Part D

The Integrity of River and Drainage Basin Systems: Challenges from Environmental Change

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Chapter D.1

Introduction

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The foregoing parts demonstrate that the dynamics and biophysical character of land-atmosphere interactions are intimately connected to the dynamics and biophysical character of the land-based water cycle. The hydrological cycle has been shown to play a central role in our analysis of climate change, the impacts of land use and land cover change, and vegetation dynamics.

There are additional, significant issues that must be considered to more completely define the full dimension of global change with respect to the hydrological cycle. These collectively define a central role for humans in shaping the character of the terrestrial water cycle, not only at local scales, but over regional and even global domains as well.

Humans exert an influence on the water cycle not only through the highly-publicised greenhouse effect but also through the forces of land cover change, land management practices, urbanisation, and the construction and operation of water engineering facilities. These factors all dramatically alter hydrological dynamics and form the key focal points of this section. These issues will be addressed in the context of our primary scientific question:

- Over a decades-to-century time frame, what are the relative impacts on the terrestrial hydrological cycle of (*a*) climatic variation and greenhouse warming, (*b*) land cover change and land management, and (*c*) direct alterations due to water resource management?

The global change research community has arguably focused its attention on climate change to the virtual exclusion of these other factors. Is this the correct focal point for our collective efforts? An objective answer to this central question will colour the progress of our science over the next several years, and we contend it is a necessary starting point as we look toward the future.

It is clear that movement toward a global picture of hydrospheric change – one in which humans figure prominently – will require us to identify appropriate hydrological and socioeconomic principles and to combine these within a common framework. A central goal of this chapter is to summarise recent findings and to explore their use in moving us toward a global synthesis. Our emphasis will be on the biogeophysical aspects of this question, but considering socioeconomic issues as they become relevant.

Building on a long and rich history of small-scale catchment-scale studies dating back more than 100 years, there are exciting new opportunities in the water sciences as we move toward a global view of environmental change and its impact on the water cycle. More traditional hydrological research has uncovered the mechanics of the water cycle describing such processes as evapotranspiration, soil physics, groundwater dynamics and runoff generation. Process-based knowledge has also accumulated on the mobilisation and transport of constituents – including pollution – which are entrained in runoff and river flow. This work provides us with the fundamental principles necessary to detect and interpret the ongoing forces of environmental change. It thus merits an important place in this synthesis chapter and we treat it explicitly in several sections.

Early on, scientific hydrology was turned toward a pragmatic goal of providing sufficient understanding to predict, or at least better manage, catastrophic flooding, drought, erosion and sedimentation, and pollutant source areas and eutrophication. In fact, much of what prompted hydrological analysis was driven by the needs of hydrological engineers. Humans are thus hardly passive when it comes to hydrological events and we have done much to transform the terrestrial hydrosphere into a highly managed biogeochemical cycle (Fig. D.94). This is certainly true at the local scale, and we contend that these changes are now certainly of regional importance, and ultimately pandemic in extent. With population growth and economic development will come increasing pressures to control water supplies in service to humanity. It is thus important to articulate the role of humans and to prepare for the wise management of what are in many parts of the world increasingly scarce water resources. Integrated Water Resources Management (IWRM) will constitute a key emphasis in our discussion.

The community is poised for major progress toward global synthesis. This results from the wide availability, relatively recently, of state-of-the-art datasets and analysis tools including GIS (Geographic Information System) and remote sensing. Analogous to the paired catchment study which has served as the mainstay of hydrological research at the small scale, the conceptual framework of the drainage basin as a functioning hydrological unit permits us to analyse how the spatial organisation of whole river systems conditions continental runoff. This perspective will be critical to our success in progressing upwards in scale from the small catchment to the meso-scale catchment to continents, and ultimately the globe.

We have several specific goals for this section:

- to articulate the role of humans in the terrestrial water cycle by assessing the relative importance of different sources of anthropogenic impact: climate change, land cover and land use change, and water engineering;
- to define a strategy for moving across time and space scales;
- to summarise recent developments in the field over the last 10–20 years and explore how these might be used to move us toward a more synthetic view of a rapidly changing water cycle, ultimately to the global scale; and,
- to identify appropriate water management principles that could be applied in the face of these ongoing environmental changes.

This part is structured according to a scaling framework which permits us to place recent findings into a common context. Detailed sections on local to small-catchment scale processes are followed by a regional analysis. We turn next toward an analysis of emerging trends at the global scale. At each stage we re-visit our central hypothesis, assess its validity, and identify key areas for future progress. Several case studies of specific river basins are completing the part. A concluding section identifies key steps forward.

Chapter D.2

Responses of hydrological processes to environmental change at small catchment scales

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D.2.1 Introduction

Alfred Becker

Chapter D.2 deals with elementary hydrological processes and their modelling at "small catchment scales". We specifically define such catchments as having areas from ~ 10^{-1} km^2 to 10^3 km^2, known as the hydrological micro- to meso-scale. Since the exchange processes between the land surface and the atmosphere (energy, water etc.) at small scales are already treated in Chapt. A.2, the primary focus in this chapter is on so-called "wet hydrology", i.e. soil moisture dynamics, runoff generation and resulting lateral flows of water and associated transports of sediments, chemicals and nutrients. The processes at and below the land surface in soils and aquifers represent an important part of the terrestrial phase of the hydrological cycle and associated biogeochemical cycles.

The dynamics of individual hydrological processes and their spatial differentiation is highly complex, leading to significant uncertainties. For example, the quantification of the different contributions to catchment-level runoff of particular landscapes units, such as vegetated in contrast to non-vegetated (bare or sealed), sparcely vegetated or mixed, built-up areas; or dried out in contrast to moist areas (wetlands, shallow groundwater-areas), is always problematic and often not sufficient in accuracy. The main reason is the enormous spatial and temporal variability of infiltration capacities in dependence on not only soil and vegetation type but also on current soil moisture. Accordingly various simplifications are applied in modelling. These are often acceptable in large-scale modelling. They may cause problems, however, in smaller scale simulation studies and in special investigations of, for instance, the effects of changing land use (see Sect. D.2.6.1).

With this in mind, the primary aim of this Chapt. D.2 is:

- to give an overview of elementary hydrological processes and their spatial and temporal variability;
- to summarise recent improvements in our understanding of these processes;
- to provide specific information on the different component processes of runoff generation and lateral flows along various pathways, especially below the land surface;
- to provide a review of the utility of comprehensive field studies in small catchments;
- to review the movement towards high resolution distributed hydrological modelling using GIS-based parameterisations; and,
- to highlight the rapid development and degree of application of "integrated" ecohydrological models serving to describe the complex links and interaction between energy and water and associated biogeochemical fluxes at micro- and meso-scales.

Most parts of the chapter are descriptive by intention. Equations and modelling details are generally not presented due to space limitations. But relevant references are given to available textbooks, review papers and selected papers.

D.2.2 Terrestrial hydrological processes – overview, definitions, classification

Alfred Becker

D.2.2.1 Elementary hydrological processes

Elementary hydrological processes occur roughly similar in character at all spatial scales. However, from a practical standpoint they are generally best studied at small scales, such as the plot, hillslope or small catchment (headwater) scale. An overview of these processes and their typical chronological sequence in the terrestrial phase of the hydrological cycle is given in Fig. D.1.

The left part of Fig. D.1 is focused essentially on "vertical processes" that basically define the water balance of a landscape unit. These specifically include the major processes of precipitation, evaporation, transpiration and runoff generation. An additional set of more specific component processes includes interception, snow cover dynamics, depression storage at the land surface, including initial wetting, infiltration, soil moisture dynamics

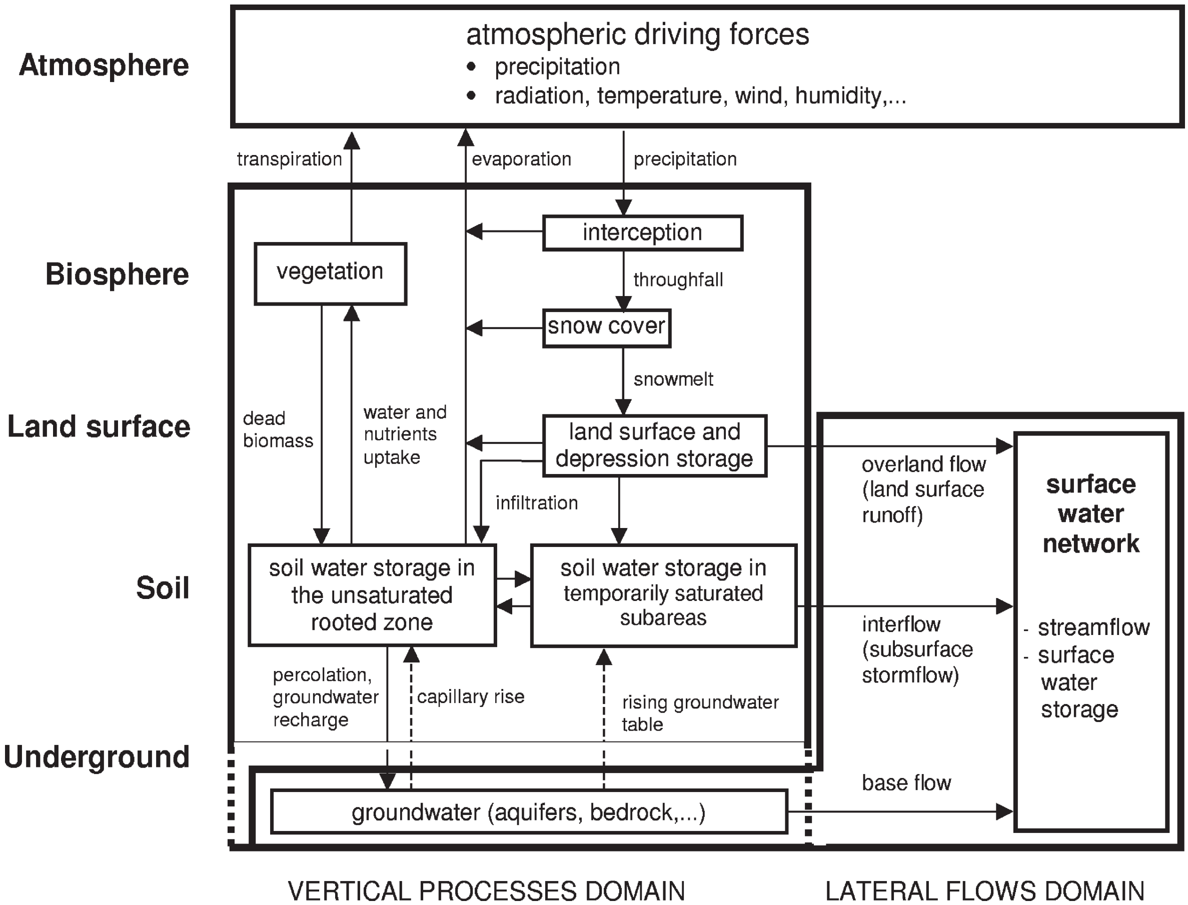

Fig. D.1. Schematic representation of the typical sequence of terrestrial hydrological processes with indication of vertical processes (fluxes in the left block marked by *up- and downward arrows*) and lateral flows (lower right part, *horizontal arrows*), after Becker et al. (2002)

in the unsaturated zone, including percolation and root water uptake, groundwater recharge and capillary rise, overland flow and subsurface storm-flow generation. These are represented diagrammatically in Fig. D.2.

Most of these processes are extensively treated in available text books on hydrology and will not be discussed here (Maidment 1993; Dyck, and Peschke 1995; Dingman 2001). This chapter therefore concentrates on their relevance to global change. A fundamental element of this relevance is the remarkable temporal and spatial variability of these processes. Selected processes are discussed in detail in the chapters below, including treatment of soil moisture dynamics (Sect. D.2.3), overland flow and erosion (Sect. D.2.4), subsurface stormflow (Sect. D.2.5), and ecohydrological processes (Sect. D.2.6).

D.2.2.2 Spatial differentiation of vertical hydrological processes

Elementary vertical hydrological processes can best be studied and understood using elementary areal units (patches) characterised by similarities in a wide array of attributes. These may include similarity in terms of topographical characteristics (elevation, slope class), land use and land cover, soil type and texture, hydrogeology (especially depth of the groundwater table or impervious layers) proximity to river networks and catchment boundaries (water divides).

Elementary areal units belonging to the same category or share similar hydrological behaviours are variably referred to as hydrotopes or Hydrological Response Units (HRU) (Becker et al. 2002; Flügel 1995; Becker and Braun 1999). Natural landscapes and river basins are composed of a variety of hydrotopes, which may clearly differ from each other in essential hydrological characteristics. Accordingly, landscapes show a well known "mosaic structure" or landscape patchiness with variably sized and shaped polygons when mapped. This is illustrated, for example, by the mixed use landscape in Fig. D.3. The mosaic structure represents an appropriate disaggregation scheme for hydrological studies, at least with regard to the vertical processes, to which runoff generation belongs.

Concerning the spatial differentiation of water balance components it should be emphasised that, for ex-

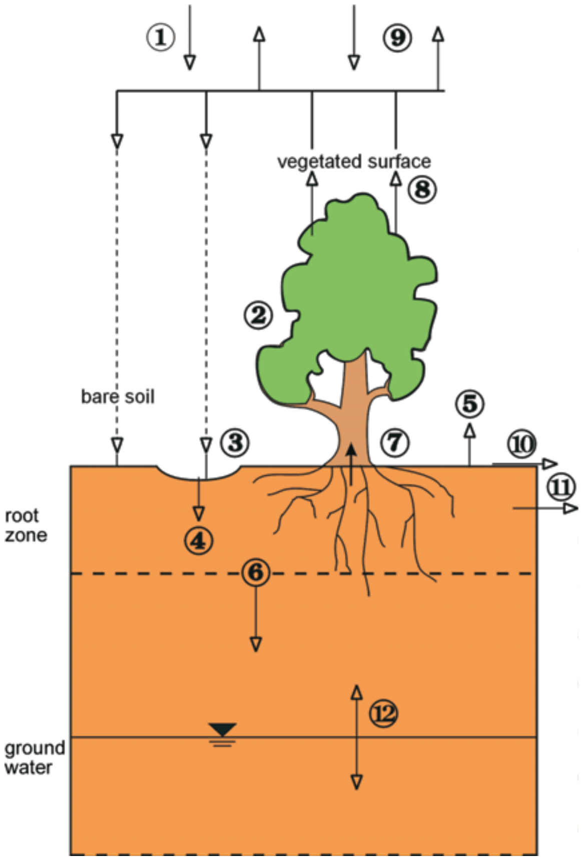

Fig. D.2. Water balance components (vertical processes) in a patch (or hydrotope). *1* Precipitation; *2* canopy interception storage; *3* depression storage at the land surface (including initial wetting); *4* infiltration; *5* bare soil evaporation; *6* soil moisture recharge and percolation; *7* root water uptake; *8* transpiration; *9* total evapotran-spiration; *10* infiltration excess/surface runoff/overland flow generation; *11* subsurface stormflow generation; *12* groundwater recharge and abstraction (by capillary rise or root water uptake); *13* snow cover dynamics (if snow cover exists; not represented in the figure)

ample, wet surfaces such as water surfaces (AW), wetlands and various shallow groundwater areas (AN; cf. Fig. D.3 and Fig. D.6), where evapotranspiration (ET) occurs at or near the potential rate, often exist adjacent to dry areas (e.g. dry vegetated areas, sealed areas, bare soils) where during dry periods ET is equal to or near zero. Such wet/dry contrasts add the further complication of advective processes. Analogously, during rainfall and snowmelt events, overland flow (RO) is normally generated only on limited areas, in particular from sealed or other impervious or less permeable areas (AIMP, e.g. uncovered rocks, clay and gleyic soils or parts of urban areas), as well as from saturated areas, whereas adjacent vegetated areas, especially those with deep groundwater (AG), do not generate any direct runoff (for comparison see Fig. D.6 in Sect. D.2.2.3).

Such, sometimes drastic, differences also exist between different environments as, for instance, high mountains versus lowlands, dry areas versus wetlands, and different climate zones (arid, semi-arid, mediterranean, temperate, humid etc.). This is illustrated by the examples in Table D.1 and Fig. D.4 (taken from L'vovich 1979 and Falkenmark and Chapman 1989, respectively). The significant differences in the partitioning of the different annual amounts of precipitation (upper left downward arrows in the three diagrams in Fig. D.4) into evapotranspiration (upper right upward arrows) with indication of both real (thick arrows) and potential (thin arrows) evapotranspiration and runoff (streamflow) are clearly visible in both the figure and the table. Additional information can be found in Dawdy (1991) and Schulze (1998).

An important feature of hydrotopes is their internal uniformity ("homogeneity" or, more strictly, "quasi-homogeneity") in essential process characteristics and related parameters that can be approximated by average values, each of which is representative for the hydrotope under consideration. A necessary prerequisite for application of such a hydrotope-related parameter estimation is a practical delineation of individual hydrotopes. This has been facilitated in recent years by the increasing availability of GIS-based maps of land surface attributes such as topography (DEMs, Digital Elevation Models), land use and land cover, soil type and texture, hydrogeology, especially depth of the groundwater table or impervious layers. By overlaying (or geo-referencing) maps of these or other attributes as listed in the previous chapter the land surface can be disaggregated into hydrotopes (e.g. Becker et al. 2002; Lahmer et al. 1999) as is illustrated in the left part of Fig. D.5. How these characteristics and parameter values can be estimated from GIS-based information is further described briefly in Sect. D.2.6.3.

Among the attributes that specifically determine land surface heterogeneity in terms of patchiness are land use and land cover. They, in addition to water use and management practices, are often subject to changes which include two broad categories:

1. direct changes in land cover due to urbanisation, industrialisation and mining, deforestation or afforestation;
2. agricultural management practices, including crop rotation, application of fertilisers and pesticides, tillage, soil conservation measures, ecological farming, animal husbandry and grazing, irrigation and drainage.

In the case of irrigation, which is often combined with surface water diversions and/or groundwater abstractions from elsewhere, water-saturated and wet areas may occur even in climatically dry periods. On the other hand, artificial drainage by ditch systems and/or pipes in the soil always generate drier and at least temporarily "dried out" areas.

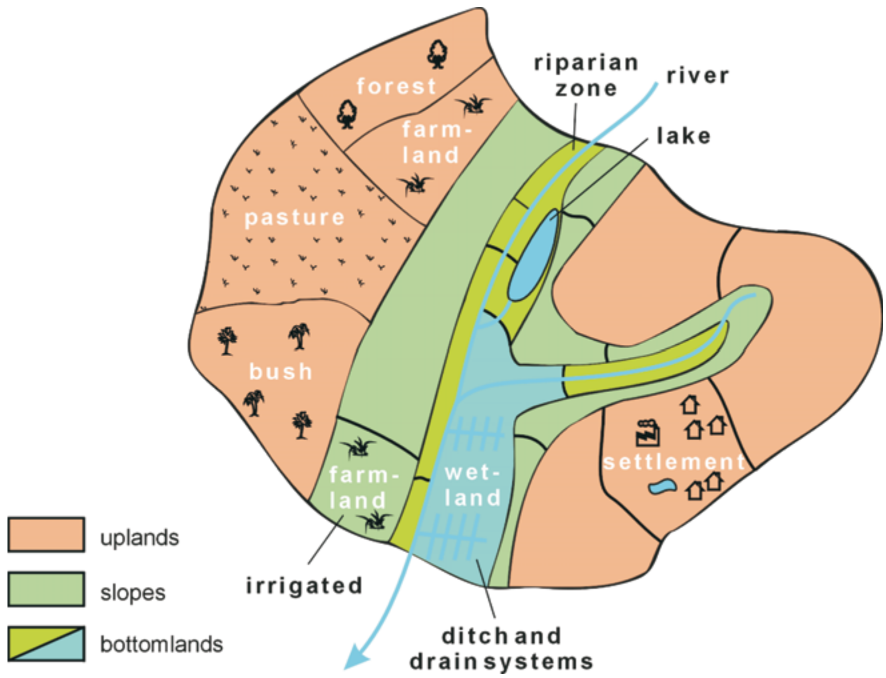

Fig. D.3. Example of the disaggregation of a landscape (or a sub-catchment) into hydrotopes

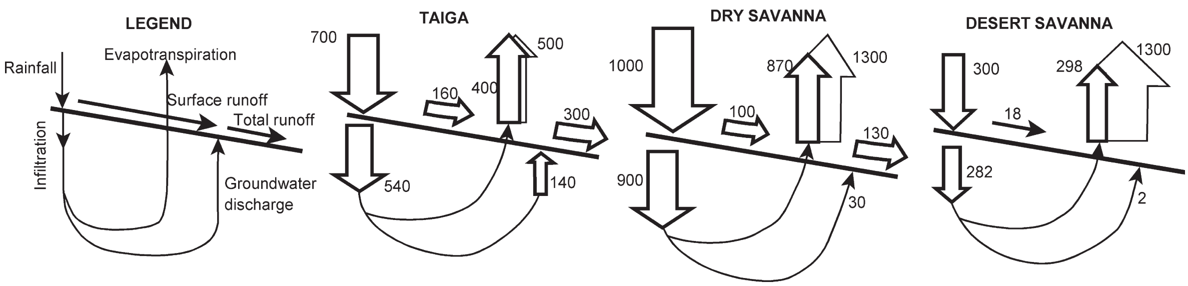

Fig. D.4. Land surface water budgets in contrasting humid and arid climatic regimes (see text for explanation) (after Falkenmark and Chapman 1989)

These changes generally propagate from the patch, hydrotope, or hillslope scale, as for example, the non-irrigated and irrigated farmlands in Fig. D.3. The distinctive hydrological behaviour of contrasting land and land-management techniques thus makes it imperative to disaggregate (discretise) the land surface into hydrotopes or similar small areal units and to apply high resolution distributed models as discussed in Sect. D.2.6.

D.2.2.3 Runoff generation and runoff components

Runoff is generated at a hydrotope whenever "excess water" occurs as the difference between interval rainfall and/or snowmelt minus evapotranspiration and soil water recharge (1 and 13, 5, 8 and 9, as well as 6 in Fig. D.2; right lower block in Fig. D.1). Lateral flows are then generated through one or more of the following flow pathways (Buttle 1998; Becker et al. 1999):

- land surface runoff (overland flow RO = rainfall or snowmelt intensity minus infiltration capacity; 1, 13, 4 and 10 in Fig. D.2);
- interflow (subsurface stormflow RI; 11 in Fig. D.2); and,
- baseflow (through groundwater recharge (12 in Fig. D.2), which becomes groundwater storage and thus generates increases in baseflow RG).

These flows are first routed downslope through the runoff generating sub-catchments along different surface and subsurface pathways to the nearest channel, then downstream along the river network and in the end constitute, in aggregate, the total basin outflow or "basin runoff" (discharge) in the final channel cross-section of the river basin under consideration (Fig. D.1, lower right block; Becker et al. 2002). This process includes a conceptual change from the primary disaggregation scheme of hydrotopes (or rasters of a regular grid) useful for the analysis of vertical processes (left in

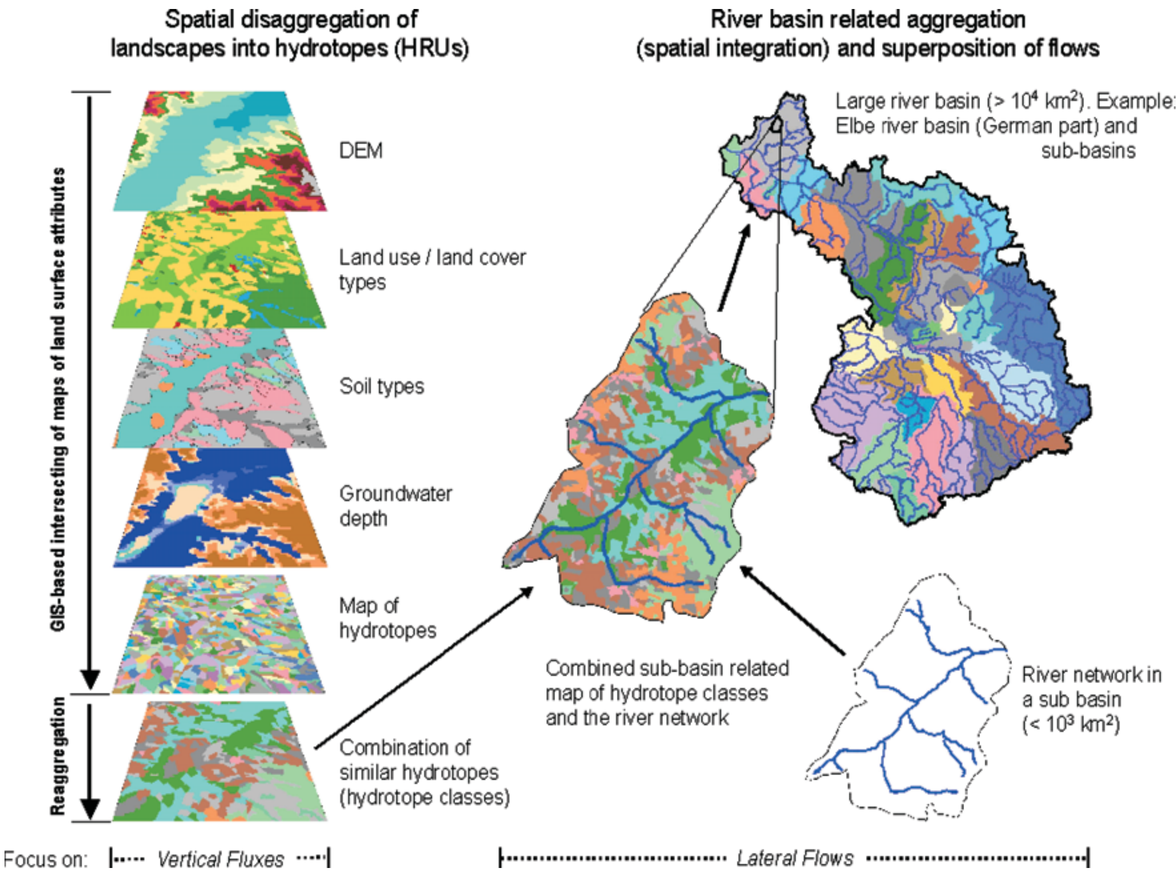

Fig. D.5. GIS-based disaggregation, re-aggregation and integration in river basin-related hydrological and ecological studies

Fig. D.5), to one involving the integration of lateral flows from various contributing areas in the river network, the geography of which is defined by rivers, river sections, lakes, aquifers and wetlands. This is illustrated schematically on the right of Fig. D.5 in terms of re-aggregation, spatial integration and superposition.

It should be emphasised that among all hydrological processes runoff generation in catchments is most variable in space and with time, depending on the combinations of three main controlling factors: (*1*) climate, (*2*) soil and geology and (*3*) vegetation. The combination of these three factors determines the amounts and thus the relative streamflow contributions of surface and subsurface runoff which may differ considerably (Buttle 1998). A brief summary of these runoff components is given in Table D.1, with reference to Fig. D.6. More information about subsurface stormflow processes and the displacement of "old" pre-event water by "new" event water is provided in Sect. D.2.5.2.

In arid and semi-arid environments, infiltration excess overland flow (also called Horton overland flow from Horton's pioneering work in 1933) is the dominating runoff component (for comparison see RO_{Hor} in Fig. D.6). This is because here high intensity rain storms represent the most important runoff generating events with rainfall intensities generally exceeding the soil infiltration capacity. A special type of this direct surface runoff generation is from impervious areas, such as bare rock (RO_{imp} in Fig. D.6) and sealed areas (built up, paved, etc.).

In more humid climates, RO_{Hor} is less prevalent and saturation excess overland flow dominates (RO_{sat} in Fig. D.6). It is generated over surface saturation areas, which predominantly occur in near-stream zones and on shallow soils due to rising groundwater tables. This is illustrated in Fig. D.6 by the dashed line in the valley floor aquifer which temporarily intersects the soil surface and thus produces dynamically growing saturated areas in the riparian zone (AN) during heavy or long-lasting rainfall and snowmelt. These areas generate not only saturation excess overland flow but also an increase in subsurface stormflow (RN) into the channel. Dunne and Black (1970) showed how this type of direct rapid surface runoff (RO_{sat}) into the channel is produced on the time-scale of events, and McDonnell et al. (1999) argued that these saturated areas seem to scale directly with catchment area since topographic gradient decreases as basin scale increases. Consequently, satura-

Table D.1. Storm runoff components and essential characteristics of landscape sub-units (see Fig. D.6) (Becker et al. 1999)

Overland flow RO	
RO_{HOR}	Infiltration excess overland flow from soils when rainfall or snowmelt intensity exceeds infiltration capacity ("Horton" flow, high spatial variability). Preferred conditions: bare soil and cropland, esp. in arid and semi-arid regions and high intensity rainstorm events.
RO_{imp}	RO from impervious areas such as bare rocks, sealed areas (paved, built-up, etc.) in all climate zones (nearly constant areal extent). After an initial loss of very few millimetres, RO_{imp} amounts to 100% of rainfall or snowmelt in each event.
RO_{sat}	Saturation excess overland flow ("Dunne" flow) from dynamically varying saturated areas due to rising groundwater tables intersecting the land surface, with RO_{sat} – amounting also nearly equal to rainfall or snowmelt. Preferred conditions: near-stream riparian areas, flat valleys with gentle concave slopes, and shallow groundwater areas, mainly in humid and semi-humid regions, even with low intensity long lasting rain or snowmelt.
Subsurface stormflow (interflow) occuring as short-term exfiltration of subsurface water to the land surface in depressions or at lower slopes, or directly into channels:	
RI_1	Subsurface stormflow through preferential flow pathways such as macropores, pipes, highly permeable layers, e.g. at the soil bedrock interface, often induced by transmissivity feedback.
RI_2	Piston flow (subsurface pressure wave transmission especially in mountainous terrain).
RI_3	Groundwater ridging (subsurface pressure wave transmission in lowland and riparian zone aquifers).
RN	Direct subsurface flow (quick return base flow) into the channel system from the riparian zone.
Typical landscape sub-units (hydrotopes)	
AG	Areas with the groundwater table deep below the surface so that plant roots cannot reach it.
AN	Areas with shallow groundwater table, e.g. wetlands, near-stream riparian areas.
AW	Open water surfaces.
ASL	Slope areas with increased potential for infiltration excess overland flow generation.
AIMP	Impervious or less permeable areas, e.g. uncovered rocks, clay and gleyic soils, sealed areas.

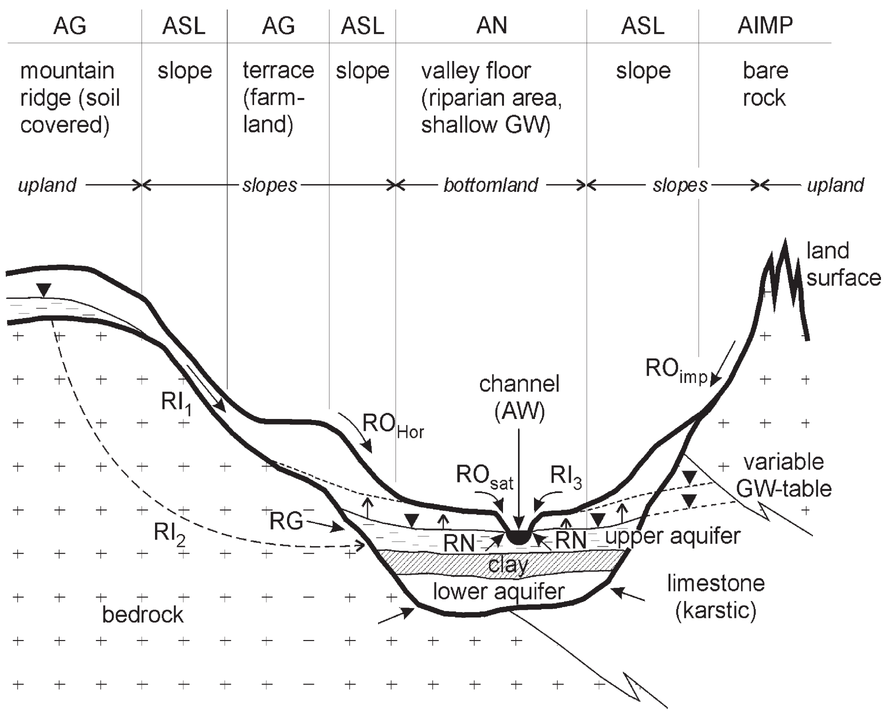

Fig. D.6. Representation of a valley cross-section indicating (*i*) typical landscape sub-units similar in their runoff generation and evap-oration behaviour and (*ii*) pre-ferred runoff generation areas of the different flow components (abbreviations see Table D.1)

tion excess overland flow (RO_{sat}) is a main runoff producing mechanism across scales but plays an increasing role over larger spatial domains. The variable source area concept of Hewlett and Hibbert (1967) can be considered as the best formulation of this kind of catchment-scale runoff generation process.

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