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Contribution of a GIS in the spatial modeling of the hydrologic balance of Allondon watershed (France, Switzerland)

S. Ebener[1], W. Wildi[1], M. Bouzelboudjen[2], J.-M. Jaquet[1], J.-P. Fortin[3]

[1] Institut Forel - University of Geneva, Switzerland
[2] Hydrogeological Centre - University of Neuchâtel, Switzerland
[3] INRS-Eau- University of Québec, Canada

ABSTRACT

This paper discusses the development of an approach allowing the spatial distribution of the hydrologic balance at the watershed scale using Geographical Information Systems (GIS). Methods were developed in order to obtain the intensity distribution of precipitation, interception, infiltration, runoff and evapotranspiration. These methods have been applied on the Allondon watershed (France, Switzerland). At the scale of this watershed (142 km^2), the annual input of rain reaches $190*10^6 m^3$, the snow melt contributing to $4*10^6 m^3$ to this amount. Vegetation intercepts $26*10^6 m^3$ from which $8*10^6 m^3$ aren't evapotranspired but reaching the ground. On the ground surface, $176*10^6 m^3$ are divided into runoff for $92*10^6 m^3$ and infiltration for $84*10^6 m^3$. The evapotranspiration generates a return of $61*10^6 m^3$ in the atmosphere. This volume of water comes from interception and from the stock observed in the soils.

Keywords: Spatial modelling, GIS, Hydrology, France, Switzerland

INTRODUCTION

The management and protection of water-resources is based on a good knowledge of the hydrological cycle at the heart of the geographic units that represent the watershed. In this context, the establishment of a regional hydrologic balance offers a number of advantages. The breakthrough in information technology in recent years lead to the creation of powerful information tools. Among these tools, the Geographic Information Systems or GIS are directly applicable to the field of natural environmental science. The spatials funtionality offered by this tool add a new dimension to hydrologic modelling. (Maidment, 1993, Kovar and Natchtnebel, 1993). Models such as IHSI [De Smedt, 1997], HYDROTEL [Fortin et al, 1995], PCRASTER one of the first dynamic GIS (Van Deursen and Kwadijk, 1993), or the latest versions of MIKE SHE (SOFTWARE developed by the Danish Hydrolic Institute) are good examples. The current study uses to this new GIS approach with the evaluation of a spatially distributed hydrologic balance.

MATERIALS AND METHODS

The Geographic Information System represents the key tool used in the framework of this research. At the heart of these systems, information can be presented either in vector mode and in raster mode. Using vector mode we have created precise numerical documents, raster mode have allowed for the use of analytical functions in spatial modelling of various processes. Numerical cartographic modeling techniques are described in detail by Tomlin (1983).

In vector mode, we worked with the Arc/Info workstation software (Version 7 open VMS&UNIX), as well as with ArcView (version 3 Windows). Idrisi software (version 2 Windows) provided the raster GIS tool.

The approach consisted of the creation of a numerical database in vector mode at a scale of 1:25'000 covering all the natural partitions involved in the hydrologic balance. We then extracted the parameters necessary for the application of different models used to arrive at the spatial distribution of the hydrologic balance elements. Once all the elements were mapped, we have evaluated the spatial distribution of hydrologic balance at watershed scale. On a temporal scale, monthly time steps were selected to produce a sufficiently detailed study the evolution of the intensity of the process during the course of the year. A part from the numeric altitude model, which already satisfied the needs of the study in terms of resolution (25m grid) and raster format, two steps were followed to produce sufficiently high resolution raster documents necessary for the modeling, (i) the digitizing of existing hardcopy data (geology, pedology, land cover), (ii) the creation of maps from point data (climatic data).

Existing hardcopy data documents we was resorted to a scanned before digitising. The files obtained this way were modified again in Arc/Info in vector mode resulting in the creation of the topology, wich was then converted into vector format. The numerical database in Arc/Info consists of land cover, the physiognomy and the distribution of the vegetation series, pedology, lithology as well as the hydrographic network. For the climatic data (precipitation, temperature, and global solar radiation) point data taken from measuring stations were first treated in order to make them reflect the chosen observation period (1973-1996). In a second step, regionalisation methods were developed and/or applied in order to set up monthly distribution maps for these hydro-climatic parameters in raster format (25mx25m). Modeling the spatial hydrologic balance, was carried out in stages, dealing with each process: precipitation, interception, runoff, evapotranspiration and infiltration.

For precipitation, of which the regionalisation of the total volume had already been carried out, a model was refined in order to regionalise the storage and snow components. For the other processes, bibliographic research was carried out in order to produce simple models, appropriate to the scale selected in a moderate humid zone. Based on this research, a series of empirical models using parameters that can be regionalised from the numerical database previously created. The order of application of these models allows finally for the constitution of the hydrologic balance at the watershed scale. As we have already mentioned, a first model made it possible to know the distribution of precipitation. The results obtained in this way were then used in the framework of a second model, simulating the distribution of interception. A third model, independent from the first two made it possible to generate distribution of the real evapotranspiration. Finally, the results of three models have provided by compilation into a single model, the distribution of runoff and infiltration.

For interception, the work of Dunn and MacKay [1999] (Fig. 1a) allowed for the estimation of monthly interception coefficient by vegetation type (Fig 1b). By combining the land cover map with those acquired for the vegetation series, we regionalised the distribution of interception coefficients. The maps made in this way were applied to the monthly rainfall distribution maps.

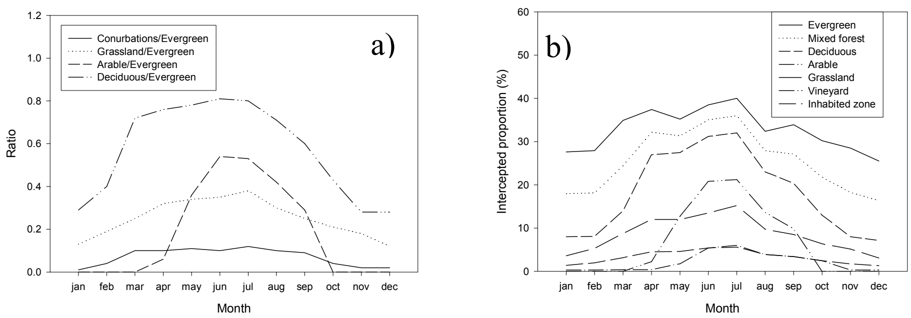

Figure 1-a) Relationship between the intercepted water over four types of land cover and those retained by conifers for 1989 (from Dunn &Mackay, 1995)
b) Average monthly proportion of water intercepted by different types of vegetation. Values adapted for the Allondon watershed.

Evapotranspiration mapping, ompleted. Firstly, potential evapotranspiration was regionalised based on the monthly maps of the distribution of temperature and global solar radiation. Using Turc's formula [1951, 1954, 1955] the spatial evaluation of the real evapotranspiration was carried out in two stages. Firstly by applying the monthly cultural coefficients, regionalised on the basis of the land cover maps, the second by evaluating the variations of soil water content considering corrective factors, regionalised on the basis of the pedologic map.

For infiltration and runoff it was necessary to develop a computer code independent of the GIS tool used. This approach allowed, starting from the month of March, simulation of the hydrologic balance for a complete year by generating hydrological reports from one month to another of the volume of water store in the soil. Integrated in a spatial way in the simulation: the hydrographic network, the karst system recharge zone, the height of water saturation of the soils, the orientation of slopes, the height of rains, the snow melt, the real evapotranspiration, the volume of intercepted water by vegetation, the runoff coefficients and the height of water in the soil at the beginning of the month in question. The distribution of the runoff coefficients was obtained by combining 3 previously regionalised parameters in the database, to know: the slope, the soil granulometry and the corresponding land cover. The integration of all the elements at the heart of this programme allowed us to ensure the coherence of the hydrologic balance at the watershed scale.

APPLICATION

The methods set forth previously were applied on the Allondon watershed (Fig. 2.)

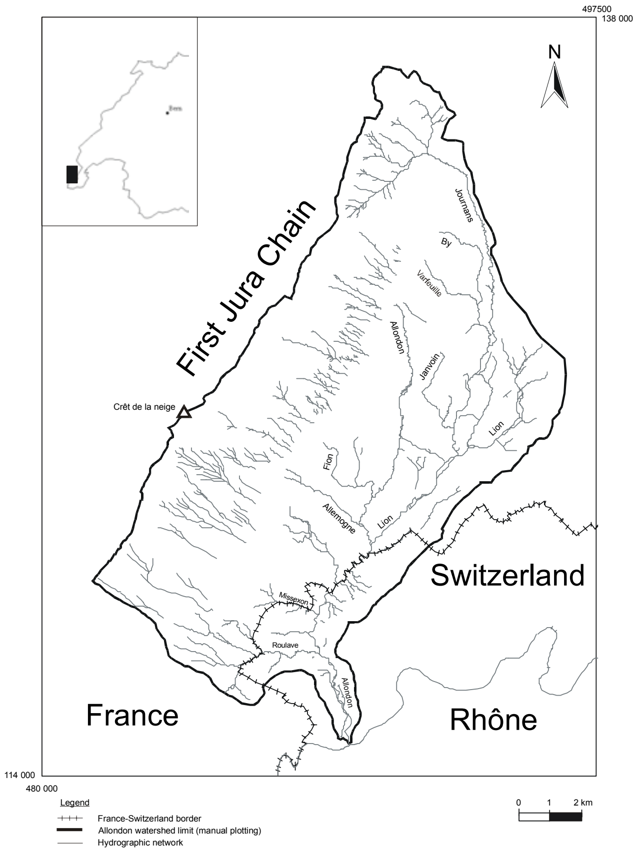

Figure 2- Allondon watershed. Localization, hydrographic network

This watershed wasse of selected because of its average size (147 km^2), its heterogeneity in terms of natural and/or anthropogenic conditions meets (topography, land cover, geology,…), the presence of two distinct hydrological systems (karst system on its north side and porous on the plateau) and the large quantity of data available.

In the absence of precise information concerning the extension of the hydrogeologic watershed,we decided to stretch the limits of the zone being studied beyond the one of the hydrologic watershed. This is then how the numerical database that was constituted, contains information plans covering the whole rectangular surface making up the framework of Fig. 2. The main physical characteristics of the watershed and the distribution of different land cover types are presented (Table 1&2).

	Values
Surface (km^2)	146.9
Perimeter (km)	61
Compacity Index	1.4
Maximal altitude (m)	1698.2
Minimal altitude (m)	346.5
Mean altitude (m)	735.5
Median altitude (m)	550
Min/mean/max slope (°)	0/10.5/52.6
Mean slope orientation (° East)	152

Table 1 - Morphological characteristics of the hydrologic Allondon watershed

	surface (km2)			
Classes	Total	Switzerland	France	tot prop (%)
Grassland	31.8	0.7	31.1	21.6
Wooden surface	55.5	4.3	51.2	37.7
Arable	44.8	4.9	39.9	30.5
Vineyard	2.1	2.1	0	1.4
Surface without vegetation (permeable	2.2	0.1	2.1	1.51
Inhabited areas	9.9	0.3	9.6	6.7
Surface without vegetation (impermeable)	0.7	0.3	0.4	0.4
Water surface	0	0	0	0

Table 2 - Distribution of the different types of land cover for the Allondon watershed surface

At the pedologic level, the watershed presents a wide diversity of soils at the granulometric as well as the textual level. This is linked to the wide morphological, climatic and lithological range encountered. In the framework of this study we were essentially interested in their granulometric aspect. From a lithological point of view, the area being studied can be split into two distinctive areas: The alluvial plateau on the south-eastern side and the Jura limestone chain on the north western side. This differentiation is at the basis of the separation between the two hydrogeological systems described earlier. Regarding the climatic characteristics of the area being studied, the climatic station network installed, allowed us to evaluate and regionalise the monthly average of precipitation (32 measuring stations), temperature (11 stations), and global solar radiation (2 stations) for the period of 1973-1996. Table 3 presents the monthly average obtained for the 3 parameters at watershed scale.

Months	Total precipitation (10^6 m3)	Temperature (°C)	Global solar radiation (W/m^2)
1	18.01	0.1	49.7
2	17.16	0.9	88.9
3	14.96	3.3	127.1
4	11.67	6.0	166.7
5	14.99	10.5	199.6
6	15.52	13.7	224.2
7	13.18	16.5	242.9
8	11.58	16.0	209.6
9	17.13	12.6	158.3
10	18.22	8.4	96.2
11	18.50	3.4	52.2
12	21.15	0.8	42.0

Table 3 - Monthly total volume of precipitation, average temperature and average global solar radiation for Allondon watershed surface (Average 1973-1996)

With the help of above mentioned empirical models mentioned we regionalised the interception intensity and real evapotranspiration. The application of the computer code made it possible to evaluate infiltration and the monthly variations of water reserves in the soil, as well as estimating the volume of water reaching the hydrographic network in the form of runoff on the whole watershed. A description of the models used as well as the mapped results in colour are provided in Ebener (2000) and can be consulted at [http://www.unige.ch/forel/fr/steeve/ebenglish.htm]. Annex 1 shows the hydrologic balance for April month through four colored maps (Rainfall, interception, real evapotranspiration and infiltration).

Table 4 represents the modelled volumes of water for these different parameters at watershed scale.

	1	2	3	4	5	6
March (model start)	1.45	1.77	1.22	-0.14	5.29	10.67
April	1.98	1.93	3.27	-0.33	6.13	6.37
May	0.52	2.83	8.08	-1.09	7.35	5.55
June	0.00	3.57	12.52	-2.10	9.22	2.81
July	0.00	3.15	14.25	-3.88	9.01	1.03
August	0.00	1.99	11.20	-2.16	8.82	0.77
September	0.00	2.62	6.36	4.65	11.26	3.47
October	0.00	1.81	2.80	2.79	7.85	9.35
November	0.00	1.53	0.54	1.59	5.88	12.24
December	0.00	1.31	0.13	0.52	5.10	14.45
January	0.00	1.28	0.07	0.11	4.27	12.30
February	0.00	1.30	0.27	-0.01	3.81	12.55
March (model end)	1.45	1.77	1.22	-0.09	5.34	10.62

Table 4 - Result of the modelling on the watershed surface for : 1) Snow melt; 2) Interception; 3) Real evapotranspiration; 4) Soil stock variation; 5) Infiltration; 6) Runoff. All values are expressed in 10^6 m^3

By choosing the month of March as a starting point for the modeling, we could assume that the soils were saturated, as a first simplifying hypothese. As can be seen in table 4, the application of the model developed enables for the collection of monthly coherent values that keep to the annual scale. In fact, the simulated values for the month of March at the end of the modelling, are very close to the values used at the beginning of the modelling for the same month.

Based on this volume, it is possible to set up the surface hydrologic balance for the Allondon watershed. One can show a hydrologic balance with different levels of detail. In the framework of this study we have chosen to express it by considering that the volume of water entering the watershed in liquid form (rainfall, snow melt), for a given month, was distributed between the different storage (infiltration in the karst and storage in the soil) and the volumes leaving the watershed (evapotranspiration, runoff). Figures 6a & b illustrate the different volumes expressed as percentages of the total volume entering the watershed surface in the liquid.

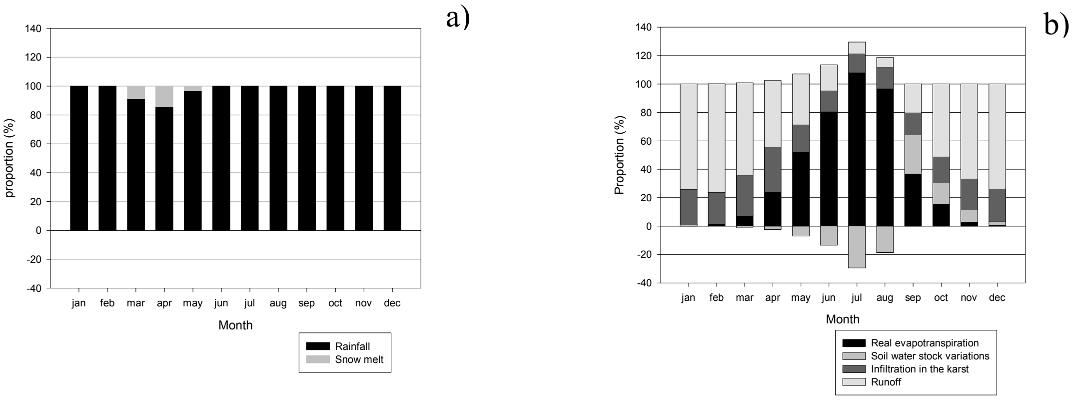

Figure 6 – a) Distribution of the monthly entries in the liquid form for the surface of the Allondon hydrographic watershed

b) Distribution of the reserve variation and monthly leaks in the liquid form for the surface of the Allondon hydrographic watershed

One can then observe that the model used produces coherent results at Allondon hydrographic watershed scale and that the hydrologic balance is maintained. It is how for example the hydrologic deficit produced by real evapotranspiration, in the period going from the month of March to the month of August (Fig. 6b), is compensated by the reduction in water reserves in the soils.

CONCLUSION AND PERSPECTIVES

This research is based on the following activities, the developement compilation methods, the construction of a numerical database, and the spatial distribution at the monthly scale of the processes intensity, allowing the elaboration of an hydrologic balance for a watershed. The creation of monthly maps for the processes involved in development of the hydrologic balance at the watershed scale constitutes an undeniable contribution to this research. Through this mapping, the GIS tool contribution for the dynamic comprehension of the processes is important. The use of standard commercial software, as well as the simplicity of the methods and models proposed, are a major stength of this approach. However the approach has some constraints. These include the requirement for a performing workstation to allow the validation and integration of the information to be treated in a spatial database. This way, easy computer manipulation cannot hide the numerous possibilities for error propagation in the context of this work. An unfortunately estimation of this component has not been made. We can however mention one example of frequent error all too. The comparison between the figures 8a and 8b show two slope maps perceptibly different stemmed from the digital elevation model treatment. We can see that the numerous artefacts on map 8a are linked with the interpolation method used. The influence of this parameter is fundamental in the runoff calculation for example.

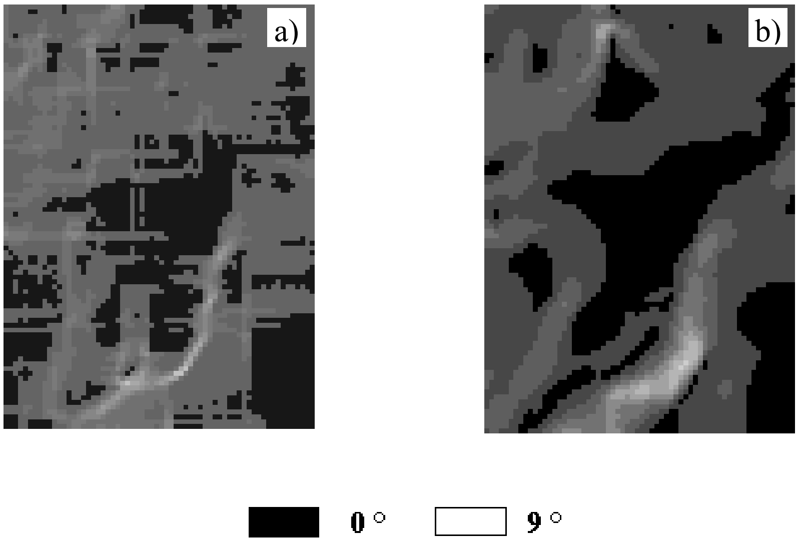

Figure 8 - Extracts of the slopes maps (a) file by OFT Swiss Topography Office, b) corrected file)

An important reflection has to be done during the numerical database contruction as well as during the method application in order to maintain the necessary consistency for the the spatial hydrologic balance evaluation.

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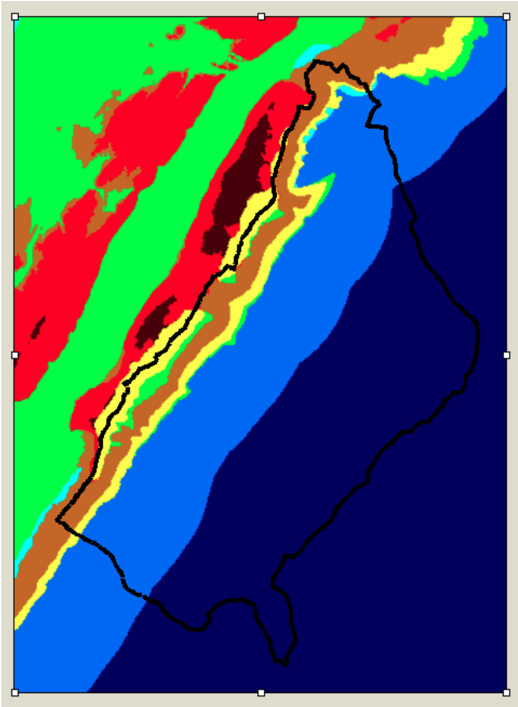
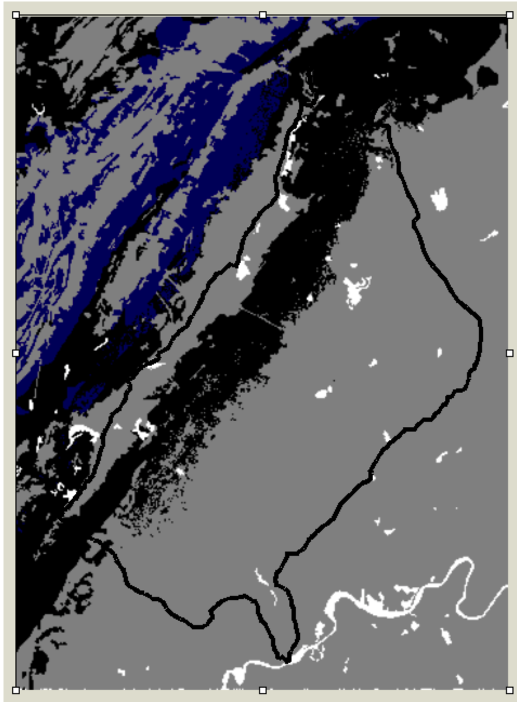
Corresponding author: Steeve Ebener, University of Geneva, 10 route de Suisse, 1290 Versoix, Switzerland. Email: ebeners@who.int

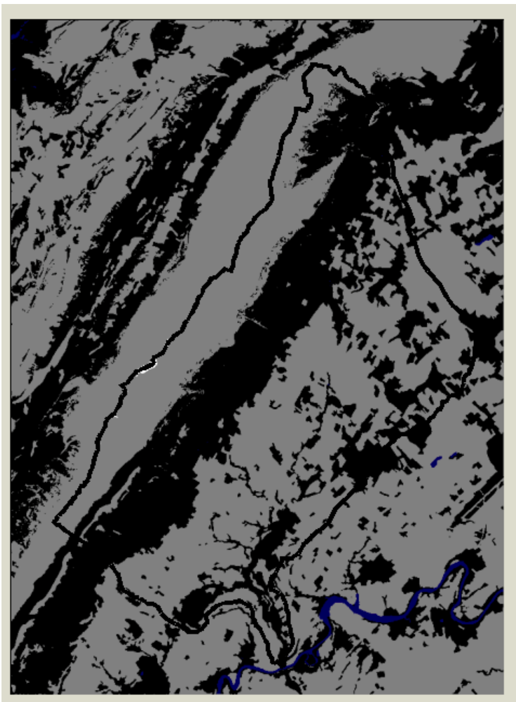
Annnex 1: Spatial modeling of the hydrologic balance of Allondon watershed for April month



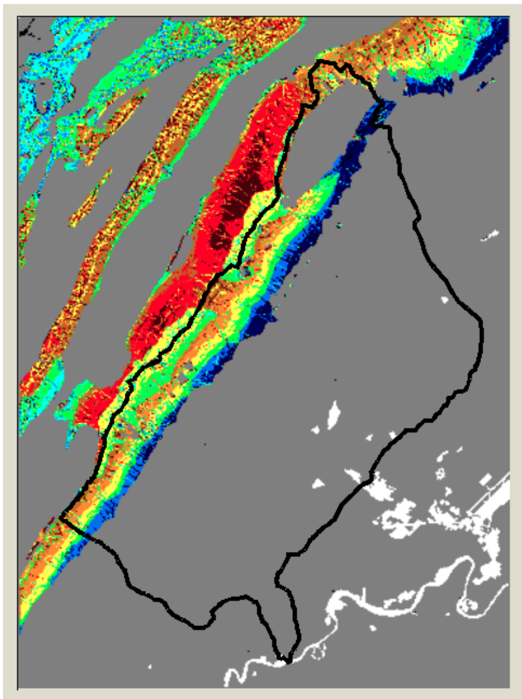
Rainfall



Interception



Real Evapotranspiration



Infiltration