Chapter 1

Introduction

> *"Our land, compared with what it was, is like a skeleton of a body wasted by disease."*
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> **Plato** *(4th century B.C.)*

> *"O earth, what changes hast thou seen!"*
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> ***Alfred Tennyson*** *(1809–1892)*

> *"Russian forests crash down under the axe, billions of trees are dying, the habitations of animals and birds are layed waste, rivers grow shallow and dry up, marvellous landscapes are disappearing forever.... Man is endowed with creativity in order to multiply that which has been given him; he has not created, but destroyed. There are fewer and fewer forests, rivers are drying up, wildlife has become extinct, the climate is ruined, and the earth is becoming ever poorer and uglier."*
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> ***Anton Pavlovich Chekhov*** *(1860–1904)*

1.1 Description of the Problem

The adaptations of the landscape by the action of man either to create better living conditions or to cope with the demand of resources required to fulfil man's subsistence have taken place since the dawn of mankind. The impacts associated with them, though insignificant at the beginning, have transformed the face of earth for good or bad as no other living species has ever done. Since the Industrial Revolution, the availability of new machinery powered by more efficient energy sources has multiplied the human power by thousands, making, as a result, this transformation process even faster.

Many writers and philosophers in the past have clearly documented these misdoings; unfortunately such alterations were often associated with progress and prosperity. Consequently, a coordinated action against them was rarely implemented. Nowadays, many regions on earth remain deeply transformed, with all their beauty and wealth lost forever. In those cases, the natural system was forced to a new state with higher entropy (i.e. disorder) and where the point of no-return has been largely surpassed. Fortunately, many sectors in the political and scientific spheres have become aware of these issues, but still much is to be done in this respect.

The present study deals with the hydrological consequences of land use, land cover, and climatic changes and their integration in a holistic land use planning framework that pursues sustainability[1].

This research is based on the following facts:

1. The land use and land cover of a region is changing over time due to either anthropogenic reasons or natural phenomena (i.e. climate). Well known, and devastating examples can be found in both the Amazon and the Aral Sea basins (McNeill et al. 1994),
2. The transition rates from one land use type to another depend on several place-specific driving forces that can be categorised into four major classes: political, economic, demographic, and environmental (Turner and Mayer 1994),
3. A change in land cover will originate sooner or later a change in the water cycle based on the actual knowledge of the physio-chemical laws that govern it. This change will influence the proportion of surface runoff, infiltration, interception, and transpiration from soil moisture (Savenije 1995),
4. The magnitude of the impacts may vary according to the geographic location and the scale at which the analysis is carried out (Calder 1993), and
5. The acknowledged urgent need for more practical research that helps planners to understand the complexity of the water system (BBR 2000).

In this study, the term *land use* is used in the sense of human employment of the land, whereas the term *land cover* is used to denote the physical state of the land (Turner and Meyer 1994). The former is related with the anthropogenic system whereas the latter is related with the natural system. These two concepts are connected in principle, but it is not necessarily true that one land use category has to correspond to a unique land cover class. The level of agreement depends upon how such categories have been defined.

Land use change may “involve either a *shift* to other land use type or an *intensification* of an existing one”; while *land cover change* implies a *conversion* and/or a *modification* of the land surface. C*onversion* is understood to mean “the change from one land cover class to another” (e.g. from forest to grassland, or from grassland to cropland), while *modification* is “the change of condition within a land cover class” (e.g. thinning of a forest or cropland intensification) (Turner and Mayer 1994, Skole 1994).

Firstly, an attempt to systematize the complex interactions between anthropogenic activities and the natural system is to be presented, whose schematic representation is depicted in Figure 1.1. As a direct consequence of anthropogenic activities, large amounts of toxic substances, either in solid, liquid or gaseous phase, are yearly returned to Nature as a result of the chemical and physical processes associated with such activities. These outflows are called emissions, and in general they disrupt the natural system (e.g. climate or the ecosystems’ equilibrium) in various intensities. For instance, there

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[1] **Sustainability**: Term coined by the famous Brundtland Commission (UN) in 1987. This term defines the utmost principle of a development plan that enforces to “meet present needs without compromising the ability of future generations to meet their needs" (WCED, 1987).

is strong evidence, and it is widely accepted within the scientific community, that the increasing concentrations of greenhouse gases (e.g. CO_2, NO_x, CH_4, H_2O, and chlorofluorocarbons) are responsible for a steadily increasing global average surface temperature at the rate of about (0.3°C/decade) (Houghton et al. 1990, 1992, 2001, Wigley and Raper 1992, Rowland 2000), a phenomenon commonly known as global warming. Although this problem, along with many others such as non-point source pollution, water bodies pollution by untreated sewage, groundwater contamination due to over fertilizing, are serious threats to mankind at the moment, they will not be thoroughly considered in this study.

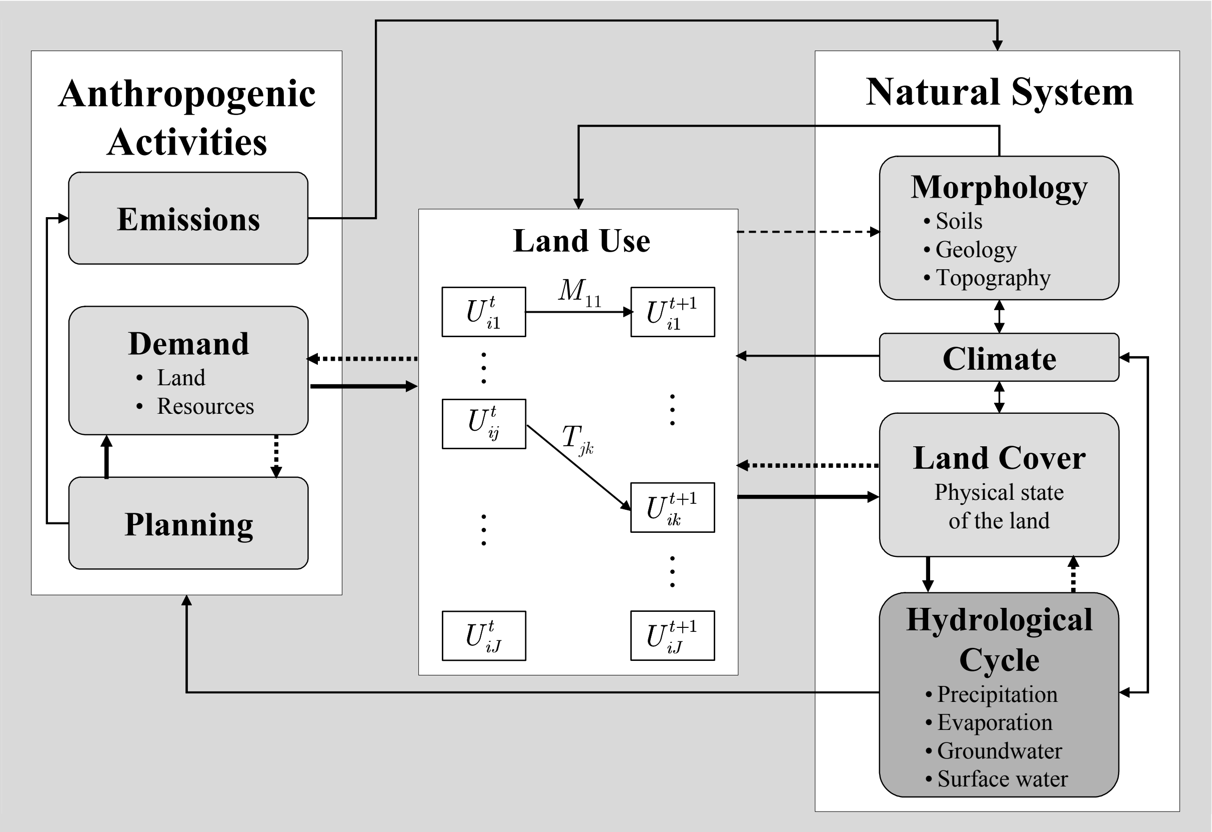

Figure 1.1 Interactions between anthropogenic activities and the natural system.

Land is one of the essential production factors for almost all human activities, such as: agriculture, mining, forestry, manufacturing, energy generation, water catchment and storage, transportation, settlement and recreation. However, it is a finite resource whose use is constrained by either Nature (i.e. vegetation -land cover-, soils, topography -slopes-, and climate) or human regulations (e.g. planning laws, property rights), or both (Turner et al. 1993).

Since the onset of the Industrial Revolution human actions rather than natural forces are the main source of change in the states and flows of the biosphere (Turner and Meyer 1994). As said before, most human activities demand land to be accomplished satisfactorily, hence, they constitute the proximate driving forces that maintain ($U_{ij}^{t} \rightarrow U_{ij}^{t+1}$) or transform ($U_{ij}^{t} \rightarrow U_{ik}^{t+1}$) a land use ($U$) category j to a category k in a given spatial unit i from time point t to time point $t+1$ (see Figure 1.1). According to Turner and Meyer (1991) and Stern et al. (1992) possible human driving forces can be grouped into six categories, namely: demographic factors, technology, level of affluence, political structure, economic factors, and attitudes and values. These driving forces also change over time due to many reasons (e.g. economic cycles or population attitudes), hence, the transition rates from one type of land use to another may be influenced as well (see Figure 1.2).

In general, it is possible to state that the resulting land use in a given spatial unit i is the outcome of competing potential uses - seldom complementary to each other - under certain constraints imposed by land use planning laws, administrative systems, political institutions, property rights laws, market and culture (Rayner et al. 1994).

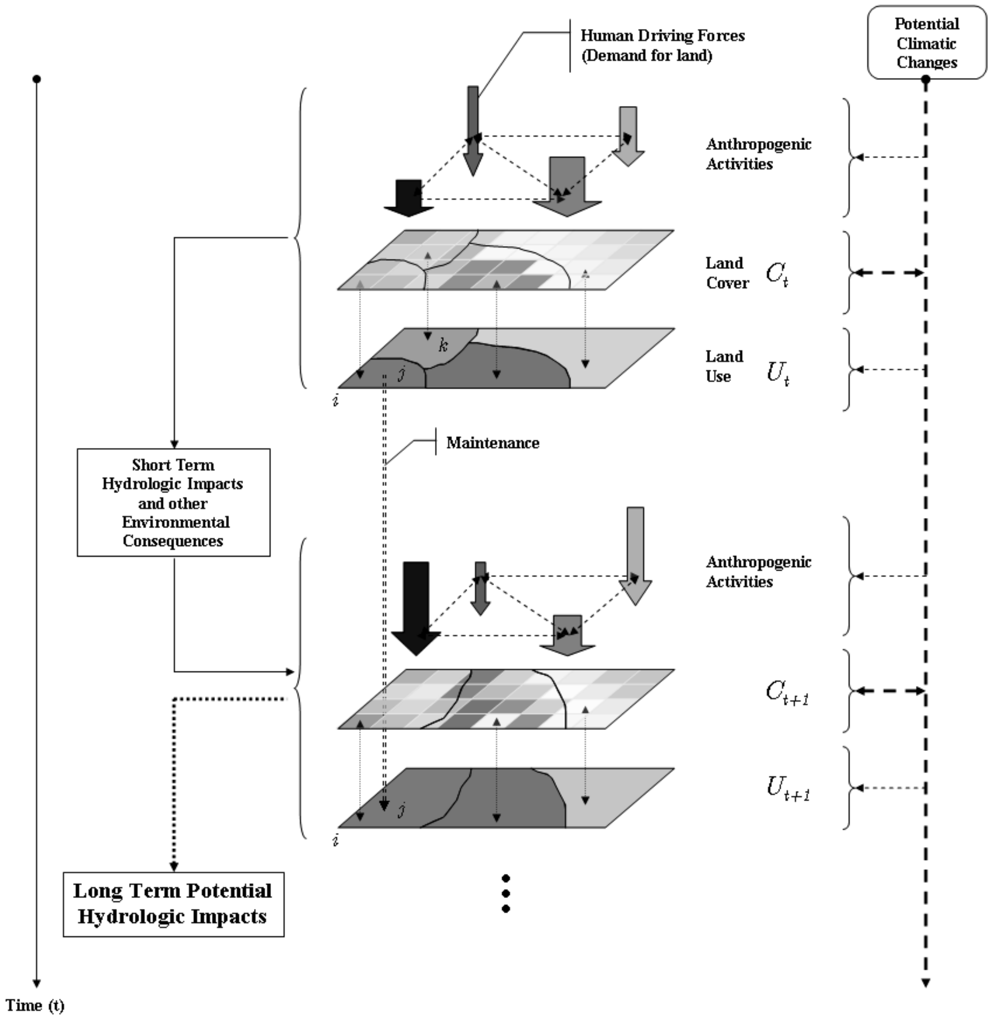

Figure 1.2 Mechanism of land use/cover changes induced by underlying human driving forces along the time axis.

Moreover, if the land use k in a spatial unit i and time t changes due to anthropogenic reasons to land use j in time $t+1$, then this change of land use will likely cause sooner or later a land cover change in the affected area of the spatial unit i, and conversely, a land cover category in this spatial unit may change to a different one even if the land use j remains unaltered during the same period as it is depicted in Figure 1.2.

The interactions between the atmosphere and the lithosphere involve exchanges of mass, momentum, and energy that are closely dependent upon the nature and structure of the earth's surface (Avisar and Verstraete 1990). At the global scale, atmospheric circulation is also affected by land cover changes as has been shown by recent applications of the state-of-the-art global circulation models (Henderson-Sellers 1990, 1992, 1993 and Foley et al. 1998). A feedback effect of such distorted circulation patterns is the alteration of the global precipitation distribution, which, in turn, may alter the actual vegetation coverage and the existent land uses (Salati et al. 1979).

As shown in Figure 1.2 land cover changes may have a large scope of influence in space (at micro, meso, or at macroscale) and time (short term or long term). Changes of land cover often occur at microscale (e.g. at parcel level) with no apparent impacts in the climatic and/or the hydrologic regime of the basin (i.e. mesoscale) in the short term (Sartor 1998). Conversely, their *long-term-cumulative* hydrologic consequences will be only perceived at mesoscale (Reimold 1998). Consequently, land cover changes will occur in the future because it seems that nothing has been affected. This characteristic of the problem is what makes it difficult to be assessed and to be perceived by the population. It simply takes time to undermine the fragile water balance of a mesoscale basin. Those infinitesimal but cumulative impacts will be aggregated by the stream network (Cada and Hunsaker 1990) until someone realizes that they have been caused by anthropogenic activities, and eventually takes serious actions to stop them. Even if the rate of a land cover change is reduced to zero and some measures are taken to recover the original land cover, there is no guarantee that the original state will be reached again. By the time the measures are taken, there may be a number of irreparable damages on the basin, for instance a river bed will be deepened by erosion, hillslopes will have lost large quantities of valuable fertile soil, and the micro climatic regime of the basin may have changed, among others.

It is known that "*streams and rivers serve as integrators of terrestrial landscape characteristics and as recipients of pollutants from both the atmosphere and the land*", hence, rivers are good indicators of cumulative impacts (Cada and Hunsaker, 1990). Cumulative impacts, according to Dickert and Tuttle (1985) are "*those that result from the interactions of many incremental activities, each of which may have an insignificant effect when viewed alone, but which become cumulatively significant when seen in the aggregate. Cumulative effects may interact in an additive or a synergistic* (sic!) *way, may occur onsite or offsite, may have short-term or long-term effects, and may appear soon after disturbance or be delayed.*" Land cover change is a good example of cumulative impacts.

Finally, the long-term impacts of the hydrological cycle will eventually have feedback effects on the demand for land and the land use. The correctives of the misdoings can only be addressed by applied research and integrated planning.

1.2 The Complexity of Modelling the Water System at the Mesoscale Level

In the hydrologic cycle, water passes through the hydrosphere, the lithosphere and the atmosphere driven by two external energy sources: the thermal radiation emitted by the sun and the gravity force. The former is responsible for evaporation and condensation, and the latter for precipitation, infiltration, and runoff. It is a process with no beginning or end, and it has been present since the beginning of the earth's atmosphere and will be present until this ceases to exist. This does not mean that this process has been stationary; the weather and climate of the earth have fluctuated dramatically over time, mainly due to very long periods of cyclical deviations of the Earth's orbit that are collectively termed the *Milankovitsch cycle* or due to extraordinary natural events. However, the basic functioning of the system has remained the same.

The hydrologic cycle within a drainage basin has been defined as a sequential, dynamic system in which water is the major throughput (Chow, 1964). Due to the great complexity of the relationships among the components of the system it is very sensitive to alterations of its actual state. This means that unpredictable consequences may be triggered by small changes that occurred inside or outside the basin. For this reason, the water cycle is also considered as a stochastic process.

Why is this system so complex? The intricacy of the water cycle is not only a consequence of the intertwined linkages of the sub-processes involved such as physical, biological, and geological ones, but also due to the large range of time and spatial scales at which the feedback mechanisms operate (Savenije 1995). On top of that, another continuous cause for disruption of the system has appeared - the anthropogenic activities - which, as was explained before, will convert and/or modify the land cover.

Since the present study deals with mesoscale catchments, the global scale atmospheric processes governing the circulation of large amounts of moist air from the sea to the continents will not be considered. Therefore, it is assumed that the influx of moist air that will eventually condensate and precipitate in a mesoscale basin are controlled by the macroclimate.

The functioning of the system within the basin can be summarized as follows. The moist air originated outside the boundaries of a given basin, plus that originated due to evapotranspiration within such basin, will precipitate to the basin's surface in the form of ice, snow or rain. Part of this precipitation will evaporate before even reaching the surface due to the activity of the sun. Effects of land cover changes will operate at this stage since land cover determines surface roughness, albedo[2], and latent and sensible heat flux, variables which, in turn, are related to wind speed, air temperature at the surface, and hence, with the evaporation process (Savenije 1995). When the rest, called net precipitation, reaches the earth's surface, it may face four alternatives in general. Either it hits bare soil, a surface covered by vegetation, impervious materials or a water body.

The paths for a drop of water which reaches a part of the earth's surface covered by vegetation are twofold; either it is intercepted by the canopy, or it passes trough the gaps in the canopy without being intercepted and finally reaches the earth's surface. If a drop of water is in contact with the foliage it can be either evaporated or rundown the tree trunk and become stemflow, and then eventually reach the earth's surface.

Once a drop of water reaches the earth's surface composed of either soil or a semi-permeable material the long process of infiltration and percolation to the underground will begin only if the upper soil

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[2] A measure of the reflecting power of a nonluminous body, such as the surface of a planet, expressed as the ratio of energy reflected in all directions to total incident energy (Chambers Dictionary of Science and Technology).

horizon has not reached the soil's water holding capacity, in other words, if it has not reached its saturation level. If the opposite takes place the remaining net precipitation will be converted into surface runoff.

The fraction of water that reaches the upper soil horizon can be evaporated by the vapour pressure gradient between the earth's surface and atmosphere, and the wind profile, or it can be evaporated by the action of the plant physiology (evapotranspiration). Vegetation plays also in this stage of the water cycle a very important role because it is a key factor for determining the soil moisture in the root zone, which, in turn, governs the subsurface flow or interflow. Due to this reason bare soil is less permeable than vegetated soil (Savenije 1995).

Within the soil matrix and the underlying rock, very slow and complex processes will occur, namely: macro- and micropore infiltration and then deep percolation. Macropore infiltration is mainly governed by gravity, whereas micropore infiltration and deep percolation are governed by capillary forces (Bronstert 1995), which will lead water to percolate the rock stratum and hence to form groundwater reservoirs, or to the formation of subsurface flows which are responsible for maintaining the baseflow of streams and rivers.

If a drop of water reaches the earth's surface covered by impervious materials, mostly all net precipitation will be rapidly transformed into surface runoff, the rest will be evaporated. In such a case, a significant increment of the flooding hazard may be expected downstream from such locations. The effects of this land cover are twofold: the concentration time and the infiltration potential will be drastically decreased. As a result, groundwater recharge will be significantly diminished, too.

Eventually, the sum of all contributions of surface runoff and subsurface flows will become streamflow of a drainage system, and then, either be transported to the sea and then returned to the atmosphere due to evaporation, or be evaporated along the way to the sea. The same fate will befall the share of precipitation that has reached a water body. In this way the water cycle will continue forever.

Based on this short description of the water cycle, the following question can be stated: How can this complex system be analysed? In principle, there may be two different approaches, namely:

1. The first alternative consists in calibrating and validating a known rainfall-runoff model with past observations. Later, such a model can be used, for instance, to assess the impacts of land cover change based on future land use scenarios. The application of PRMS[3] in a municipal watershed in Ecuador by Samaniego (1997) is an example of this method. This technique, however, has many shortcomings that will be conveyed next.

   The state-of-the-art in hydrological modelling, either the conceptual type models such as HBV (Bergström and Forsman 1973), PRMS (Leavesley et al. 1983) or the physically-based and distributed-parameter models, for instance TOPMODEL (Beben, 1986), SHE (Abbott et al. 1986),

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[3] PRMS "*is a modular-design, deterministic, distributed-parameter modelling system developed to evaluate the impacts of various combinations of precipitation, climate, and land use on streamflow, sediment yields, and general basin hydrology*" (USGS, 2002).

TOPOG (O'Loughlin et al. 1989), HILLFLOW-3D (Bronstert 1995), require temporal and spatially distributed data with high resolution in both domains. The main difference between these two modelling approaches lies in the fact that the conceptual models consider analogies to the perceived system's behaviour whereas the physically-based and distributed-parameter ones are based on the differential equations describing the phenomena.

Nevertheless, the existing generation of distributed models are really *lumped-conceptual models,* according to Beven (1989), because their governing equations are based on small scale physics, which then are applied at the mesoscale. Regarding data availability, only in ideal cases, after costly surveys, model parameters have been measured (Vertessy et al. 1993); generally, most of the existing models just determine these parameters during the calibration phase of the model because of the uncertainty and unknown heterogeneity associated with their spatial distribution (Abbott 1986, Refsgaard 1997).

It can be said in general that these models work satisfactorily for small and well-documented catchments, but would provide poor results at mesoscale basins due to the following reasons:

- Lack of data describing the spatial distribution of all variables employed in a model with a reasonable small uncertainty (Vertessy et al. 1993);
- The unknown spatial heterogeneity of parameter values at mesoscale (Abbott et al. 1986, Refsgaard 1997, Nandakumar and Mein 1997);
- The high risk of overparameterization during the calibration phase of the model (Bergström 1995); and,
- The inherent complexity of the system as to temporal scales and the stochasticity of the processes concerned (Savenije 1995).

Considering these limitations, it would be very difficult, if not impossible, to use existing rainfall-runoff models to assess hydrological impacts of land cover change (Nandakumar and Mein 1997).

2. The second alternative consists of using past data to derive empiric cause-effect relationships and linkages among observed variables. In this case, statistical methods or fuzzy rule-based modelling can be applied. This study will deal with this approach only.

1.3 Empirical Quantifications

There are, at the moment, many empiric relationships that have been used by soils scientists, engineers, and planners to assess the effects of land cover changes; unfortunately, their applicability is constrained by several facts:

1. They can be applied only for micro-catchments ($\ll 5\,\mathrm{km}^2$);
2. They are meant only to assess peak flows or total soil loss, and
3. Normally, their use would involve a high uncertainty when applied to mesoscale catchments.

Examples of such methods are, for instance, the SCS curve number method (USDA-SCS, 1985), the rational method, which is often employed in urban hydrology [Kuichling (1889) in Chow (1964)], or the USLE (Wischmeier and Smith, 1978) among others. Therefore, such methods are not suitable for assessing the effects of land cover change at mesoscale basins.

1.4 Research Question and Objectives

Hitherto, there are still many important open questions regarding the issues discussed above. One of those questions that has strong implications to the planning system can be stated as follows:

> *How will a land use/cover change under certain geographic conditions affect a specific characteristic of the hydrological cycle and in what intensity?*

For example, if the settlement area at a certain location is expected to grow by one percent per year, how much will the flooding and/or drought hazards of those areas located downstream change in the future? If the answers to similar questions were known in advance, a planning authority might take adequate measures and employ land use restrictions to mitigate the future impacts of the forecasted land use changes.

In order to provide convincing answers to the question stated above, the following objectives shall be considered:

1. To develop a general methodology aimed at differentiating between the impacts produced by an exogenous macroclimatic change and those originating from anthropogenic activities,
2. To select and validate numerical models that quantify such impacts on several characteristics of the hydrological cycle at mesoscale level, and
3. To test these numerical models within the context of an integrated approach aimed at the assessment of the impacts of climatic and land use/cover changes on the hydrological cycle at mesoscale level.