Land Cover and Land Use Changes and their Impacts on Hydroclimate, Ecosystems and Society

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T. Oki, EM. Blyth, E.H. Berbery

1. Introduction

Land surface provides lower boundary condition to the atmosphere interactively: it receives precipitation, downward short wave and long wave radiations, and returns fluxes, such as upward short wave and long wave radiation, momentum, sensible heat, latent heat, and carbon dioxide, to the atmosphere under given conditions of surface pressure, temperature, humidity and wind. Excess water from land discharges into the ocean, changes the salinity and temperature in the ocean, and possibly influences the formation of sea ice and thermohaline circulation, at least on local scales.

The energy, water, and carbon balances determined by land surface processes are characterized by the land surface conditions such as topography, land cover, soil properties, and geological formation. Land cover can be characterized by the vegetation over it, such as forests, shrubs, grass, or bare soil, or open water. Since vegetation types are dominantly determined by climatological conditions, land surface interacts with atmosphere in longer temporal scales, such as decadal to centennial. Even though storage volumes are not as much as in the ocean, land stores heat, water, and carbon, and land surface is one of the key components in the climate system on the Earth.

Further, any kind of climatic variations and changes will have dominant impacts on human societies and activities over land, therefore it is relevant for climate system science to monitor and predict the climatic variations over land. At the same time, human activities are modulating the climate system even on global scale through the changes of land use and land cover, and through the interventions on water cycle components, for example.

Research over land in climate systems has been mainly studied under GEWEX in WCRP. GHP has been promoting and synthesizing the field campaigns measuring, estimating, and seeking to close the regional water balances in various climatic zones on continents. GLASS has been promoting and organizing numerical studies assessing the coupling between land and atmosphere, and it also supported creating comprehensive datasets of the climatic properties over land. The products from GSWP2 (Dirmeyer et al., 2006) contributed to illustrate the global water cycles as **Figure 1**. In this position paper, land in the climate system is illustrated in section 2. The interactions with ecosystems are briefly summarized in section 3, and societal needs for researches on water over land are introduced in section 4. Section 5 identifies current gaps and future challenges for the research on land surface processes in climate system.

(more inputs necessary)

2. LCLUC and hydroclimate

Long term changes to the land surface state occur when there is a significant change in the land cover, such a forest to crops. Many researchers have worked to quantify the impact that has on long term outputs such as river flow. In the WATCH project, Rost et al (2008) studied the impact of the change in evaporation due to land cover change and showed that the change in land use has reduced the evaporation by 3% and increased river flow by 5%.

However, this study did not include the feedbacks from the land to the weather. For that a 3-dimensional climate model is needed. A group of scientists collated their modelled Land-Use change experiments in an attempt to understand the overall climate-impact of the wide-scale deforestation that has occurred over the last century (see Pitman et al, 2009). The idea was to quantify if the current regional weather has been influenced by the anthropogenically altered landscape. In general, the models were not consistent in their results of the changes to the other variables that were studied: namely evaporation and rainfall. The changes were small and some of the models went up and some down.

However, the models were in some agreement about the changes in the air temperature: by removing the forests and replacing them with shorter vegetation of crops and pasture has cooled the summer air by about 1 degree in the last 100 years in the two key regions of largest land use change: the middle of the USA and the West Russia. This result is supported by an observational study of fluxnet data by Teuling et al (2010) which shows how forests and grass affect the overlying PBL characteristics. Teuling et al (2010) also showed how this changed drought conditions. **Figure XX** summarises the findings of Teuling et al (2010) and of Pitman et al (2009).

The changed in the PBL characteristics has an impact on the evaporative demand through changes in cloud cover (Ek and Holtslag, 2004) and the air temperature and humidity (Schubert et al, 2004). These changes are important for water resources. For instance, Cai et al (2009) have demonstrated the role that the land-atmosphere feedbacks have had on the recent Australian drought.

This relationship between the land and the atmosphere is part of the natural interplay of the land and the atmosphere that happens all around us: if there is a reduction in the rainfall, then the land dries out and this warms and dries the atmosphere which leads to further drying out of the land. This interplay means that a percentage drop in rainfall does not lead to the same percentage drop in runoff: it is always greater.

Several researchers have managed to capture this relationship between climatological precipitation (P), evaporation (E) and potential evaporation (PE) and, by implication, runoff (R), but possibly the most famous is Budyko (1974). He laid down the following equation to express it:

$$E = \frac{P\,PE}{(P^n + PE^n)^{1/n}} \qquad (1)$$

The shape of this curve for various values of 'n' is as follows (value of 'n' is indicated in the legend by Series number):

The regional long-timescale runoff (i.e. assuming minimal storage) is the difference between precipitation and evaporation loss:

$$R = P - E \quad (2)$$

We can calculate the resulting runoff for a given potential evaporation regime from this set of graphs. The runoff reduces more quickly with a reduction in precipitation: this is referred to as a gearing ratio, defined as the fractional change in Runoff with fractional change in Precipitation. **Figure 2** shows how this gearing ratio changes with precipitation.

Some analysis by Zhang et al (2004) showed how the annual catchment scale relationship between river flow, precipitation and evaporation followed a curve, but that the curve was slightly different for forests and grass:

Roderick and Farquhar (2011) point out that Fu (1981) (the equation used in Figure YY) identified the same functional relationship between the three variables: P, PE and E that Budyko (1974) (Equation 1) formalised. Fu (1981) laid it out as follows:

$$E = P + PE - (P^{\omega} + PE^{\omega})^{1/\omega} \quad (3)$$

The two equations (1 And 3) give the same functional relationship between the variables if value of ω = n + 0.72. Using the linear relation with the Budyko 'n' factor, the change from Forest to Grass decreases the 'n' from 2.12 to 1.83, which is a factor of 0.86. This demonstrates that forests have a higher feedback strength than crops. This is consistent with the result of Teuling et al (2010) which showed that forests have a conservative approach to the water use, so as precipitation drops and evaporative demand increases, the evaporation decreases quickly. Grasses and crops however do not drop their evaporation so quickly (they have a more linear response to precipitation decrease) and they lose the water, thus leading to hotter drier conditions in drought conditions.

The stronger feedback strength of forested regions is also consistent with the finding of McNaughton and Spriggs (1989) who used a PBL model and found that the Preistley-Taylor parameter – which is a measure of the strength of land-atmosphere interactions - should be higher for forests than for grasses (Figure 3).

According to Figure 2, the impact of having a decreased level of feedback between the surface and the atmosphere when changing the land cover from forest to crops and pasture is to reduce the runoff-gearing ratio. This will mean a more linear relationship between changes in precipitation and river flow, with less conservation of water and more drought vulnerability.

The proposed and modelled links between land cover change and feedbacks and riverflow should be tested further using the outputs from the LUCID project (Pitman et al, 2009) and using observed PBL strengths over forested and cropped areas. The results are important with regards to drought prediction and the possible mitigation strategies that might be employed in future.

3. LCLUC and ecosystems

Climate is the main regional driver of ecosystem structure and functioning through the timing and amount of energy and water that is available in the system (Stephenson, 1990). In turn, ecosystems influence climate by determining the energy, momentum, water, and chemical balances between the land-surface and the atmosphere (Chapin III *et al.*, 2008). Hence, extensive impacts on ecosystems, both from natural origin (e.g., climate extremes) and human made (e.g., land use changes), may alter one or several pathways of the ecosystem–climate feedbacks, which may end up affecting the regional and global climate.

The ecosystem-climate feedbacks are a central problem not only for modeling the land-atmosphere interactions of the climate system (Mahmood et al., 2010), but also for many other biological and environmental issues. Ecosystem-atmosphere interactions and feedbacks depend on the physical properties of the underlying surface, like surface albedo, surface roughness, stomatal resistance, and others.

These properties affect the radiation balance at the surface as well as the exchange of momentum, heat, moisture, and other gaseous/aerosol materials. Changes in the structure and functioning of the ecosystems will thus have an impact on those exchanges.

The exchanges of mass and energy may be modified by at least two mechanisms: by human activity changing the land surface conditions (land cover and land use changes) or by natural variability in climate that affects the ecosystems health, performance, and biophysical properties.

Many land surface models do not consider the concept of ecosystems. Models of intermediate complexity have static vegetation classes with look-up tables to identify their corresponding biophysical properties. More complex models employ land-cover classifications that identify patches of the land surface that are homogeneous in terms of their Plant Functional Type composition. Plant Functional Types are groups of species that share similar functional features such as leaf life, metabolic route or nitrogen fixation. However, the precision of these a priori classifications to predict biophysical properties at the ecosystem or regional level has been questioned (Wright et al. 2006). In addition, land cover type that is assumed to remain constant in the composition of the PFTs, in reality may experience important changes. For instance, the biophysical properties of a typical vegetation type during a wet period should be very different during a drought. The same is true during anomalous periods of intense rain that can create numerous ponds, or flooding. Interestingly, for a model that assumes constant surface properties, all these cases will behave similarly in terms of land-atmosphere interactions, the radiation budget, and the surface water, energy and carbon cycles. Dynamical vegetation models that include the carbon cycle are a significant advance in the area of ecosystem-atmosphere interactions, as they allow for vegetation changes and have advanced assumptions regarding surface processes.

Plant Functional Types (PFTs) are defined as a class is that is dominated by a set of plant species that share a few functional traits such as leaf type, life span, and physiognomy and that differ from other classes (e.g. evergreen forest versus annual grassland). As plant species can be grouped into plant functional types, ecosystems can be grouped into Ecosystem Functional Types (EFTs), but defined at a higher level of the biodiversity hierarchy. In ecology, such classifications into functional units aim to reduce the diversity of biological entities (for instance genes, species or ecosystems) on the basis of processes, and allows for the identification of homogeneous groups that show a specific and coordinated response to the environmental factors. EFTs are groups of ecosystems that share functional characteristics in relation to the amount and timing of the exchanges of matter and energy between the biota and the physical environment. In other words, EFTs are homogeneous patches of the land surface that exchange mass and energy with the atmosphere in a common way (Valentini et al. 1999, Paruelo et al. 2001; Alcaraz-Segura et al. 2006).

Ecosystem Functional Types and land-cover classifications based on Plant Functional Types are thus different from each other. The latter denomination refers to the functioning of one plant species and assigns those attributes to a region with similar plants (e.g., trees → forest), thus called a bottom-up approach. EFTs are computed from satellite information (e.g., spectral vegetation indices), so they do not identify the functions of a given plant, but instead identify a patch of land that has homogeneous properties in terms of exchanges of energy and mass over a given region. EFTs can thus be considered a top-down functional classification directly based on ecosystem processes.

4. Societal needs for researches on water over land

All organisms, including humans, require water for their survival. Therefore, ensuring that adequate supplies of water are available is essential for human well-being. Water issues are related to poverty, and providing access to safe drinking water is one of the key necessities for sustainable development, even though less information on hydro-climate system might be necessary to solve the current issue. Any change to the Earth's climate system, hydrological cycles, and social systems has the potential to increase the frequency and severity of water-related hazards, such as: storm surges, floods, debris flows, and droughts. Global population is growing, particularly in the developing world and is accompanied by migration into urban areas, and could be associated with large scale land use/land cover changes including deforestation. The urbanization threatens to increase the risks of urban flash floods and per-capita water resources scarce. Global economic growth is increasing the demand for food, which further drives demands for irrigation water and drinking water, demands more cropland, and changes LULC potentially. Therefore is critically important to consider both the social and climate changes (Fig.4-1).

In the past, water issues remained local issues; however, due to the increase in international trade and mutual interdependence among countries, water issues now often need to be dealt with on the global scale, and require information on global hydrological situation and its changes associated with climate changes for their solutions. Sharing hydrological information relating to the transboundary river basins and shared aquifers will help reduce conflict between relevant countries, and quantitative estimates of recharge amounts or potentially available water resources will assist in implementing sustainable water use.

Global hydrology is not only concerned with global monitoring, modeling, and world water resources assessment. Owing to recent advancements in global earth observation technology and macro-scale modeling capacity, global hydrology can now provide basic information on the regional hydrological cycle which may support the decision making process in the integrated water resources management.

It should also be examined to what extent such a framework of offline simulation of land surface models can be applied to finer spatial and temporal scales, such as 1-km grid spacing and hourly time interval (Oki et al., 2006; Wood et al., 2011). For such research efforts, observational data from regional studies can provide significant information for validation, and efforts to integrate datasets from various regional studies should be promoted.

Certainly it is demanded to assess the impacts of human interventions on hydrological cycles in climate system including land use changes, such as deforestation and urbanization, reservoir construction and water withdrawals for irrigation, industry, and domestic water uses, and emission of air pollutants which would have been suppressing weak rainfall and modulate precipitation occurrence weekly.

(more inputs necessary)

5. Current gaps, and future challenges

Current global land surface modeling has not yet integrated most of the latest achievements in process understanding and regional- or local-scale modeling studies. Global simulation of the occurrences, circulations, and balances of solutes and sediments are emerging. Both natural and anthropogenic sources should be considered as for nutrients, and probably such models should be coupled with agricultural models which simulate crop growth. Precise information on the land use/land cover is essential to have better estimates on material cycles, and coupling of the LULC change model with biogeochemical land surface model would be necessary for convincing future projections considering both climate and societal changes.

Hydro-meteorological monitoring networks need to be maintained and further expanded to enable the analysis of hydro-climatic trends at the local level and the improvement in the accuracy of predictions, forecasts, and early warnings. As clearly illustrated in Fig.5-1 (from Oki et al., 1999), global hydrological simulations are relatively poor in the areas with little in-situ observations. Basic observational networks on the ground are critically indispensable for proper monitoring and modeling of global hydrology; however, it is also required to utilize remotely sensed information in order to fill the gaps of in-situ observations. Reliable observational data are essentially necessary not only as the forcing data for global hydrological modeling, but also for the validation of model estimates. River discharge and soil moisture data are critically important for global hydrological studies. However, contributions from the operational agencies in the world are not yet well established and need to be enhanced.

Some of the land surface processes have not been emphasized in the current global climate models or earth system models due to their relatively minor impacts on the climatic feedbacks from the land surface to the atmosphere. However, it should be the time to develop land surface models primarily for responding to the demands of understanding the land surface processes and possible future changes for supporting various decision-making in society. From this point of view, the integrated land surface models, which consider anthropogenic interventions explicitly in addition to biogeochemical cycles should be developed and implemented in order to provide more realistic impact assessment and support the design of practical adaptation measures.

(more inputs necessary)

6. Concluding remarks

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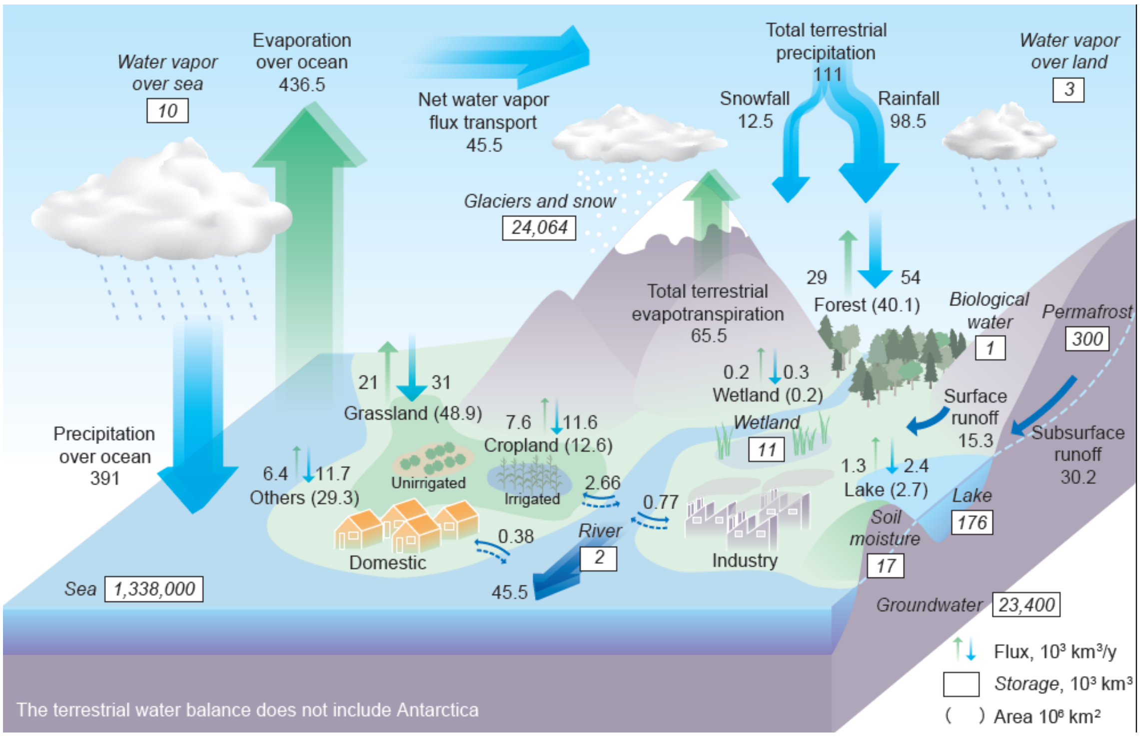

Figure 1: Global hydrological fluxes (1000 km^3/year) and storages (1000 km^3) with natural and anthropogenic cycles are synthesized from various sources (Dirmeyer et al., 2006; Korzun, 1978; Oki et al., 1995; Shiklomanov, 1997). Big vertical arrows show total annual precipitation and evapotranspiration over land and ocean (1000 km^3/year), which include annual precipitation and evapotranspiration in major landscapes (1000 km^3/year) presented by small vertical arrows; parentheses indicate area (million km^2). The direct groundwater discharge, which is estimated to be about 10% of total river discharge globally (Church, 1996), is included in river discharge

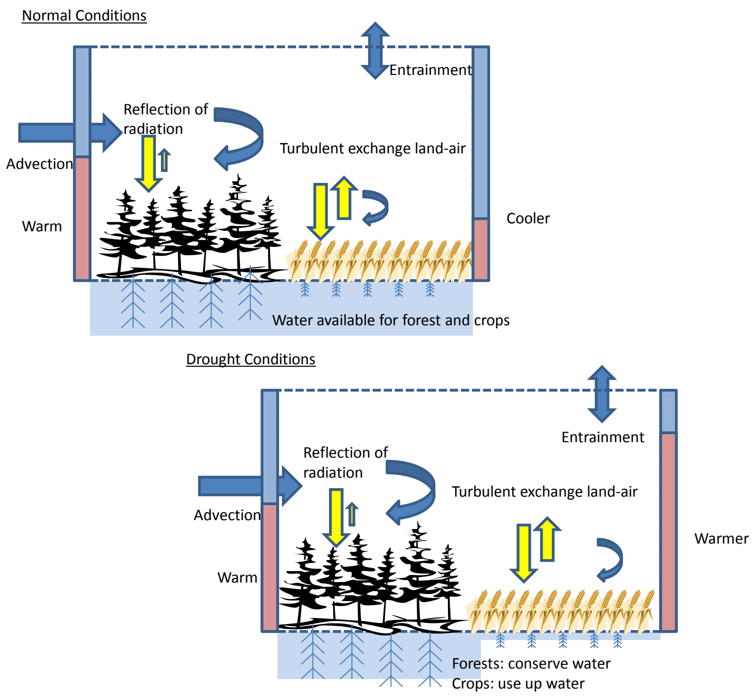

Figure2-1. Summary of impact of land-cover on atmospheric conditions

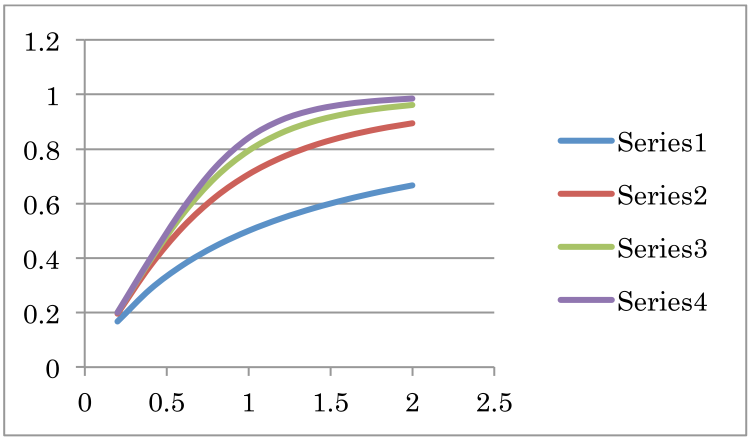

Figure 2-2: Ratio of evaporation to potential evaporation as a function of the ratio of precipitation to potential evaporation (aka the Budyko Curve) for different values of 'n'

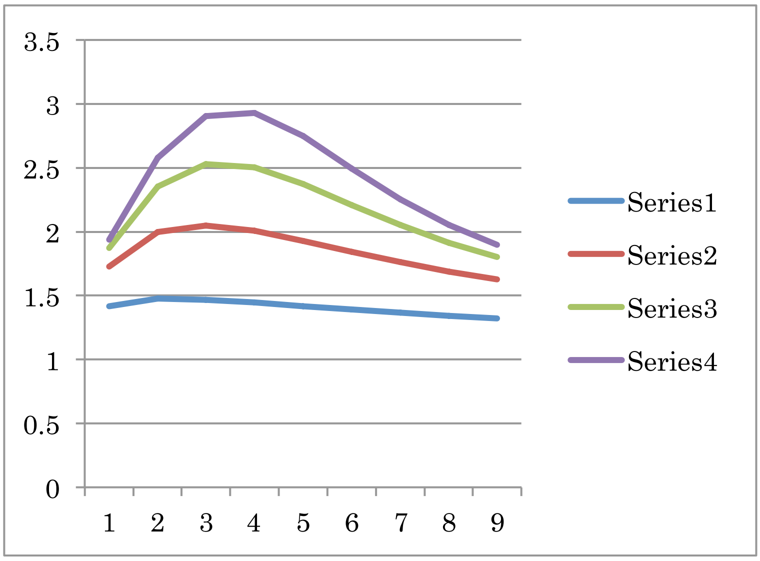

Figure 2-2. Gearing ratio (fraction of runoff increase or decrease as ratio to fraction of precipitation increase or decrease) plotted against precipitation for different values of 'n'

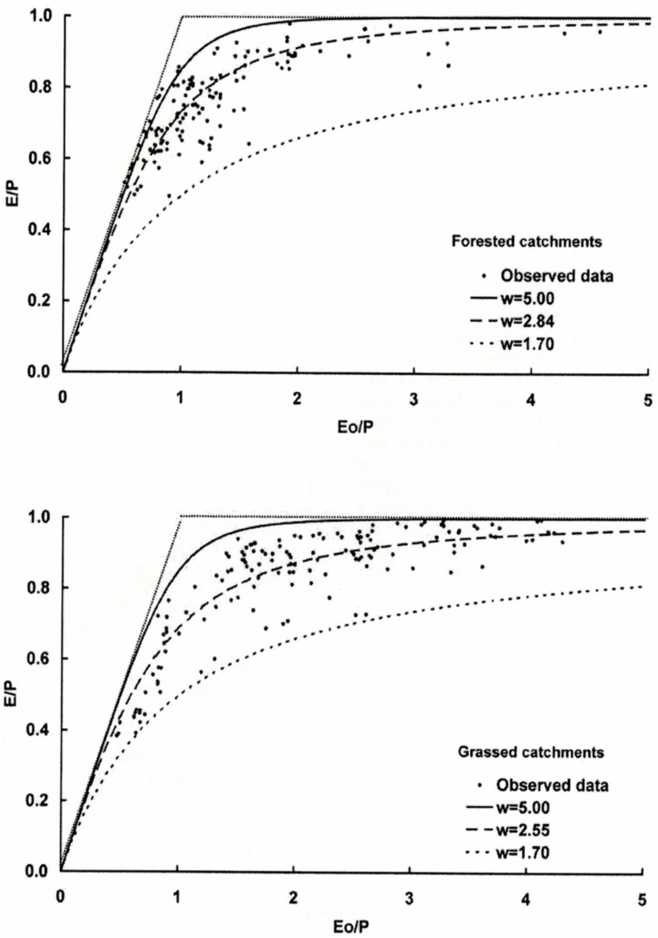

Figure 8. Scatterplot of evapotranspiration ratio (*E/P*) against index of dryness (E_0/P). Each point represents one forested catchment, with evapotranspiration taken as the difference between precipitation and runoff. Lines are the relationships represented by *Fu* [1981] with different values of *w* parameter. Top panel is for forested catchments with the best fit *w* value of 2.84, and bottom panel is for grassed catchments with the best fit *w* value of 2.55.

Figure2-4: taken from Zhang et al (2004) – their Figure 8.

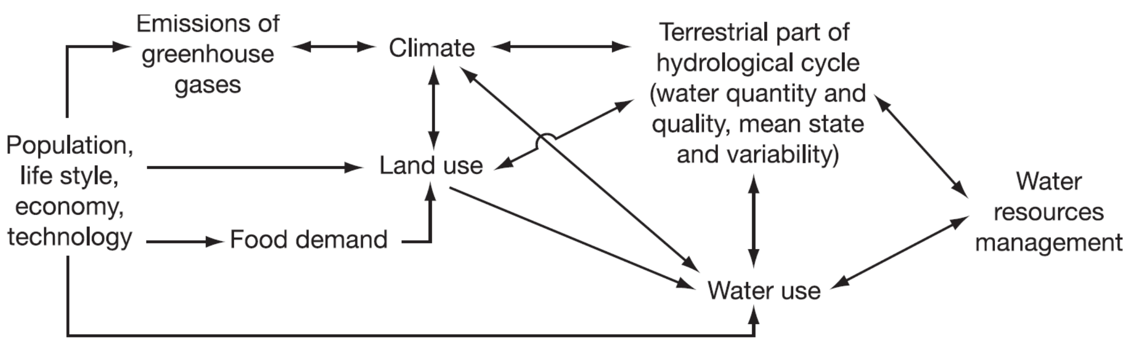

Fig.4-1 Impact of human activities on freshwater resources and their management, with climate change being only one of multiple pressures (modified after Oki, 2005).

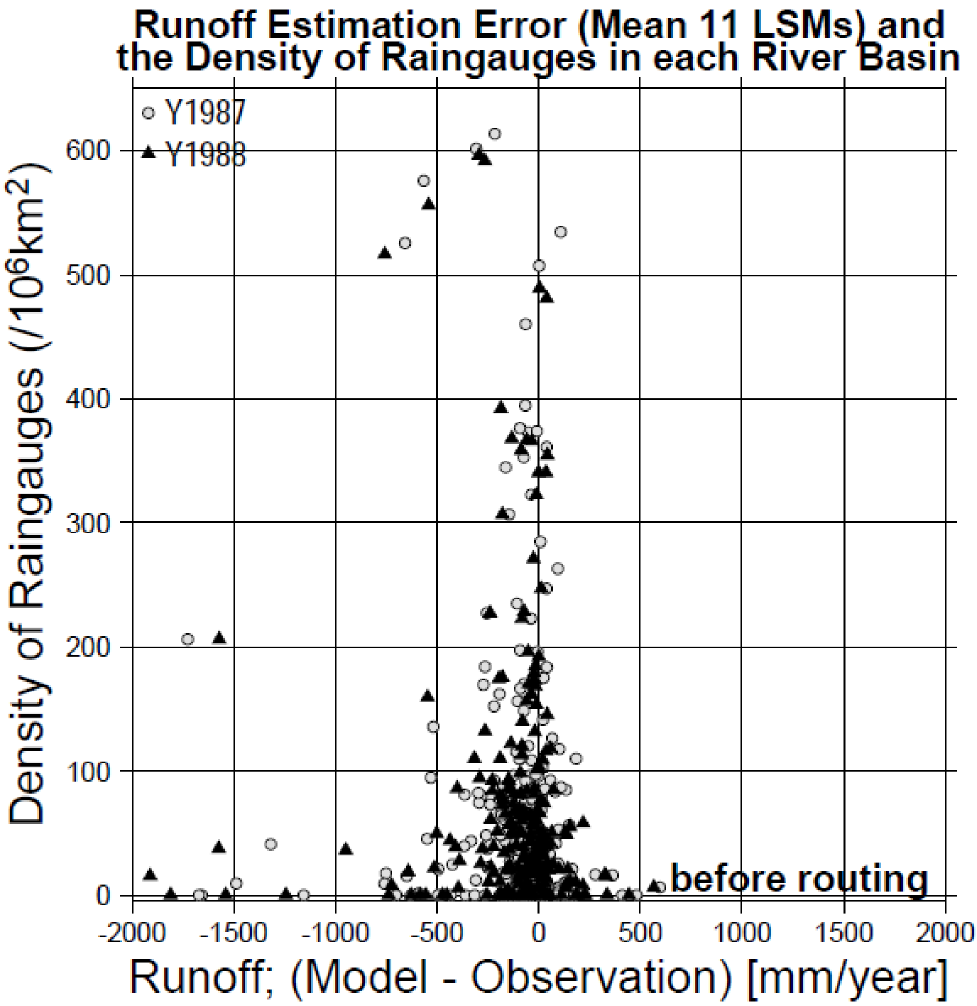

Fig.5-1: Comparisons between the density of rain gauge [/10^6 km^2] used in preparing the forcing precipitation and the mean bias error [mm y^{-1}] of 11 LSMs for 150 major river basins in the world in 1987 and 1988 (Oki et al., 1999).