and temporal response of hydro-geomorphological processes, noticeable even on the catchment scale.

Returning to the key questions mentioned earlier: processes generate patterns in the two geo-ecosystems discussed, and patterns observed are related to current processes and complex system interactions, specifically at the finer and intermediate scales.

The second key question was how to deal with spatial heterogeneity without ending up in an infinite sampling design, and the use of response units was proposed. Response units integrate the complex geo-ecosystem relationships on the hillslope or sub-catchment scale and may provide a useful framework for up-scaling, and for understanding catchment hydro-geomorphological response. They reflect the partial areas in the Luxembourg system, whereas in the dry systems they are reflected in distinctive land units with specific vegetation structure and associated soil heterogeneity, dictating hydrological and degradational response. Quantification of unit response can be done easily by measuring when they are topographically distinguishable and have concentrated flow lines of fluxes. However, when units are connected in a diffuse way, for instance along a boundary between lithological units perpendicularly on a slope, fluxes are much more difficult to measure. This imposes uncertainty on the approach as does the classification of the units. The third key question dealt with linking landscape units. Connectivity of runoff-generating and runoff-absorbing areas is important on all scale levels. Connectivity is dominated by both the rainfall magnitude–frequency–duration characteristics and physically and biologically controlled thresholds that have to be surpassed to connect runoff-generating areas to lower channel areas. Different critical thresholds are applicable at the scale ranges discussed here, ranging from initial soil moisture contents to the presence of water harvesting structures.

Disturbance of the described complex relationships would lead to changes in spatial patterns and to a temporal alteration of system responses. In the case of the Spanish site, drought or overgrazing would ultimately lead to a decrease of vegetation and hence also to deteriorating water capture by vegetation, at the fine and intermediate scale, and consequently runoff generation and degradation frequency would shift to shorter time scales, also for the broadest scale studied. Vegetation pattern and its complex feedback mechanism with the environment would adjust to the new conditions on all scales involved.

For the Luxembourg situation a similarly complex system has evolved under the current situation, but disturbances such as drought or air pollution could lead to changes in the system that would shift the system to other types of behaviour. Dryer conditions would lead to lower biological activities in the soil, decreasing the areal extent of worm activity and partial area domains, also affecting the system response at higher scale levels.

Response units are land units that express a specific hydro-geomorphological response in reaction to rainfall events. For both Spain and Luxembourg response units have been derived that reflect their specific hydro-geomorphological response. The spatial configuration of these units and their connection to the channel system determines the geomorphic and hydrologic response at the catchment scale as they are linked through the channel systems. To elaborate on this is a challenge for the future and is an important topic for current geomorphological research. It may form a bridge between many fine-scale process studies in geomorphology and geomorphological evolution. Results have to prove whether such an approach is an improvement on existing models, although results from hydrological work seem promising.

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