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Hypsometrical Approach as a Decision Tool for Rational Management and Planning of Watersheds to Meet Sustainable Development

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Abstract

Holistic watershed management strategies are needed to allow making rational development within an entire watershed. This study reports on an integrated watershed approach based on hypsometrical distribution of different quantifiable indicators. The upper part of Ziz watershed at Foum Tillicht gauging station in Morocco is the experimental site for this case study. The research approach used allows an in-depth analysis of future situations; it allows making forecasts based on different socio-economical evolution scenarios. The basic data that needed for this approach include high resolution watershed characterization, e.g., geometry, morphology, geology, soil, and land cover/use. In addition, this work details the field experimental activities conducted within the watershed of interest. There is detailed description of the watershed resources mainly watershed equipment, watershed network for the observation of climate and water resources, hydrology, human activities (agriculture, industry, and urbanization), social and economical aspects, environmental considerations, fauna and flora. Results presented are very useful as a pilot integrated methodology for Morocco.

Keywords: Hypsometrical model, integrated approach, watersheds planning and management, advanced technology, interaction between upstream and downstream of watersheds, environmental considerations, and sustainable development.

Abbreviations : GIS (Geographical Information System), RS (Remote Sensing), DBMS (Data base Management System), DBRMS (Data Base Relational Management System), DEM (Digital elevation model), LASH (Laboratoire d'Analyse des Systèmes Hydrauliques), EI (equivalent inhabitant) or in substances (SSM (suspended matter), OxM (oxidizable matter), OrM (organic matter), FU (livestock fodder units), CU (cattle units).

1. Introduction

Social and economical developments increase the degradation of natural resources. These changes modify the natural state of the environment, exert stresses on water, soil and vegetation and consequently affect people's life. Sustainable management of these resources requires integrated management approaches at the watershed scale level. This work reports on a hypsometrical approach that uses watershed's physical, hydrological, and biological data. This approach allows the user to relatively compare the effects of different future and current management scenarios and make choice on ways to improve or at least preserve the environment and natural resources.

2. Location of the Study Area

Foum Tillicht basin (Figure 1) is located in the south of Morocco within the Midelt province (Aqid et al., 2002(1)). The area

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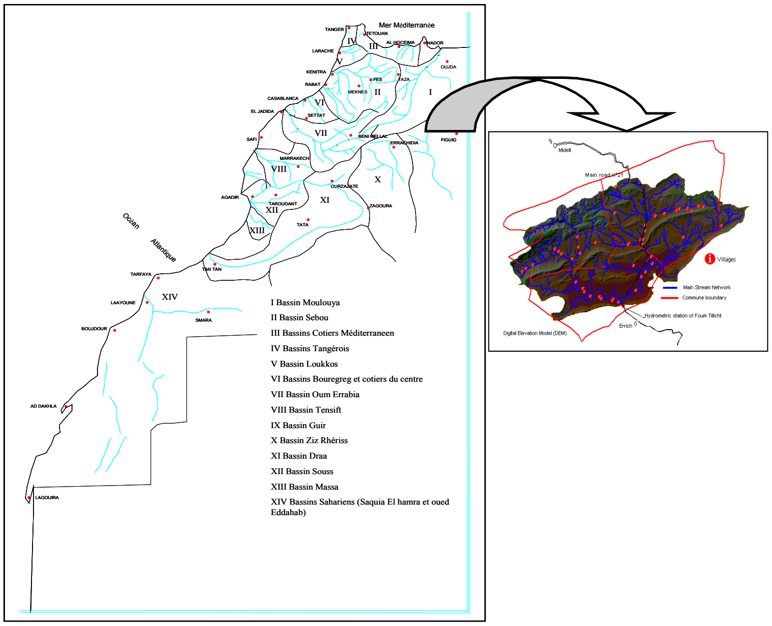

Figure 1. Geographical location of Foum Tillicht watershed.

of the basin is around 1243 square km and its perimeter is about 189 km. The watershed is enclosed between the (Latitudes) parallels 32°10' and 32°40' and the (Longitudes) meridians 4° 00'and 5° 00'.

3. Characterization of the Watershed Area

The following sections have detailed of the topography, hydrology, climate, geology and soils of the watershed.

3.1 Climatic and Hydrologic Aspects

The climatic data was not well detailed because of the lack of the number of equipment used in the study, the limited number of stations across the watershed. There were only two rainfall gauging stations; one of these stations is located at the outlet of the basin. The historical record of the meteorological data is short.

This is an arid/desert area characterized by a low irregular precipitation of about 200 mm annually. The average air temperature is 19°. The average wind speed is 13 km h-1 and a maximum speed of more than 90 km h-1. The total annual evapotranspiration potential exceeds 3000 mm. The average water resource per capita per year is 3,642 m3; these water resources are decreasing due to population increase and depletion of non-renewable water resources.

3.2 Topographic Aspects

Foum Tillicht watershed is a mountainous region; its highest elevation is 3420 m. The mountainous area of the watershed has steep slopes. The slopes of the transitional areas between the high slopes and the valley part of the watershed decrease smoothly over relatively long distances. It is common to encounter some wetlands/micro-ponds with variable sizes across the watershed.

Both the digital elevation model (DEM) and the hypsometric curve show geomorphologic aspects within the basin (Figures 2 and 3). With GIS tools, slope and aspect maps are produced from DEM (Figure 4 and 5).

3.3 Geological Aspects

The relief of the watershed is dominated by structural geology and lithology. The basin deeply penetrates in the high Atlas mountain chain in the north near Midelt town as shown in Figure 2 and in the cretaceous level of south Errachidia town located 70 km downstream of Foum Tillicht basin.

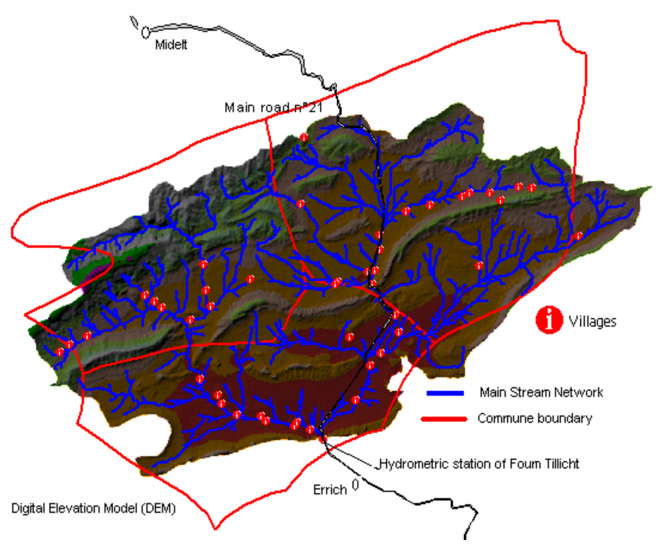

Figure 2. DEM of Foum Tillicht watershed need to show elevation in the legends.

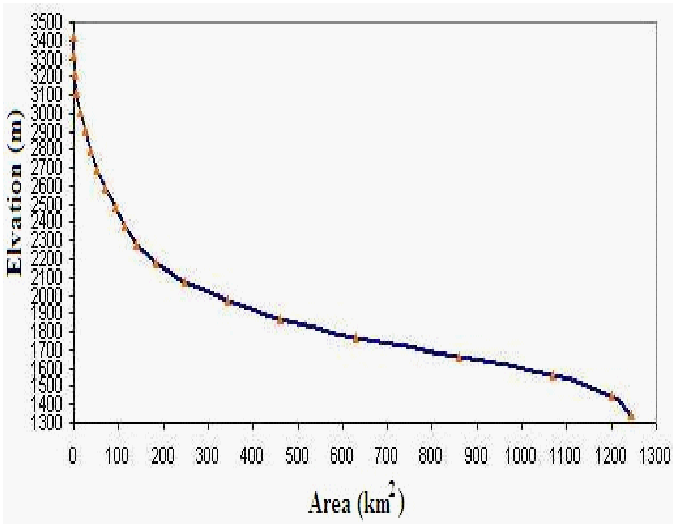

Figure 3. Hypsometric curve of the Foum Tillicht watershed.

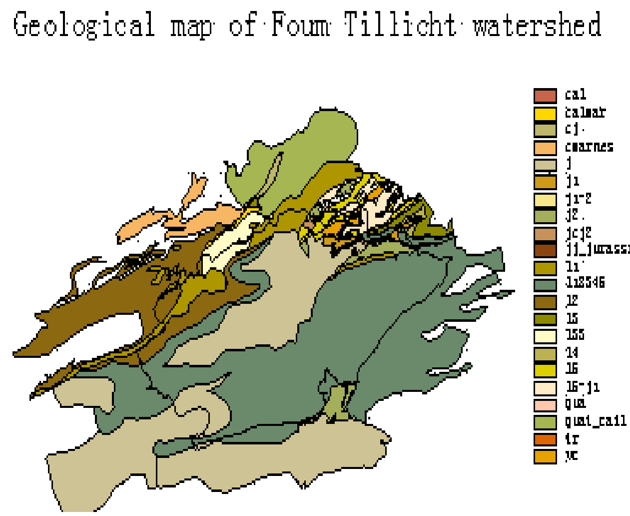

Figure 6. Geological map of Foum Tillicht watershed.

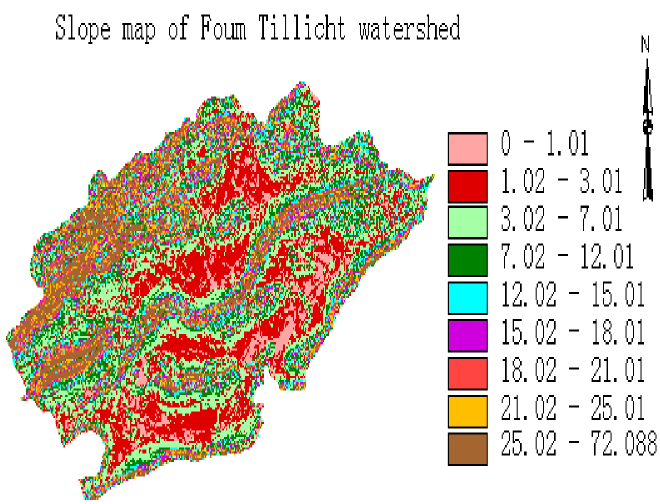

Figure 4. Slope map of Foum Tillicht watershed.

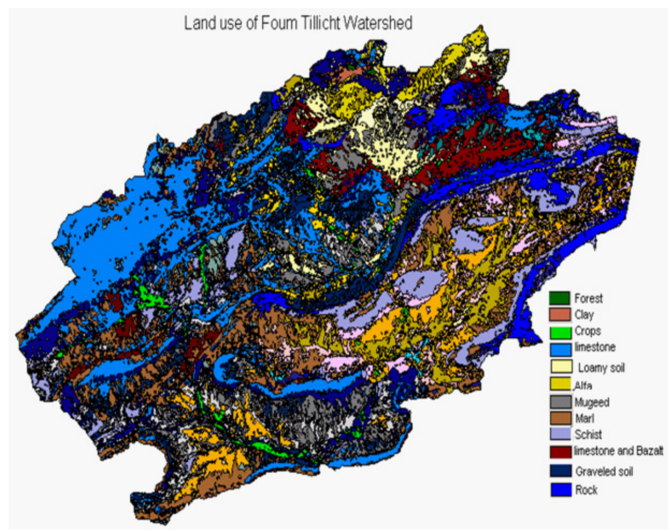

Figure 7. Soils and vegetation map (Foum Tillicht-watershed).

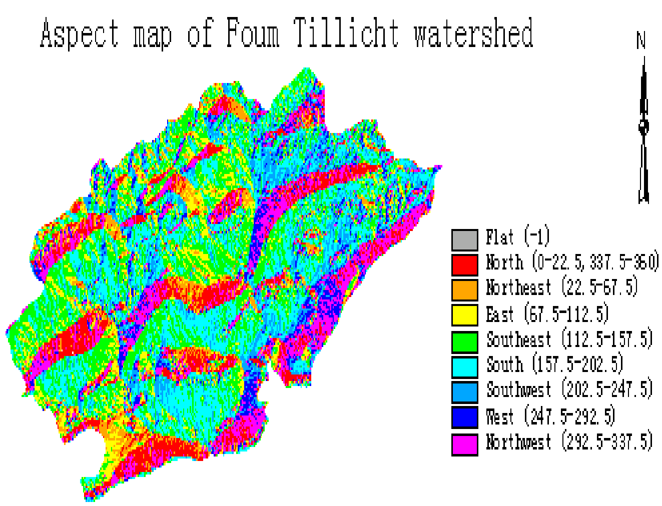

Figure 5. Aspect map of Foum Tillicht watershed.

The stratigraphic succession starts with Triassic continental red beds, followed by doleritic flood basalt at trias-lias transition. Transgression progressively begins in the lower lias with the deposition of massive dolomitic limestone, followed by bedded limestone in alternance with marnely levels and clay levels of Jurassic age. The different geological structures encountered within the basin are shown in Figure 6.

3.4. Soils, Vegetation Cover and Land Use

Most of the soils of the watershed are young; they are not well developed. Plains are usually dominated by silt covered by variable stone sizes. The piedmont zone is mainly composed of schistous soils. The mountains are calcareous with sparse basaltic formations. In the upper part, a layer of Triassic red clay to silty soil exists over a limited area.

For the watercourse, the bed is covered with stone without any classification form of the gravelly material. The bank of

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the main watercourses is covered by a deep layer of silty soil. Because of the arid climate of the basin, the species diversity of Foum Tillicht watershed is not significantly rich. A sparse cover of vegetation growth is found on the muddy and schistous surfaces with variable stone cover. The main species growing both on limestone, muddy soil and schistous soil are Mugweed (*Artemesia herba alba*) and Alfa (*Stipa tenacissima*). Some other plant growth is restricted to river/stream bank surfaces. A detailed account of land use map is given by spot-data processing. The zone of agriculture is clearly concentrated on spots where availability of water is reliable (Aqid et al., 2002 (1)).

Analysis of satellite data and use of optical and radar technology are done by Paloscia et al., (2001). It was oriented towards the determination of the contribution of radar signal to soil roughness and stone cover (Aqid et al., 2001). To fit the results, field measurements were made by LASH (Laboratoire d'Analyse des Systèmes Hydrauliques) team (Ouazar et al., 2001) using a custom-made profilometer. A small number of samples are selected from the basin. The aim of this experiment is to extrapolate roughness information to another homogeneous area within the watershed based on the spectral response analysis of the radar images. Therefore, kriging statistical technique is used to interpolate the results for the entire watershed and characterize each plane element resulting from DEM segmentation.

Optical satellite data (from spot field measurements) are used for soils and vegetation identification. Land use/cover given by spot image classification and NDVI computation is shown in Figure 8.

The watershed is covered by a variety of natural vegetation (Figure 8). This vegetation disappears at the highest parts of this watershed; this could be to the environmental stresses at those elevations, mainly lack of rainfall and low temperatures.

3.5. Hydrographical Aspects

The North-Eastern/South-Western disposition of the relief in higher synclines and eroded anticlines naturally allows drainage channels route through the throats. The stream network is dense in the highly sloppy zones, fairly dense in the piedmonts zone and through the plains. However, it is practically degraded in very weak sloppy zones and low depressions areas.

According to the Horton classification, the stream network of Foum Tillicht watershed is of seven orders as shown in Figure 9.

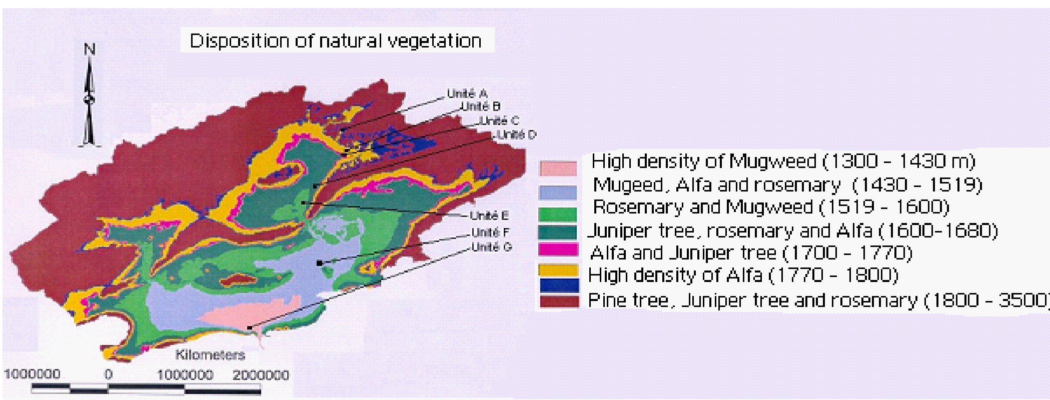

Figure 8. Natural vegetation cover of the Foum Tillicht-watershed.

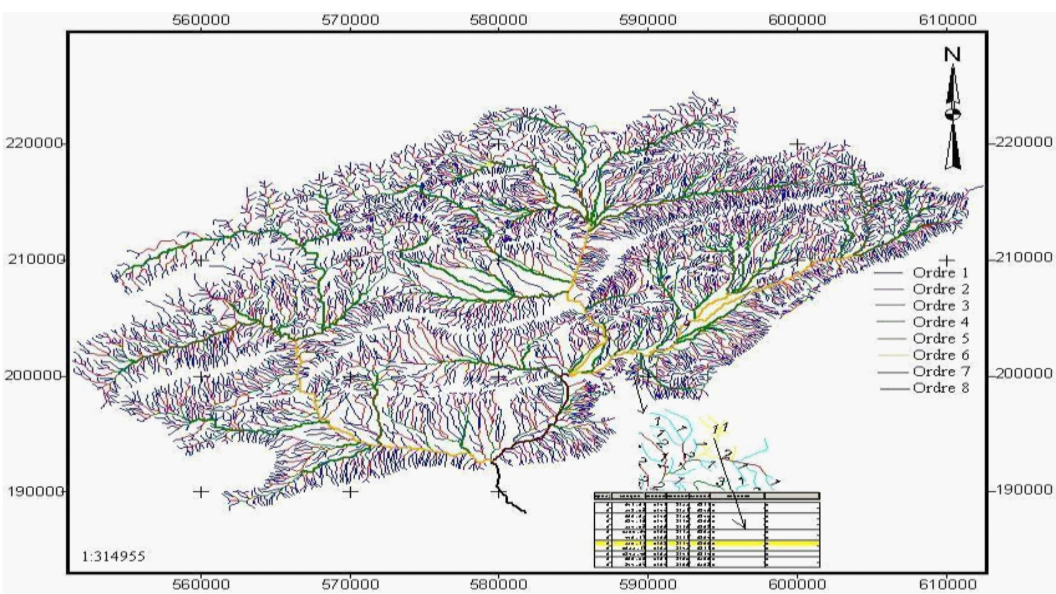

Figure 9. Hydrographic network of Foum Tillicht watershed.

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3.6. Social and Economic Aspects

Foum Tillicht watershed is home of 42 rural villages which are divided into three rural communities. This is the smallest administrative entity in Morocco with different levels of economic development. Based on the 1994 census records, the number of inhabitants is more than 16,000; 3,500 of them are nomads. The population density is very low, about 13 inhabitants per square kilometer. There are 2,648 households with an average of 6.3 inhabitants per household, which exceeds the national average of Morocco.

The economic activity is focused on agriculture, small commercial food distribution points, and commercial exchanges in souks (the weekly organized meeting to sell and buy domestic products). These economic activities generate low revenues for subsistence. The same approach can therefore help to assess and monitor the importance of this subsistence.

3.7 Environmental Degradation Indicators

The main sources of degradation, without any industry, are focused on the following environmental parameters:

- Climate severity,
- Cultural practices,
- Access of watershed water to Hassan Addakhil dam supply, and
- Absence of environmental protection measures.

The Main environmental components impacted by the above factors were taken into account in this study and they are as follows:

- Erosion
- Floods and inundations
- Degradation of natural resources

3.8. Assessment of the Hydrologic Resources

The hydrology of the watershed is the main driving force in this watershed; it impacts other natural resources at the watershed level, e.g., land use which is discussed here. Thus, modeling the hydrologic cycle of this watershed is detailed below.

This hydrologic modeling work used the U.S. Army Corps of Engineers' Hydrologic Engineering Centers Hydrologic Modeling System (HEC-HMS). As the first of HEC's "Next Generation" (Nex-Gen) software packages, HEC-HMS compute the rainfall-runoff transform. The assessment of natural resources is made by modeling the hydrologic cycle. In addition, CEQEAU software, a deterministic semi-distributed hydrologic and surface water temperature model, was used to simulate they hydrology and surface water temperature on a daily step. Details on this modeling exercise are detailed in Figures 10-13.

Even if these models are very precise, they need a very detailed, complete and continuous data which are not available for the area. The results used in our study are from a global model using the runoff rate from the rainfall. It is assumed to

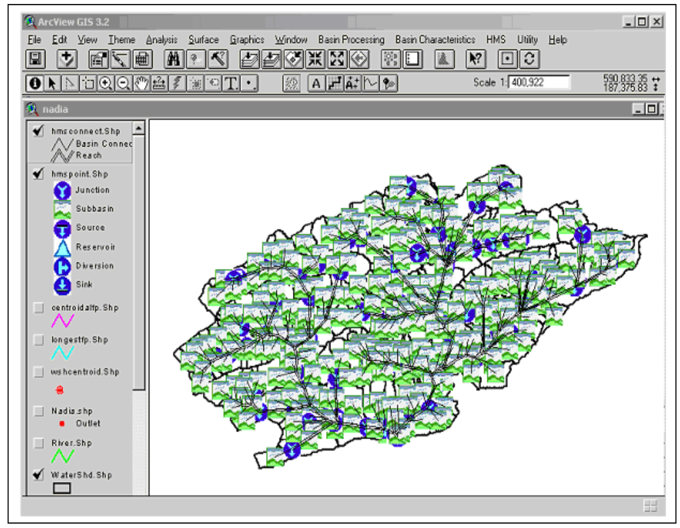

Figure 10. HEC Mödling schème of Foum Tillicht basin.

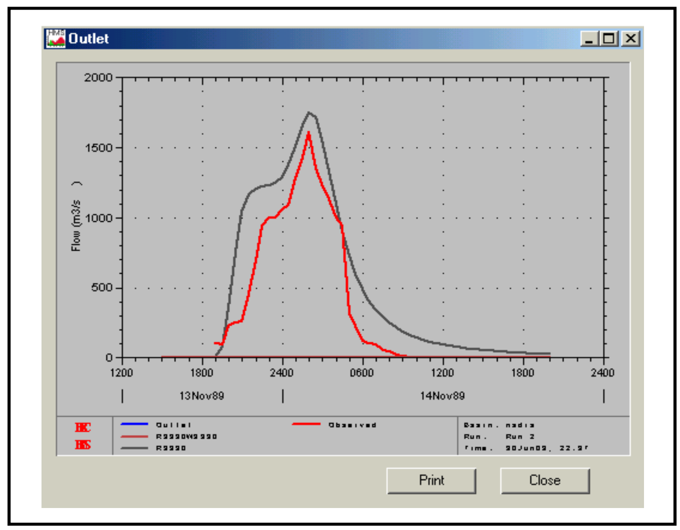

Figure 11. Computation of the flood that occurred in November 14th, 1989 using Kinematic wave within Foum Tillicht basin.

be the best way to compute average values over several years.

4. Methodology

The modeling component of this work was based on the computation of the hypsometrical distribution of the potentialities, the indicators of environmental considerations and the indicators for the future sustainable development we assume to reach in order to improve the socio-economical level and living standards. Then a series of scenarios were built based on these computations. We can put any hypsometrical distribution together to assess watershed potentialities, fit any need, measure the impact, analyze the interaction between indicators, and finally check their relations within the watershed. Moreover the optimal solutions for rational planning and management are made with the hypsometrical approach. Such approach can be performed for a small sub-watershed as well as the whole watershed.

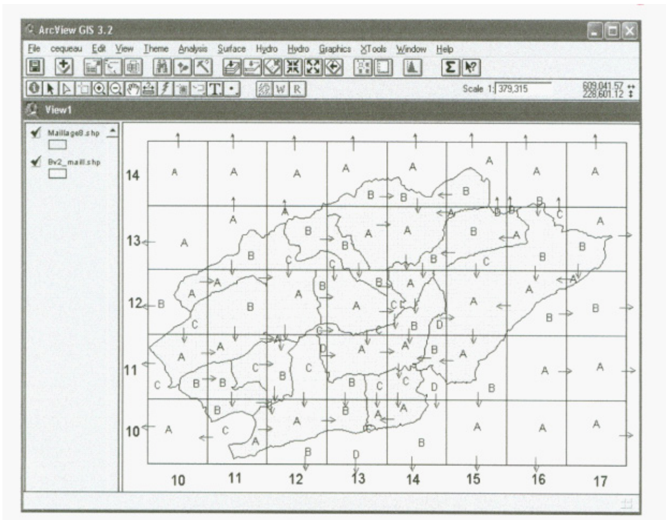

Figure 12. CEQEAU grid preparation for Foum Tillicht basin.

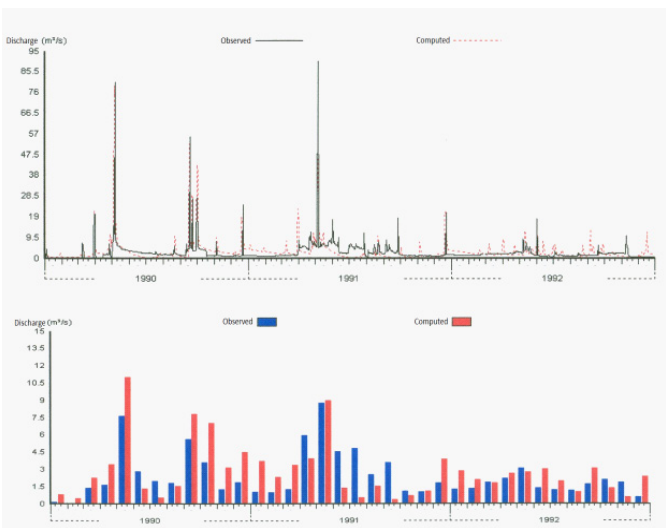

Figure 13. Visual comparison of observed and computed daily discharges of Foum Tillicht basin through CEQEAU model.

Soil erosion is simulated using the Universal Soil Loss Equation (USLE) also known as W Wischmeier model/equation (Wischmeier et al., 1978). Values of several parameters of this equation are obtained from advanced technology (RS, GIS, and DBRMS). This equation is defined as follows:

$$E = R \times K \times LS \times C \times P$$

Where E = soil losses per unit of surface (expressed on t/ha/y),
R = rainfall index,
K = soil index or erodibility factor,
L = slope length index,
S = slope's index,
C = cultural practices index and
P = conservation of soil and water index.

5. Results and Discussion

5.1. *Evaluation of the Watershed Potentialities and the Environmental Indicators*

For illustration purposes of the application, representative curves are shown for some selected natural resources are vulnerable to degradation. Curves depicting some indicators for the assessment of domestic pollution and erosion are also given.

5.1.1. Assessment of Vegetation Potentials and Livestock Food Production within the Watershed

The distribution of each vegetation species in the study watershed is shown (Figure 14). The assessment of the potential needs is done by multiplying the value of the hypsometrical curve for each species with the yield which corresponds to the analysis objective.

For example, if we are interested in supplying food for livestock, we can express the potential in livestock fodder units (FU). However, if we are interested in the assessment of the degradation caused by livestock, we need just to process the hypsometrical curve of livestock as a number for each species of livestock in cattle units (CU). Then a comparison is made between the two curves using the normal ratio of respective curves. Thus, we can find out the level of degradation on vegetal matter.

The management of livestock within the basin can easily be performed by using the protected areas in a cycling manner instead of opening the whole area to livestock at once. This rotation allows the vegetal cover to grow back and be protected. This way, we can also assess the production of meat, milk and any other animal products within the watershed.

5.1.2. Assessment of the Domestic Pollution

The domestic pollution is closely related to the population distribution indicator within the watershed (Figure 15).

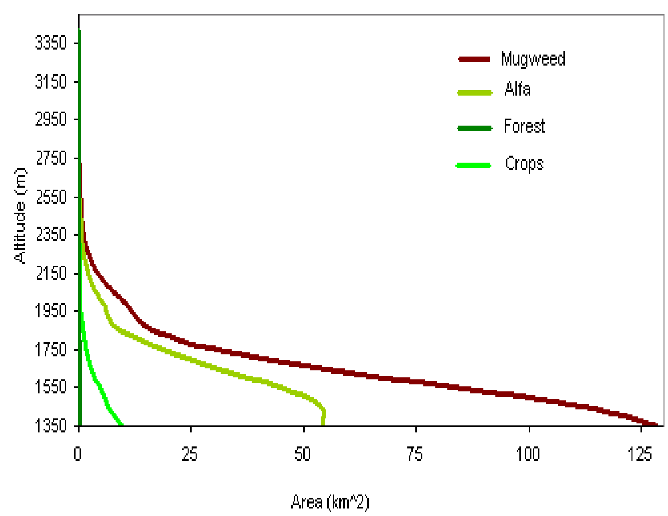

Figure 14. Hypsometrical distribution of livestock fodder zones covered by Mugweed and Alfa vegetation species.

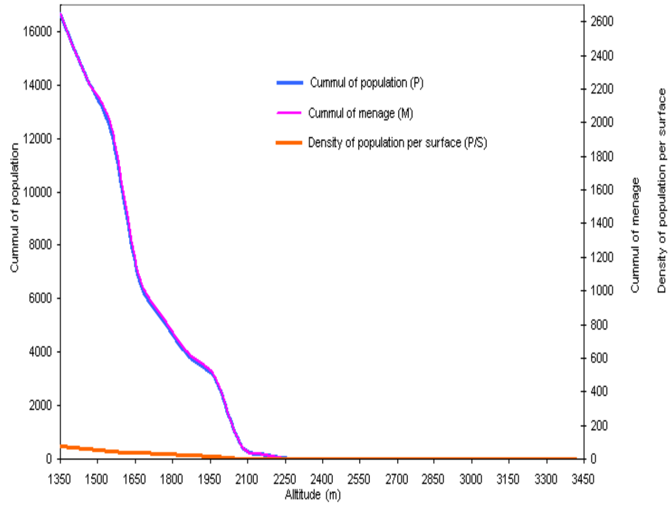

Figure 15. Hypsometrical distribution curve of inhabitants (animals) and households.

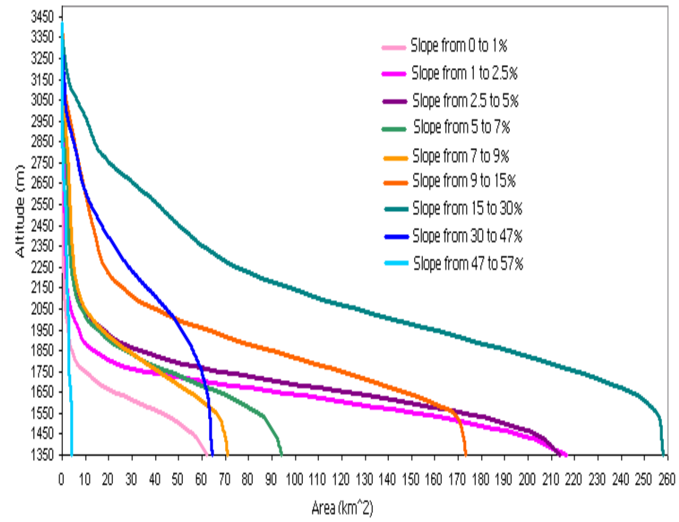

Figure 16. Slopes class distribution curve as a hypsometrical model.

Practically, we can work in generic indicators as “equivalent inhabitant” (EI) or in substances (suspended matter (SSM), oxidizable matter (OxM), organic matter (OrM)) or in any element (organic or mineral nitrogen, Phosphorus). For this kind of analysis, we need both flow discharge curves to be in the form of hypsometrical curves to take into account the contamination rate of water and the auto-cleaning rate of the discharge. The period of time (daily, monthly or yearly) is important at this level. In this case we consider annual averages.

5.1.3. Assessment of Slope Indicator for the Purpose of Erosion Study

Erosion is a natural phenomenon that degrades environment in two ways, first by soil losses and second by the dam capacity losses through the sedimentation phenomenon. To study erosion, Wischmeier model 1978 (Wischmeier et al., 1978) is used. Among the factors needed for this model, the slope index is the most difficult to obtain. The watershed information system allows us to obtain this important factor in detail. This factor is summarized in the form of hypsometrical model (Figure 16) for each class of slope. Furthermore, efficiency of the countermeasures is also analyzed.

5.1.4. Dam Sedimentation Impact to Consider

The overall rate of sedimentation in the dams of Morocco is about 70 million cubic meters per year. The total sedimentation from all of the dams of Morocco is 1600 million cubic meters. The latter accounts for 9.4% of the total storage capacity of these dams (Hasnaoui et al., 2009). For the Hassan Addakhil dam constructed downstream of the Foum Tillicht watershed, the sedimentation recorded, as presented below, and show one third is coming from Foum Tillicht watershed.

It is known that the rate of dam storage capacity loss in Morocco is increasing according to the continuous outflow of water through reservoirs. Also it is possible that the severe loss rate is resulting from increasing rate of erosion, which in turn is mainly due to the vegetal cover degradation and non appropriate agricultural practices. To maintain the storage capacity to its actual level, reservoirs need a continuous effort of dam construction.

The watershed management faces a big challenge as its aim is to regulate and preserve the quantity and quality of water at the source. This will be implemented through a certain strategy of soil conservation using either biological and/or mechanical techniques such as benches and sills in rural areas and rain water harvesting in urban areas (Hasnaoui and Touji, 2011).

The techniques used allow a certain rate of 25% erosion reduction by using trees or livestock food vegetal material, and 75% erosion reduction in case of terraces construction.

In our study according to the sites identified in §5.1.3, we can easily locate the sensitive segment or area by combining hypsometrical curves for slopes, vegetal cover and soils. Then, we obtain the right treatment by the same hypsometrical model.

5.2. Watershed Water Allocation Planning

For the purpose of the water allocation planning within a watershed, we need to compute the following components:

1. Available water at different elevations (Figure 17),
2. Storage potentialities of the watershed at different elevations (Figure 18), and
3. Water demand at different elevations for both drinking water (Figure 20) and irrigation water (Figure 21)

Storage potentialities of the watershed are shown in the hypsometrical curve (Figure 18). Automatically, site inventory (in Figure 19) for the dam is performed to calculate the storage potentialities mentioned in Figure 18.

Water demand for both drinking water and irrigation water are shown respectively in Figures 20 and 21 (Hasnaoui et al., January 2007). Potentiality of irrigation areas was determined through remote sensing (RS), GIS and DEM.

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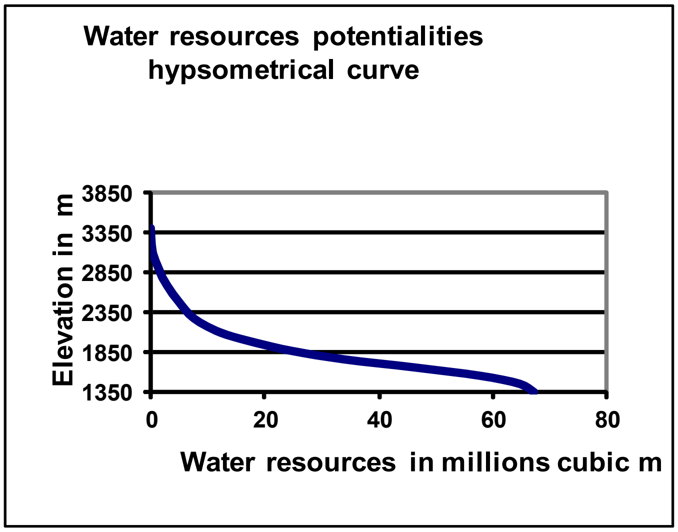

Figure 17. Hypsometrical distribution curve of water resources potentials.

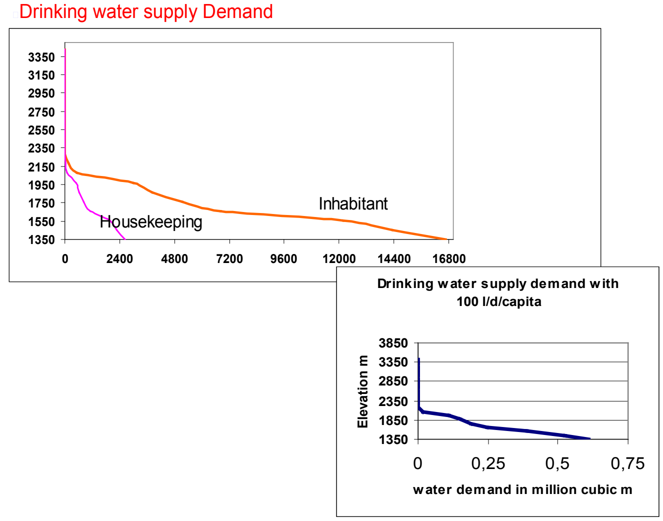

Figure 20. Hypsometrical distribution curves for drinking water demand.

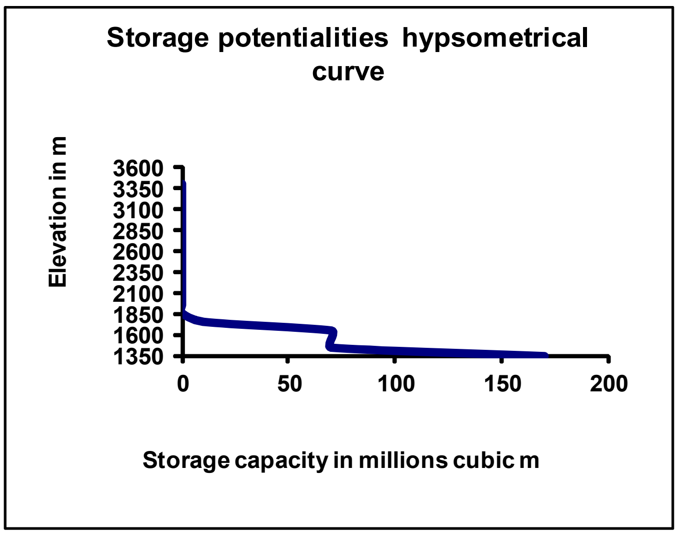

Figure 18. Hypsometrical distribution curve of storage potentialities.

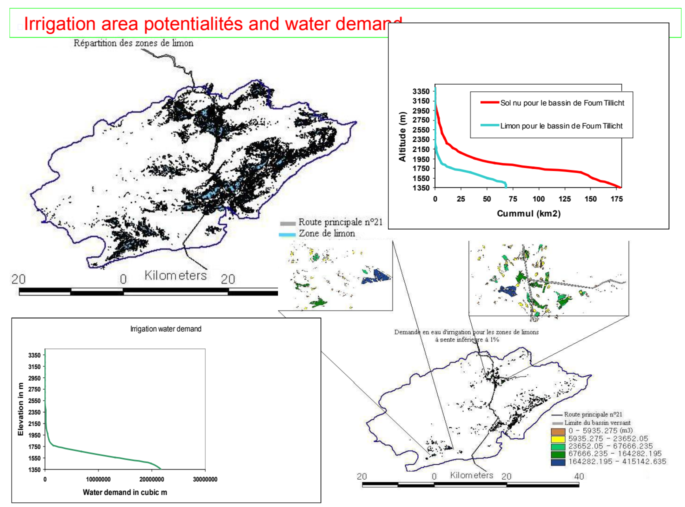

Figure 21. Automatic land selection and hypsometrical distribution curves for irrigation demand.

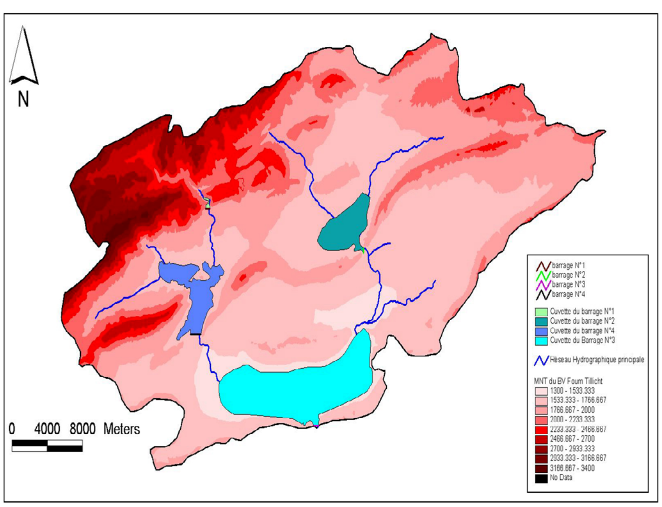

Figure 19. Results of automatic site inventory for storage potentials.

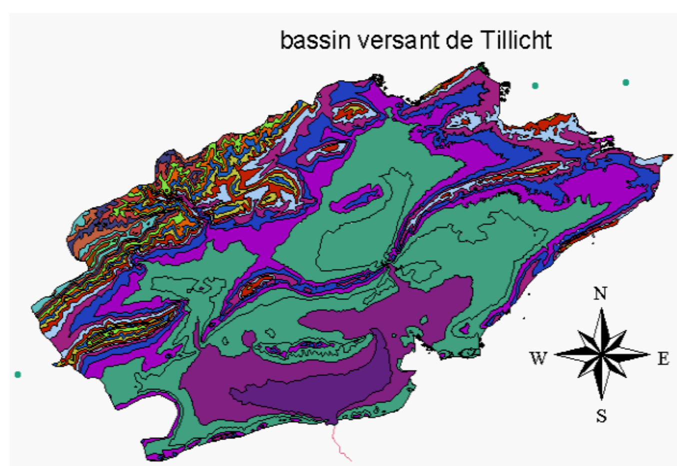

Figure 22. Integrated approach based on the hypsometrical Model (Hasnaoui and Ouazar, February 2007) and (Hasnaoui and Ouazar, November 2007).

We used an integrated approach with the environmental considerations (shown in Figure 22) by comparing the hypsometrical curves between every potentialities and indicators. Then we calculated the impact of these factors on sustainable water planning and management.

We performed classic economical calculations based on costs and direct benefits. For the case study, we used a mean annual interest rate of 7%.

6. Conclusions

With the recent development of the computer tools like GIS, RS, DBMS and the modeling software in many fields including the hydrologic and ground water topics, the study of any consideration within the watershed is becoming possible today.

Among the main conditions that allow sustainable development, making optimal projects can improve or at least preserve the environment. In our case, we have run a hypsometrical model as an integrated approach to allow optimal solutions for sustainability of watershed planning and management. Because of all the factors within the basin and the interaction between them, only an integrated approach is able to come up with the right decisions.

The application was performed on Foum Tillicht watershed which belongs to an arid zone with a great shortage of natural resources. The results are very promising, and therefore we can confidently say that the complete governance of planning any situation within the watershed can be achieved following this approach.

The complex problem was simplified and most of its aspects were dealt with in our approach. The analysis can be performed in the whole watershed as well as in any sub-watershed within the basin. This aspect of our approach increases the performance of the analysis.

7. Acknowledgments

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