The Compilation of a Geodatabase from the Hydrogeological Map of Lesotho

Luigi Simeone

SUMMARY

Geographical Information Systems can be successfully employed for the management and analysis of hydrological and geological data saved in paper maps. Maps compiled before the "digital era" can be the sources of a wealth of georeferenced data. Old maps can be digitized and data retrieved for comparison with fresh data.
The work described in this paper was carried out with data digitized from the published Hydrogeological Map of Lesotho and from the published technical notes accompanying the map.

The (digital) Hydrogeological Map of Lesotho (1994 – G. Arduino, P. Bono, P. Del Sette, Department of Water Affairs of the Kingdom of Lesotho) was imported into a GIS and georeferenced according to the geographical projection of the map. The hydrological data have been digitised and stored into a geodatabase. Data have been analysed and compared.
The hydrological data were digitized into "feature classes" (points, lines and polygons), these are:
Rainfall (Rainfall stations storing mean annual precipitation, mean annual Evapotranspiration, mean annual Effective Precipitation); Geological Dikes; Geological Formations; Rivers; Hydrological Basins; Linear Springs; Contours of Mean Annual Precipitation; Contours of Mean Annual Effective Precipitation; Hydro-stations for the measurement of Runoff; Location of rural settlements.

The amount of water (Effective Precipitation and Runoff) was calculated from 1) the contours of the Effective Precipitation Map (inset map), from 2) the punctual Rainfall stations by applying the Thiessen polygons and 3) from the observed Runoff measured at the hydro-stations (gauges) (m^3/sec). The results obtained from points 1 and 2 (calculation of Effective Precipitation) were compared to results obtained from point 3 (measured Runoff at gauge stations). In the large basin drained by hydro-station SG3 the amount of water calculated from the rainfall data with Thiessen polygons and with the contours is 35% higher the amount observed at the SG3 hydro-station: 171 mm of water (mean annual discharge) observed at the hydro-station and 232 mm of water (mean annual discharge) from Thiessen polygons built with the Rainfall stations.
The amount observed at the SG3 hydro-station/gauge is surface Runoff and it does not count the infiltration, which is one component of the Effective Precipitation. Adding at SG3 hydro-station (gauge) the estimate of infiltration, the two values (one measured at SG3 gauge hydro-station and one measured from Effective Precipitation with Thiessen Polygons and contours) will be reasonably closer. In some sub-basins located upstream to SG3 hydro-station the amount of water calculated from the rainfall data stations with Thiessen Polygons and contours is much larger of the Runoff observed at the corresponding hydro-stations (discharge gauges). It is possible that the values of Effective Precipitation calculated from contours and from Thiessen polygons were overestimated in some sub-basins (SG27, SG10, SG36) and that the Effective Precipitation values need to be re-assessed after the addition of dummy points with "fictitious" values of Rainfall (calculated with the observation and analysis of temperature, elevation, wind direction, exposure, etc.) and by the definition of a new set of Thiessen polygons to better represent the trend of the region.

In many sub-basins, hydro-stations registering Runoff (m^3/sec) are probably not enough to make a reasonable correlation with rainfall data measured at the meteorological stations.
However, the primary reason of this work was to have map data into a Geographical Information System for visualisation, cartography; to demonstrate the value of GIS as practical tool to conduct hydrologic analysis. This work is the starting point to delineate a GIS procedure for the calculation of the hydrological balance which might be replicated in different regions and contests. Further analysis can be conducted when and if more data will become available.

A follow up to this work could be the calculation of the "Inverse Hydrological Balance" (Civita 1973-75, Civita et al.1974, Civita et al. 1983, Civita et al. 1984, Civita et al. 1981, Civita et al. 1994, Civita et al. 1995), an indirect methodology to achieve the hydrological balance by a numerical model, implemented into a GIS. The values of hydrological parameters are evenly distributed and assigned to a grid of (squared) cells (the dimension of each cell not exceeding 1000 m).

In the annexes 3.1/3.2 the GIS operations are illustrated.

INTRODUCTION

This paper illustrates the work done with data digitised from the published Hydrogeological Map of Lesotho, (1994, by G. Arduino, P. Bono, P. Del Sette, Department of Water Affairs-Kingdom of Lesotho) and with data from the technical notes (P. Del Sette, G. Arduino) of the map. The technical notes were enriched with details of the work accomplished by the Ground Water Project in Lesotho (GWP) during years 1983-1994 and with hydrogeological data collected. In short, the work explained in this paper consisted in digitizing the hydrogeological themes and parameters and in the storage of these data in a geodatabase.

A geodatabase is a collection of geographical data spatially defined by a geographical projection, represented with geometries (points, lines and polygons) and numbers, stored into a geographical information system (GIS).
Data stored into a geodatabase can be accessed, analysed and updated to provide further information on hydrology, groundwater, etc. They can be retrieved and analysed with tools and functions available in the GIS.

The Kingdom of Lesotho is a small country of about 30,500 Km^2 located in Southern Africa, completely surrounded by the Republic of South Africa. It is a mountainous country, with elevation ranging from 1,300 m to 3,500 m above sea level. About one third of the Country is occupied by the Maluti Mountains, a rough and remote area of difficult access, with sparse population living in small and dispersed rural communities.

About a quarter of the Country (the western part) is flat with an average elevation of 1400 – 1700m, still high but known as the lowlands in opposition to the mountainous highlands, the Maluti, with peaks reaching almost 3,500 m.
Because of its geographical position (southern hemisphere; temperate zone) Lesotho has a distinct seasonal climate with mild and hot temperatures in summer and cold temperatures in winter. Rainfalls are concentrated in summer; frost is common in the highlands as well as snowfalls occurring erratically toward the end of winter in the lowlands and more frequently in the highlands. Thunderstorms might occur in summer with hails causing serious damage to agriculture. Lightning are rather common, and pose a serious treat to people particularly in rural areas.

One of the major natural resources of the Country is its water and this important resource was at the origin of the feasibility study of a regional and trans-boundary hydro project, the Lesotho Highlands Water Project (LHWP) which started in 1983. The first phase of the project was completed in 2002 with the construction of the Katse Dam and the Mohale Dam.
The project will transfer water from Lesotho to South Africa (Gauteng Province) in exchange of income. The system is also providing hydroelectric power to satisfy the needs of Lesotho.

The Hydrogeological Map of Lesotho was compiled with the purpose to present concisely the results obtained and the experience gained over the 11 years of implementation of the Ground Water Project (GWP) (1983-1994) (P. Del Sette, G. Arduino).
The final task of the Project was to compile the map and draw together data from different sources, predominantly collected by the Ground Water Project/Division (GWP-GWD).

The map was meant to facilitate the following tasks (P. Del Sette, G. Arduino):

- Assessment and proper exploitation of groundwater resources
- Research on new groundwater sources
- The protection of aquifers against contamination
- Input into a coordinated study of all water resources leading to the preparation and management of a Water Resources Master Plan.

It has not been intended that the map should be used to solve specific operational problems, which would require investigation on a more detailed scale (P. Del Sette, G. Arduino).

It is important to stress the overall objectives of the GWP, to cooperate with the local authorities and assisting them in the accomplishment of tasks like the drilling of boreholes for rural and village water supply, the training of personnel for the assessment and management of groundwater resources in Lesotho, the maintenance and sustainability of the facilities constructed.

The work illustrated on this paper was conducted in different steps, 1) the digital map was imported into a Geographical Information System, 2) the digital map was geo-referenced to the cartographic projection in the GIS and 3) the data of the map digitized in separate layers and stored in different geometries (points, lines, polygons, grids).
Once all the layers were digitized and saved into layers, they have been stored into a geodatabase. After this, cartographic layouts (maps) have been compiled to show the layers separately or together for observation and analysis.

In the paragraphs below, the details of the work done.

1. CARTOGRAPHY

The Hydrogeological Map of Lesotho in digital format was imported into a GIS. The map was then georeferenced according to the geographical projection printed on the map. The projection in the map (scale 1:300,000) is a TM – Clarke 1880 (Modified) 29° East of Greenwich. The geographical grid lines printed on the map have been used to geo-reference the digital map.
The cartographic projection stored in the GIS library, the Cape datum Clarke UTM 35S was modified to have the following parameters:
Name of the custom projection: Cape_UTM_hydromapLesotho29centrmerid
Projection: Transverse_Mercator
False_Easting: 500000.000000
False_Northing: 10000000.000000
Central_Meridian: 29.000000
Scale_Factor: 0.999600
Latitude_Of_Origin: 0.000000
Linear Unit: Meter
GCS_Cape
Datum: D_Cape

After having set the projection parameters in the GIS project environment, a set of points (spaced at 15' geographical coordinates interval) were digitized.
The digital map was displayed in the project map window and the grid points 15' interval of the geographical coordinate system printed on the map "linked" to the points previously digitized at intervals of 15' in the project map window having assigned to the same geographical coordinate system.

The next step was the definition of an Area of Interest (AOI) to include the spatial extension of the data into the map. The AOI was chosen to cover the entire original map.

The Hydrogeological Map of Lesotho, the digital version of the original paper map, was imported as a raster GIS object with all the points and boundaries ready to be digitally copied and stored into a geodatabase. Elevation contours and some geological details were not digitized due to the poor resolution of the map. A second more detailed version of the geology layer was digitized later - see paragraph marked with (*) after bibliography.

Here are the hydrological data digitized from the map and imported into the geodatabase:

- Rainfall stations
- Hydro-stations (gauges where the Runoff was measured)
- Contours of mean annual precipitation (Rainfall) (digitised from the scanned map of annual Rainfall)

- Contours of mean Effective Precipitation (digitised from the scanned map of effective annual mean precipitation)
- Geological dikes
- Geological formations
- Rivers
- Springs
- Location of drilled boreholes
- Hydrological basins
- Location of rural settlements

In order to simulate the regional trend of rainfall, a grid of lines ("fishnet") and its centre points with the AOI previously determined. The points were evenly spaced 500m for a total of 305793 records.

Two dataset were generated: *rainfall_grid_values_interpolation_500m* (point file - 305793 records) and the *fishnet_500m_rainfall_grid*. In the attribute table of the point file the field [mm_rainfal] was added, to store the values of Rainfall in mm. The rainfall field was populated (we had 305793 records to assign a value of Rainfall).
The point file was converted into a grid of rainfall data and compared to the contours of the Rainfall inset map of the Hydrogeological Map of Lesotho.

2. HYDROLOGY

One of the most important endeavours and objectives of a hydrogeological research is the evaluation of volumes of water available in a hydrological basin. Mapping the volumes of water of a region (surface water or underground water) is fundamental for the assessment of available water. The identification and the computation of the amount of water available are also important as an authentication of the elements and physical factors which have been recognised to identify and characterize a hydrological basin.

The calculation of the hydrological balance is the basic process to achieve this goal. The hydro(geo)logical balance is fundamental in the recognition of the different sources of water availability (surface, underground) and it will help define a project framework for the most efficient exploitation of this resource.

The hydrological balance is the solution to the following equation:

$$P = E_v + R + I$$

P is total Rainfall (mean yearly or daily, or weekly or other).
E_v is Evapotranspiration, the amount of precipitation intercepted by plants (transpiration) and the amount of water which evaporates back into the atmosphere (evaporation).
R is "surface Runoff", the amount of water (water from rainfall and/or irrigation) flowing overland and not infiltrating into the ground.
I, the infiltration, is the effective amount of water going underground and reaching the groundwater.
Runoff + Infiltration (R+I) are making the Effective Precipitation or Effective Rainfall, that is, the amount of water reaching the basin, making the volumes of Runoff surface water and groundwater. The calculations of these parameters are complex and often the volumes of water pertaining to a parameter can only be estimated indirectly from the others. For example, it is somehow difficult to separate the amount of Runoff from Infiltration, both of them making the Effective Precipitation.
In the Hydrogeological Map of Lesotho, the Effective Precipitation and the (total) Precipitation values are provided as 1) a list of points of meteorological stations where rainfall are measured and 2) in contour maps.

While data from stations are punctual data, map contouring is the representation of the model in the region characterizing the physical dimension of the rainfall. Unless we have a very dense grid of experimental data in the field, contours will be traced as a result of extrapolation.

The validity of contouring stems from different factors like the knowledge of the area, the experience of the operator, the frequency and availability of data in the region and their reliability, the complexity of the hydrology in the region.
In this work we have analysed the Effective Precipitation values from stations located in the area (*Fig. 1*).
The map of contours of Effective Precipitation (mean yearly values) was scanned and georeferenced. Contours have been digitized and saved as feature class in the geodatabase.
In the paragraphs below, the recorded hydrologic parameters are described along with the work conducted with the GIS.

2.1 Precipitation (Rainfall) and Effective Precipitation (Effective Rainfall)

Rainfall is the main source of water, a fundamental supply to underground water and surface Runoff.
It is measured in meteorological stations provided with hydrometers or pluviometers distributed across a region and monitored. The distribution and the density of the network of stations are fundamental to get a correct picture of the trend of precipitations on a yearly and seasonal timeframe.
The geomorphology of the region and its accessibility is important for the position of the stations, as well as the elevation and wind exposure.
A well-designed network of meteorological stations is essential for the collection of reliable data and for the generation of meaningful time-series which can be efficiently utilised in the appraisal of the hydrological parameters and for the calculation of the hydrological balance. The amount of rainfall is measured in mm of height of precipitation and can be referred to a day, a week, a year, an average (daily, weekly, etc).

The Hydrogeological Map of Lesotho has 90 stations displayed, with rainfall data collected during years 1984 -1993. Effective Precipitation and Precipitation have been considered for a simple analysis carried out during this work. The average (mean) Effective Precipitation is referred to a yearly mean value calculated for the 1984-1993 period.
Rainfall or Precipitation is expressed in mm of height of water, transformed into volumes of water for the area considered (km^2).

The most demanding process is to define the amount of Precipitation reaching the area, i.e., to analyse the punctual rainfall data and define an average value of Precipitation for the area considered. The data collected and recorded at the stations, are analysed to generate a model of rainfall conditions/trends of the area considered. This can be achieved in different manners and different methodologies.

The recognition of a trend or a pattern of Precipitation is generally a complex and time-consuming task.
It will take time and efforts to get a real picture of the distribution of Rainfall in the region. Experience and a good knowledge of the area are pre-requisites for the achievement of realistic results. Experts have developed different approaches.
Three methods are mentioned here: the weighted average, the Thiessen polygons and the hysoiets (contouring). The weighted average is the simple arithmetic calculation of the mean value of precipitation (mm) from the hydrometric stations for the area considered.

The Thiessen polygons are constructed from the hydrological (Rainfall) stations to create a network of polygons covering the area. Each polygon is assigned the amount of Precipitation (Rainfall) of the hydrometric station in the polygon.
Each Thiessen polygon defines an area of influence around its sample point, so that any location inside the polygon is closer to that point than to any other sample points.
Thiessen polygons are named for the American meteorologist Alfred H. Thiessen (1872-1931).

In this analysis the Thiessen method gave more precise results than weighted average measured from contours, when compared to the volume of water calculated from Runoff at the gauge hydro-stations.

The hysoiets (contours) are drawn by interpolating the values of precipitation recorded at the hydro-stations by joining the points believed to have the same value of precipitation expressed in mm (contour).
Contouring is perhaps the quickest way in not only representing the average rainfall but also in the portrayal of the trend of rainfall of the region.

Contouring will require a very good knowledge of the area and of the local physical conditions (elevation, exposure, wind direction). Without taking into account these factors, hand (and computer) contouring might lead to a gross misinterpretation of the rainfall trend in the area.
By applying contouring, it is implicitly assumed that the variation of rainfall between two hydrological stations is linear as the segment linking two stations is subdivided in evenly spaced portions to represent a constant change of rainfall.
Contouring is not the best methodology to represent rainfall trend in mountainous and impervious morphology while it works better in flat areas. When measured data are not available it is possible to find correlations between altitude and rainfall and this is why digital elevation models are much needed.

Here below some formulae, not applied in this work, where experimental data can be interpolated with the linear regression analysis (least squared method), where the deviations of rainfall values from mean rainfall assumes the minimum value (P. Celico – Prospezioni Idrogeologiche Vol. II):

$$\sum_{i=1}^{n} = (y_i' - y_i)^2 = \text{val.min.}$$

where:
y_i'= height of rainfall at altitude x_i
y_i = measured height of rainfall at the pluviometer i at altitude x_i
n = number of pluviometers

If y is rainfall and x the altitude we have:
$y_i' = b_0 + b_1 x_1$

b_0 and b_1 are calculated with the following formulas:

$$b_1 = \Sigma_1^n (y_i - m_y)(x_i - m_x) / \Sigma_1^n (x_i - m_x)^2$$

$$b_0 = m_y - b_1 m_x$$

where:
y_i = measured height (m) of rainfall at pluviometer i placed at elevation x_i
x_i = altitude (a.s.l) of pluviometer where measure of rainfall y_i was recorded
m_y = average of rainfall (m) measured at the stations (pluviometers)
m_x = average of elevation of stations (pluviometers) (a.s.l.)
n = number of stations (pluviometers)

The formula above can be calculated in the GIS, by calculating the different members of the equation in the attribute table of the rainfall station's point feature class.

The analysis carried here was applied not to the (total) Precipitation (Rainfall) but to the Effective Precipitation, which is the (total) Precipitation/Rainfall minus the amount of water going into Evapotranspiration and Evaporation.
The Effective Precipitation can be split in two parameters: "Runoff" (water flowing on the surface) and "Infiltration" (water going into the subsurface). However, the best approach would be to analyse each parameter independently: Precipitation, Evapotranspiration and Evaporation and from each of these to obtain the Effective Precipitation by subtraction.
The direct calculation of Effective Precipitation is more difficult because of the many physical factors involved and can lead to mistakes.

The objective of the work here however, was to test the GIS methods and procedures and not to undertake the complex resolution of the hydrological water balance.

The work was conducted according to the following steps: 1) georeferencing of the Effective Precipitation contour map in the GIS; 2) digitization of contours of Effective Precipitation; 3) observation and analysis of the contour trend and generation of a grid of points with values of Effective Precipitation assigned.
Values of Effective Precipitation were assigned to grid points from values of contours and from values registered at the hydrological (Rainfall) stations.
The analysis was repeated with the Thiessen polygons method.
The values of Effective Precipitation were assigned to sub-polygons resulting from the intersection of the hydrological sub-basins and Thiessen polygons. This analysis was done in hydrological sub-basins where the values of the mean Runoff (m^3/sec) were available from the Hydrogeological Map of Lesotho.

The Runoff and Effective Precipitation were compared and analysed. In the table below, results obtained from the different calculations applied to sub-basins having the Runoff measured at hydro-station points (gauges).

N° Hydro-station/Gauge	Mean Tot. disch. measured at hydrost. (mm)	Mean Tot. disch. from effective precip. contours (mm)	Mean Tot. disch. from Thiessen polygons (eff. prec. values at weather stations) (mm)	Percent above (or below - ref. to the Thiessen calculation). The value measured at the hydro-station = 100%	Runoff coefficient percent of Effective precipitation (ref. Thiessen polygons)
SG27	**89.78075**	**318.499643**	**294.979341**	**+228%**	30.43%
CG24/SG61	**158.554088**	**219.2675**	**259.238975**	**+63.5%**	61.16%
SG10/11/12	**355.832314**	**203.025007**	**717.719269**	**+101.7%**	49.57 %
SG17	374.237451	475.7845	401.555558	+7.3%	93.1%
SG18	164.53563	272.606851	221.138283	+34.40%	74.40 %
SG36	**87.547821**	**380.990445**	**316.00467**	**+260.97%**	27.70 %
SG41	168.786462	324.981162	195.221466	+15.66%	86.45 %
SG64	192.5345	200.784142	201.041454	+ 4.42%	95.76 %
SG7	**155.651717**	**242.957273**	**214.172815**	**+37.59%**	72.7 %
MG19	**224.363444**	**465.703791**	**336.754376**	**+50.09%**	66.62 %
SG45	484.817614	581.324688	570.694925	+17.71%	84.95 %
SG3	171.64573	249.714614	232.444734	+35.42%	73.84 %

(Table 1)

From *Table 1*, in bold are the values of Runoff recorded at gauge stations (hydro-stations) showing a much lower value of Effective Precipitation (compared to Runoff) obtained from Thiessen polygons.
With the Thiessen polygons the Effective Precipitation is extrapolated in the area from the Effective Precipitation values recorded at the Rainfall stations.
As introduced before, 90 Rainfall stations provided with pluviometers have been digitised from the Hydrogeological Map of Lesotho; the records of the hydrologic parameters have been registered into the GIS attribute table and the geographical location of the stations were used to construct the Thiessen Polygons (a simple and fast operation in the GIS package).
Thiessen polygons and hydrological sub-basins were geometrically intersected (with a GIS operation) and the value of the Effective Precipitation of the station falling in the Thiessen polygon assigned to the area defined by the geometrical intersection. The two results (Effective Precipitation from Thiessen and Runoff from the gauge station) were compared.

The reason to compare was to better understand the rainfall trend of the region and eventually to better model the rainfall trend with contours. The values are “mean” or average yearly values from data referring the 1930-1993 period. The match between the two values (Effective Precipitation from Thiessen and Runoff from the gauge station) were found reasonably close in a large basin, covering approximately 13,000 Km^2

and drained by the SG3 hydro-station/gauge. The match was not close in smaller upstream sub-basins (SG27, SG10/11/12, SG36, MG19, SG7, CG24/SG61).

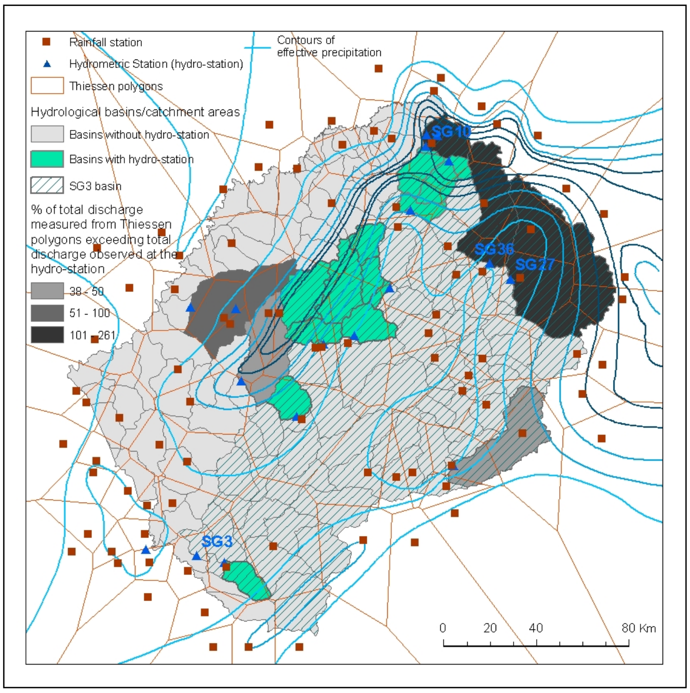


Fig.1) Red.: Rainfall Stations; Blue: hydrometric stations (gauges); Dark/green areas: Sub-basins with Effective Precipitation larger than Runoff measured at hydro-stations (gauges)

The reasons of this inconsistency between the two sets of data in the sub-basins can be explained by the poor definition in shape and numbers of the Thiessen polygons. Elevation values, land cover, land use, wind distribution, wind speed and wind frequency, landscape exposure, morphology and geology can help to position more “dummy” points with values of Effective Precipitation reflecting the real local situation.

Dummy points will help to add Thiessen polygons and will better represent the trend of Effective Precipitation in the region. As said before, the recognition of the Effective Precipitation is not an easy task, as many parameters need to be considered and a lot of experience and knowledge of the area is required.

The knowledge of the area and the physical factors mentioned above can help to find a relation eP/h (Effective Precipitation/Elevation) and the equation $y_i' = b_0 + b_1 x_1$ resolved and applied to calculate the Effective Precipitation.
As said before, and having no time constraints, it would be better to analyse Precipitation and Evapotranspiration separately and deduce the Effective Precipitation by subtraction.

The difference of values observed in the small basins *(Table 1)* could have been caused also by a different trend (contours) of Effective Precipitation in that area, or by an inaccurate evaluation of Evapotranspiration there (underestimation of Evapotranspiration values, which would portray Effective Precipitation larger than it is in reality: by lowering the amount of Effective Precipitation measured from Thiessen and/or contours in the sub-basins the two sets of values get closer).

2.2 Evapotranspiration

The Evapotranspiration, the sum of plant transpiration and evaporation is a difficult parameter to evaluate as it depends by multiple factors. Evapotranspiration was not directly considered in the analysis conducted. The values of Evapotranspiration recorded at the hydrological stations and available from the technical notes accompanying the digital Hydrogeological Map of Lesotho have been copied in the attribute table of the hydrological data stations feature class (the 90 stations displayed on the map) in the GIS.

The calculation of the *real* Evapotranspiration with experimental data is not easy. The registration of Evapotranspiration values at Hydrological stations need complex and expensive instruments difficult to maintain. In addition, results obtained with these devices are approximate and of difficult application when these experimental data need to be extrapolated in a regional trend. It is difficult to model the Evapotranspiration pattern in the area without a very dense grid of experimental data or a very good knowledge of the region observed.

Generally the calculation is done with empiric formulae, the simplest stemming from soil temperature values. The values of Evapotranspiration available from the technical notes and the digital map and recorded at the hydrologic stations were calculated with the *Turc* formula (1961).
Turc calculates the monthly mean potential Evapotranspiration, based on relation between Evapotranspiration and other climatic factors like the mean monthly temperature of the air and the solar radiation.

A first-attempt analysis of Evapotranspiration could be conducted by observing the dependency of temperature to altitude at hydrologic stations and recognise a trend of temperature/altitude for the region by applying the same methodology described for the calculation of Precipitation (linear regression analysis). Again, experience and a good knowledge of the region helps in getting a trusty representation of this parameter in the study area.

2.3 Runoff

In this analysis the value of Runoff (i.e. surface running water) was measured at gauge stations and values have been compared to Effective Precipitation.

Geology and geomorphology greatly control Runoff and Infiltration.
In Lesotho Runoff is generally high or very high and Infiltration is low or very low, except in areas with dolerite dikes. These linear and fractured features can increase the amount of water infiltrating into the ground and their recognition can help locate promising places for groundwater (borehole/water well siting).

Runoff in Lesotho was measured during field campaigns conducted yearly for the time considered. The values of Runoff available from the map (taken at gauge stations) have been considered during this analysis. They are yearly mean values of period 1984-1993.

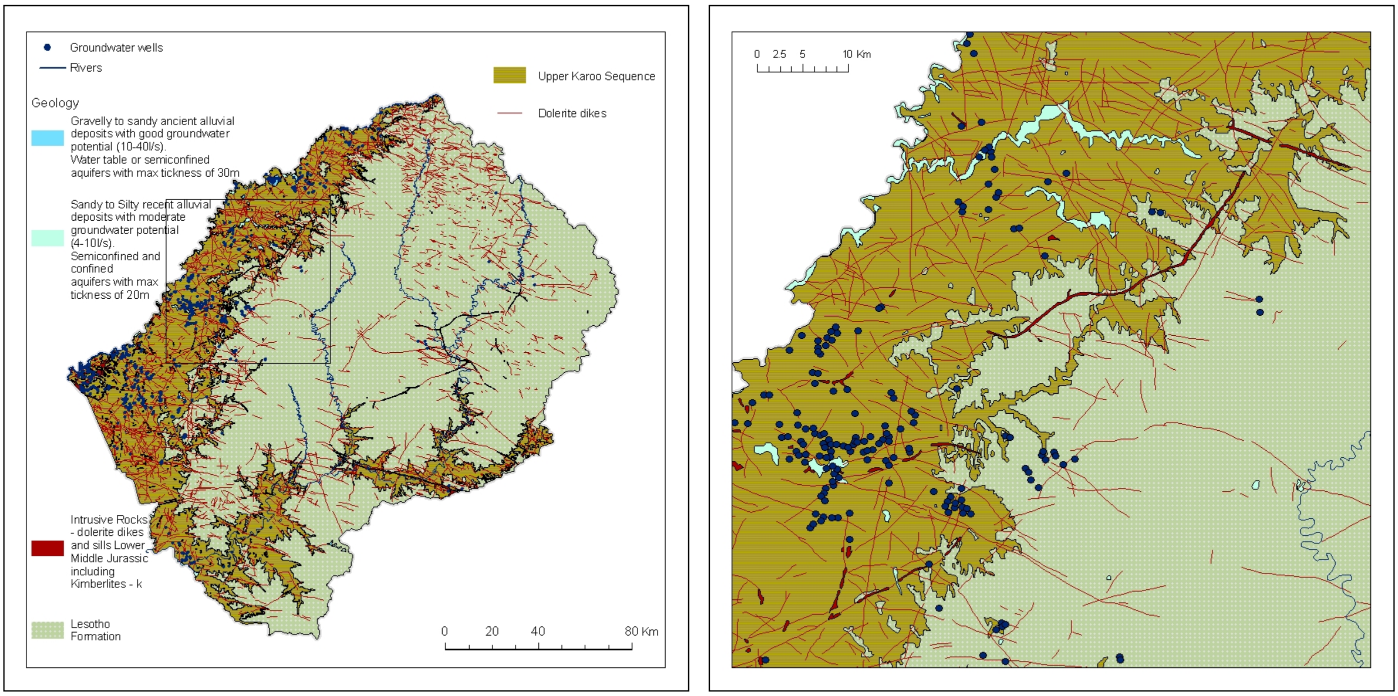
Runoff can in theory be extrapolated by mapping the geology, the morphology, the vegetation, the soil of the area. Land cover mapping is therefore a fundamental step for the characterization of Runoff in a region.

2.4 Infiltration

The value of Infiltration (the amount of water effectively going into the ground and reaching the aquifer) was not available in the hydrogeological map. The experimental measure of this parameter in the field is complex. The characterization of this parameter is often obtained by indirect methods and its value is presumed from the coefficient of (potential) Infiltration (the ratio of Infiltration and Runoff by 100).
The coefficient of Infiltration can be calculated from the geology of the region and it is expressed as the percentage (%) of total discharge which is made of Infiltration + (surface) Runoff.
In the table below, values of the Coefficient of Infiltration are reported for different lithologies (from P. Celico – Prospezioni Idrogeologiche vol. II). Within each single lithology, the value of the coefficient can change according to other factors as the slope, the land cover, the porosity, the rock weathering and fracturing.

Hydrogeological complex	Coefficient of Infiltration (%of total discharge)	Hydrogeological complex	Coefficient of Infiltration (%of total discharge)
carbonate rocks	90-100	lavas	90-100
dolomitic limestones	70-90	pyroclastic deposits	50-70
Hydrogeological complex	Coefficient of Infiltration (%of total discharge)	Hydrogeological complex	Coefficient of Infiltration (%of total discharge)
dolomites	50-70	pyroclastites and lavas	70-90
marl limestones	30-50	intrusive rocks	15-35
coarse debris	80-90	metamorphic rocks	5-20
alluvial deposits	80-100	sands	80-90
clayey-marl-sandstone deposits	5-25	clayey sands	30-50

The geology of the region and the hydrogeological complexes have been digitized from the map and stored as layers in the GIS *(Fig.2)*. The Coefficient of Infiltration can be calculated from the analysis of the lithology/geology and its values assigned to grid cells in the framework of the "Inverse Hydrological Balance" calculation (Civita 1973-75, Civita et al.1974, Civita et al. 1983, Civita et al. 1984, Civita et al. 1981, Civita et al. 1994, Civita et al. 1995) not carried out here.



(Fig.2) The Geology of Lesotho (layout compiled with datasets stored in the GIS database – March 2016)

3.1 ANNEX 1

GIS WORKFLOW – Geo-database compilation (The GIS work was carried out with the ESRI© ArcMap© Programme).

Creation of a custom map projection by modifying the parameters of the "Cape datum Clarke UTM 35S", to have the central meridian at 29°E:

Name of the custom projection: Cape_UTM_hydromapLesotho29centrmerid
Projection: Transverse_Mercator
False_Easting: 500000.000000
False_Northing: 10000000.000000
Central_Meridian: 29.000000
Scale_Factor: 0.999600
Latitude_Of_Origin: 0.000000
Linear Unit: Meter
GCS_Cape
Datum: D_Cape

The intersection points of the lat long grid (15' spaced) printed on the map have been used as spatial reference. The Hydrogeological Map of Lesotho was then imported into the GIS project and georeferenced after the generation of a graphical-input grid of points digitized at 15' interval with the xy button and placed to the corresponding intersection lat long points printed on the map.
The shapefile generated from the input graphic points is:
points_hydromapLesotho29Ecentralmeridian.shp
Cape_UTM_hydromapLesotho29Ecentralmeridian.jpg is the georeferenced raster of the Hydrogeological Map of Lesotho.

Creation of grids spaced 50m for the "Inverse Hydrological Balance" calculation. The grids have been generated but not used during the exercise.

The generation of a mesh (fishnet) spaced 50 m making 10970 segments. These lines will generate labels of over 30,000,000 (impossible to manage). Therefore the map AOI (Area of Interest) was subdivided in smaller portions.
The AOI for grid extension which was used to define the AOI of the project area has the following dimensions:

Top:	6847700.448598 m
Right:	571470.923535 m
Bottom:	6590772.985943 m
Left:	279486.930966 m

top – bottom = 256927.462655 m
256927.462655 : 20 = 12846.37313275 m

The AOI was sub-divided into smaller portions spanning 30Km (north-south) distance.
These subsets have been stored into a geodatabase (nine feature classes).
With the original digital map imported in the GIS and georeferenced the following features have been digitized and saved into the geodatabase:

- the outline of Lesotho
- the Rainfall Stations from the main map (Rainfall_stations_largemap.shp)
- the Rainfall Stations from the Rainfall inset map, which was scanned from paper map, imported into the GIS and georeferenced with the same procedure as for the main map.

This dataset was completed with other hydrological parameters from the technical notes accompanying the map:
Mean_rainfall_data_from_stations feature class - 90 points with the following data stored in the attribute table: Yearly Mean Precipitation (Rainfall), Evapotranspiration (ET), Station Number, Effective Precipitation, percent of ET over Precipitation, percent of Effective Precipitation over total Precipitation.
Hydrometric stations storing the Runoff (yearly mean Runoff in m^3/sec): *DWA_Hydrometric_Station_discharge* (m^3/sec) feature class
Dolerite Dikes (a total of 2348 dikes digitized from the main Hydrogeological Map of Lesotho at a scale 1:68000 approx.).
Geology (*geological_Lesotho_formations_boundaries* feature class). The geological units will help define the factors of the hydrogeological balance (Infiltration rate, Runoff). The geological boundary feature class was digitized in stream mode at a scale of 1: 35000 approx.

Two possible methodologies for the definition of the Coefficient of Potential Infiltration (CPI) of dolerite dikes. 1) To proceed in defining smaller AOIs, setting the grid resolution, assign CPI values to grid points. 2) To determine the density of dikes by cell/Km^2 and to apply an average value of CPI to areas displaying the same/similar density rate.
The work continued with the review of digitized geological units and dikes, to detect small polygons.
Generation of the *geological_Lesotho_formationP* feature class ("feature to polygon" function applied to *geological_Lesotho_formations_boundaries* feature class). The operation was iterated to check the presence of all of the lines making the geological polygons.
Rivers (more than 7000 segments). Rivers have been digitized mostly in stream mode. Stream mode settings have been tested and the best setting seemed to be: stream tolerance changed to 100 map units from the default value of 50. The value of group points left to the default value of 50.
Hydrological basins: *Hydrological_basins* (Feature Class). During the digitization further checking of the "*geological_Lesotho_formation_boundaries*" feature class and *dikes* feature class.
Hydrological basins were converted, after digitization, into a polygonal geometry.
Linear Springs: digitized. During digitization the Rainfall Stations, the hydrological basins and the geological formations were reviewed. Other data have been digitized: *Water Well Locations*, *Springs*, *Hydrometric Stations*, *Rural Settlements*.

3.2 ANNEX 1

GIS WORKFLOW

Analysis of hydrological parameters

Analysis of Effective Precipitation and Runoff aimed at the calculation of the water balance in some hydrological basins with data available. Here below the steps taken:
1) The Effective Precipitation map (inset map from the Hydrogeological Map of Lesotho) was imported in the GIS (*effective_precipitation_map_scanned_300dpi.jpg*)**,** geo-referenced from the point file: *Mean_rainfall_data_from_stations* (feature point), like previously done for the Precipitation (Rainfall) Map.
2) Contours of Effective Precipitation digitized from the map: *Digitized_contours_from_effective_precipitation_scanned_map* feature class
3) *Digitized_contours_from_effective_precipitation_scanned_map* feature class smoothed and densified (which means adding contours to better define the trend of Effective Precipitation values).
4) "Feature to polygon" function applied to:
1. *Digitized_contours_from_effective_precipitation_scanned_map_smoothed_densified*
2. *outline_fishnet_500m_rainfall_grid* (the AOI boundary)
Output: *polygons_to_edit_effective_precip500*
5) attribute table of *rainfall_grid_values_interpolation_500m***:** added a field [long] named [mm_eff_prec]
This will be the field to be populated after having the points of *rainfall_grid_values_interpolation_500m* selected interactively with the selected polys of *polygons_to_edit_effective_precip500*. The values to the points will be assigned according to contour values of:
Digitized_contours_from_effective_precipitation_scanned_map_smoothed_densified
6) Point to raster function:

Input Features: *rainfall_grid_values_interpolation_500m*
Value field: [mm_eff_prec]
Output raster dataset: *eff_prec_500*
Cell Assignment type: MOST_FREQUENT
Priority field: [mm_eff_prec]
Cell size: 500m
from environment→general settings→extent→same as dataset fishnet_500m_rainfall_grid

Here below steps taken to define areas of hydrological sub-basins drained by hydro-stations (gauges):

1) Copy of the "*Hydrological_basins*" polyline feature class into "*Hydrological_basins_and_catchment_areas*" feature class. This feature class will be storing the catchment areas of the hydrometric stations (*DWA_Hydrometric_Station_discharge_m3sec*). Editing of "*Hydrological_basins_and_catchment_areas*" with a code of 3 to indicate are the lines to define the catchment areas of the hydrometric stations (gauges). Code 0 is the international boundary, code 1 is the basin, code 2 is the sub-basin.
2) the *Hydrological_basins_and_catchment_areas* feature class (polyline geometry)into a polygon feature class by applying the "Feature to Polygon" function.
Input: *Hydrological_basins_and_catchment_areas*
Output: *Hydrological_basins_and_catchment_areas_poly*
The catchment area relative to the hydrometric station SG3 (the value stored in *DWA_Hydrometric_Station_discharge_m^{3}sec*), is almost the entire basin of the Senqu River. The sub-basins and catchment area drained by SG3 hydro-station have been selected and exported into a new feature class: *Hydrological_basins_and_catchment_areas_poly_of_SG3_hydrometric_station*

To calculate the amount of Runoff (m^3/year) per each catchment area, the value can be translated into mm of Runoff in the catchment area. One year is 31,536,000 sec.
The amount of Runoff read from *DWA_Hydrometric_Station_discharge_m3sec* point feature class [Mean_Annual_Discharge]) is divided by the number of sub-basins relative to the hydrometric stations.
Example of calculation applied to the SG45 hydrometric station draining catchment areas of GS14, SG10, SG12, SG11 hydrometric stations:
In the attribute table of *DWA_Hydrometric_Station_discharge_m3sec* in the field [Mean_Annual_Discharge] of selected record relative to station code SG45, we can apply the following formula: 14.38 is (Runoff of station SG45 which include also catchment areas relative to stations placed upstream: GS14, SG10, SG12, SG11) the sum of discharge expressed in m3/sec relative to GS14, SG10, SG12, SG11 drained at SG45.
The operation is applied in the field [mean_annual_disc_m3sec] of "*Hydrological_basins_and_catchment_areas_poly*" feature class. The formula is: 14.38-(3.15 +3.9 +3.73)/4 applied to the four catchments of SG45.
In the attribute table of "*Hydrological_basins_and_catchment_areas_poly*" (feature class) we add a field, type long [mm_total_discharge] to store the values of Runoff for the catchment area expressed in mm. Here below the detailed description of the procedures applied.

Analysis of SG45 hydro-station:

SG45 hydrometric station with a Mean Annual Discharge of 14.38 m^3/sec in an area of 935.377897 Km^2. This value includes also catchment areas of stations: SG10, SG11, SG12, GS14. For this analysis the value relative to GS14 won't be taken into account. The three hydro-stations SG10, SG11, SG12 will totalling an amount of 3.15+3.73+3.9+x = 10.78 + x (x the value relative at hydrometric station GS14 since we decided the value given of 39.39 m3/sec is unreliable, plus the values of the 4 catchment areas placed downstream to SG10, SG11, SG12).
The value of Runoff at SG45 station is 14.38, then: 14.38 = 10.78 + x
x will include not only the value of GS14 but also the value relative to catchment areas located downstream SG10, SG11, SG12. All together are the catchment areas of Ids No: 119, 131, 137, 138 and 134 (this 134 relative to catchment area of GS14). x = 14.38 – 10.78 = 3.6 m3/sec relative to the five catchment areas.

Analysis of SG10, 11, 12 hydro-stations:

From the "*Hydrological_basins_and_catchment_areas_poly*" feature class deleting the data relative to SG11 and SG12. Only the value of hydro-station SG10 (downstream station) is considered. Not convinced about the consistency of Mean Annual Runoff values of hydro-stations SG11 and SG12 (are larger that the value of hydro-station SG10 and would generate a discharge per unit area very large, believed to be unrealistic (1516 mm and 2197 mm).
Creation of a single feature class for the all catchment areas.
Applying the "merge" function to:
1. *Hydrological_basins_and_catchment_areas_poly* feature class
2. *catchment_area_of_Hydro-station_SG10*
output: *Hydrological_basins_and_catchment_areas_poly_all*

Analysis of catchment area of hydro-station SG3:

From the *Hydrological_basins_and_catchment_areas_poly_of_SG3_hydrometric_station* feature class we select the 31 hydro-stations placed upstream the SG3 hydro-station. We select and export them into a new feature class:
catchment_areas_with_stations_upstream_SG3 (feature class).
In the attribute table of *Hydrological_basins_and_catchment_areas_poly_of_SG3_hydrometric_station* we select again the 31 records of hydrometric stations (or hydro-stations) upstream to SG3 and in the field [Mean_Annual_Discharge] we place the values taken from:
Hydrological_basins_and_catchment_areas_poly_all.
These values will be taken into consideration in the calculation of mean annual discharge of catchment areas drained by SG3 only, since the total will be 107.2 m^3/sec. The value of hydro-station SG18 is not considered (61.4 m^3/sec).
The [Mean_Annual_Discharge] of
Hydrological_basins_and_catchment_areas_poly_of_SG3_hydrometric_station has been updated in the values referring to the 31st catchment areas (IDs: 4, 29, 32, 45, 65, 75, 81, 87, 88, 91, 93, 96, 98, 100, 101, 103, 110, 111, 113, 117, 118, 119, 126, 131, 134, 137, 138, 141, 146, 151, 153).
The Runoff drained by SG3 is 107.2 m3/sec. We will assign a constant value to the sub-basins for which we do not have any upstream hydro-station available. The sum of all the catchment areas will equal the total of 107.2 m3/sec. The sum of the 31st catchment areas is: 36.8103 m3/sec. 107.2 m3/sec - 36.8103 m3/sec = 70.3897 m3/sec. This value will be distributed evenly in the 58th catchment areas of *Hydrological_basins_and_catchment_areas_poly_of_SG3_hydrometric_station* (hydrometric station SG3 only). The value will represent a mean value for the all area of the 58 catchment areas.
We have a mean value to each catchment area (of the 58) of 1.2136 m^3/sec.

Here below we need to define areas having same Effective Precipitation values.
We will intersect the polygons resulted from contours of effective precipitation with sub-basins and catchment areas. The value of Effective Precipitation will be confronted with value taken at the gauge station, for the referred sub-basins
Intersect the
1) *polygons_to_edit_effective_precip500* with the *Hydrological_basins_and_catchment_areas_poly_all*
Intersect:
input 1:
Hydrological_basins_and_catchment_areas_poly_all
input 2:
polygons_to_edit_effective_precip500
output:
intersect_hydro_bsin_and_effect_precip
join attributes: ALL
xy tolerance: left void
output type: INPUT

Adding a new field double [sqKm_1] which will store the km^2 value relative to the new polygon generated after the intersect. The values into this new field will be calculated by dividing the values stored into the [Shape_Area] by 1,000,000 as the [Shape_Area] stores the area of polygon expressed in m^2.
Adding a new long field [mean_tot_disch_mm] into which to store the Effective Precipitation expressed in mm as calculated for the selected polygon. This mean value is the mean value calculated from the contour lines making the boundaries of the polygon. If the contours limiting the polygon are of values 350 and 400 the resulting mean (average) will be 350+400/2.

In the end, all the values of Effective Precipitation calculated and stored will be compared to the mean value of Runoff calculated at the hydro-station. We do this to verify the correctness of the contour trends as they were digitized from the printed map and added with intermediate contour lines.
We assign to each polygon generated by intersection between contours and basin boundaries the mean value of the contour lines making the boundaries of the polygon. In the end we find for the entire polygons making the basins of hydro-station SG17/SG3 a mean value from the contours [mean_tot_disch_mm] of 425.555556 mm. The mean value calculated from the hydro-station Runoff is 374.237451 mm. According to these results, the values extrapolated from the contours are a bit overestimated. We have about 12% of difference between the two values which is, given the scarce data available, reasonable. To achieve better precision we could take into account different parameters affecting the amount of Effective Precipitation, namely, the elevation data, the exposure, the slope, the geology. Elevation, exposure will influence the Rainfall while the geology, exposure, slope, soil and vegetation will influence the Runoff versus Infiltration.

The same procedure applied to the basins drained by the CG24/SG61 hydro-stations.
The mean Runoff drained measured at hydro-station CG24 (including value of SG61) is 158.554088 mm (value taken from *Hydrological_basins_and_catchment_areas_poly_all*, poly selected of IDs 80,79,90, 94 field [DischargeperUnitArea_mm]). The value of Effective Precipitation is from the contours: 229.73mm (mean value from selected polygons referring to CG24 and SG61 of intersect_hydro_bsin_and_effect_precip (15 selected records). In this case the difference is remarkable. Taking the value of 158.55 equal to 100%, the amount from contours is 44.89% higher.
In the area the trend of contours was possibly not well modelled. We should apply a much less steeply gradient.

Continuing the analysis of Effective Precipitation from contour map compared to the Runoff measured at the hydro-stations. The analysis of SG7/SG3 hydro-station shows the same trend: the value of Effective Precipitation in mm is sensibly greater than Runoff values measured at the hydro-station. In this case we have measured a mean value of 155.65mm (*Hydrological_basins_and_catchment_areas_poly_all*) of water while from the analysis of contours we have extrapolated a mean value of 218.07mm (*intersect_hydro_bsin_and_effect_precip*). In this case the value extrapolated from contours exceeds the amount from hydro-station by 40.14%.

In the analysis of hydro-station: SG64/SG3 we find these values:
mean Runoff (measured from hydro-station): 192.53mm
mean Effective Precipitation (from contour map): 213.75mm
In this case we find the value of discharge from contours exceeding by 11.03% the value measured at the hydro-station.

The analysis was than finalised by applying the weighted average calculation to Effective Precipitation from contours.
To re-calculate all the averages (mean) and apply the weighted average from the contours (isohyets),
the following calculation applied to each sub-basin and/or catchment area drained by a hydro-station:

$$\text{weighted average} = \frac{(mm_1 * S1) + (mm_2 * S2) + (mm_3 * S3) + \ldots + (mm_n * S_n)}{(S1 + S2 + S3 + \ldots + S_n)}$$

where:
mm = average mm of precipitation in the area (S) between two contour lines (isohyets)

S = the area defined by contour lines (isohyets) and basin boundaries drained by a hydro-station

In the attribute table of *intersect_hydro_bsin_and_effect_precip* feature class we add the following new fields:

[mean_tot_disch_m], double, in which we store the results of the operation:
[mean_tot_disch_mm] /1000 to get the Runoff expressed in m

[m3_year_1], double, in which we store the results of [mean_tot_disch_m] * [Shape_Area]
[Shape_Area] is expressed in m^2

We obtain the m^3 discharge of the selected polygon defined by contours and sub basin boundaries
This latter value will be divided by the sum of selected areas in m^2 from field [Shape_Area] to obtain the new Rainfall height of the selected polygon.

One more trial and a different approach by using Thiessen polygons to investigate the value of Effective Precipitation from Rainfall stations as it looks the contour values of Effective Precipitation are overestimated in some areas.
Keeping the *Digitized_contours_from_effective_precipitation_scanned_map* displayed as a reference.
Apply the Thiessen polygon function to the point file:
Mean_rainfall_data_from_stations
Output field: ALL
Output polygon feature class: *Thiessen_from_rainfall_data*
The *Thiessen_from_rainfall_data* will be intersected with the
Hydrological_basins_and_catchment_areas_poly_all feature class to generate the new intersected dataset.
Apply the intersect operation:
inputs:
1) Thiessen_from_rainfall_data
2) Hydrological_basins_and_catchment_areas_poly_all
output: *intersect_Thiessen_hydrobasins*

Adding the fields to calculate the Effective Precipitation by applying the formulas:

$$[\text{eff\_mm}] = \frac{[\text{Thiessen\_mm}] * [\text{perc}]}{100}$$

$$[\text{perc}] = \frac{[\text{Shape\_Area}] * 100}{\text{the sum of } [\text{Shape\_Area}]}$$

Summary of results are shown in *table 1*.

3.3 ANNEX 2

List of datasets stored into the geodatabase:

Layer Name	Geometry	Descript.	
wells	point	boreholes locations	
Linear_Springs	point	location of linear springs	
Mean_rainfall_data_from_stations	point	hydrologic data (Rainfall, Effective Precipitation, etc.)	
Dolerite_Dikes_featureclass	line	dolerite dikes	
DWA_Hydrometric_Station_discharge_m3sec	point	hydrometric stations (hydro-stations) with	

		Runoff	
Hydrological_basins	line	hydrological basins and sub-basins	
Hydrological_basins_and_catchment_areas_poly_all	polygon	hydrological basins and sub-basins drained by hydro-stations	
Hydrological_basins_P	polygon	hydrological basins and sub-basins	
geological_Lesotho_formationL	line	geology/hydrogeological complexes	
geological_Lesotho_formationP	polygon	geology/hydrogeological complexes	
Rivers	line		
RuralSettlements_Villages	point	location of rural settlements	

BIBLIOGRAPHY

- Rural Development and Land Reform- Republic of South Africa (http://www.ngi.gov.za/index.php/technical-information/geodesy-and-gps/datum-s-and-coordinate-systems)

- Pietro Celico – *Prospezioni Idrogeologiche* – Vol. II (Liguori Editore)

- FAO/World Water Council - TOWARDS A WATER AND FOOD SECURE FUTURE- Critical Perspectives for Policy-makers

- Department of Water Affairs, South Africa, 2012. DEVELOPMENT OF RECONCILIATION STRATEGIES FOR LARGE BULK WATER SUPPLY SYSTEMS ORANGE RIVER: SURFACE WATER HYDROLOGY AND SYSTEM - ANALYSIS REPORT - Prepared by: WRP Consulting Engineers Aurecon, Golder Associates Africa, and Zitholele Consulting. Report No. P RSA D000/00/18312/7

- Pavelic, P.; Senaratna Sellamuttu, S.; Johnston, R.; McCartney, M.; Sotoukee, T.; Balasubramanya, S.; Suhardiman, D.; Lacombe, G.; Douangsavanh, S.; Joffre, O.; Latt, K.; Zan, A. K.; Thein, K.; Myint, A.; Cho, C.; Htut, Y. T. 2015. *Integrated assessment of groundwater use for improving livelihoods in the dry zone of Myanmar*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 47p. (IWMI Research Report 164). doi: 10.5337/2015.216

- Republic of Mozambique – Ministry of Construction and Water, National Directorate for Water Affairs (DNA), *Explanatory Notes to the Hydrogeological Map of Mozambique* – scale 1:1,000,000 – 1987. Project of the Hydrogeological Map of Mozambique (sponsored by UNICEF)

- Bellwood-Howard, I.; Häring, V.; Karg, H.; Roessler, R.; Schlesinger, J.; Shakya, M. 2015. *Characteristics of urban and peri-urban agriculture in West Africa: results of an exploratory survey conducted in Tamale (Ghana) and Ouagadougou (Burkina Faso)*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 38p. (IWMI Working Paper 163). doi: 10.5337/2015.214

- INTERNATIONAL JOURNAL OF CLIMATOLOGY *Int. J. Climatol*. 18: 329–345 (1998) RAINFALL AND FLOW VARIATIONS IN THE LESOTHO HIGHLANDS - K.J. SENE*, D.A. JONES, J.R. MEIGH and F.A.K. FARQUHARSON *Institute of Hydrology*, *Maclean Building*, *Wallingford*, *Oxfordshire OX*10 8*BB*, *UK © 1998 Royal Meteorological Society*

- CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY – *The Clean Water Team Guidance Compendium for Watershed Monitoring and Assessment State Water Resources Control Board 5.1.3 FS-(RC) 2011-* Runoff Coefficient(C) Fact Sheet

- Precipitazioni - Manuali tecnici – Hoepli (http://www.manualihoepli.it/media/doc/usai_cap1.pdf)

- 2007-01 RO-i Urban Drainage and Flood Control District (from RESEARCH GATE portal: "050 Chapter 05 Runoff 2008-04 Rev.pdf")

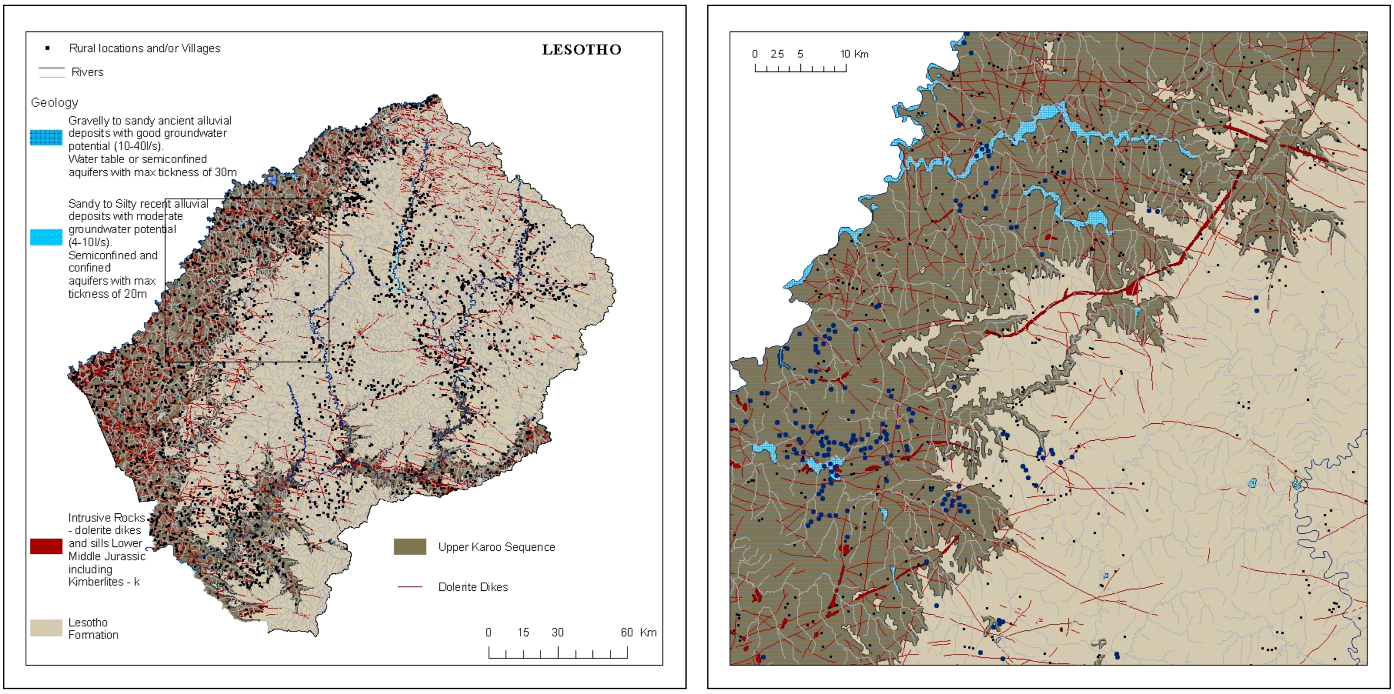
(*) In January 2017 a new and more detailed version of the Geology layer was digitized from the original paper map. The new feature class was compiled at a scale of 25K and the digitized segments assigned to classes (14 sub-domains types/classes defined in the new file geodatabase created to store the new feature classes: Lesotho_geological_map_updatedNEW_Jan17.gdb) with the following values:
1. geological boundary
2. fault
3. dike
4. sill
5. not defined or recognized boundary
6. rivers as geological boundaries
7. thrust
8. international boundary – river
9. international boundary – land
10. lakes – pounds – reservoirs
11. international boundary – dike
12. kimberlites
13. international boundary – river – dike
14. New reservoirs/artificial lakes (not existing when map published)

The river feature class was also reviewed and upgraded and some river segments have been rectified.

The database (features classes) are organized as in the following table:

Layer Name	Geometry	Descript.	file geodatabase
wells	point	boreholes locations	UPDATED_GEODATABASE_JAN17/ Lesotho_database_Mar16.gdb
Linear_Springs	point	location of linear springs	UPDATED_GEODATABASE_JAN17/ Lesotho_database_Mar16.gdb
Mean_rainfall_data_from_stations	point	hydrologic data (Rainfall, Effective Precipitation, etc.)	UPDATED_GEODATABASE_JAN17/ Lesotho_database_Mar16.gdb
DWA_Hydrometric_Station_discharge_m3sec	point	hydrometric stations (hydro-stations) with Runoff	UPDATED_GEODATABASE_JAN17/ Lesotho_database_Mar16.gdb
Hydrological_basins	line	hydrological basins and sub-basins	UPDATED_GEODATABASE_JAN17/ Lesotho_database_Mar16.gdb
Hydrological_basins_and_catchment_areas_poly_all	polygon	hydrological basins and sub-basins drained by hydro-stations	UPDATED_GEODATABASE_JAN17/ Lesotho_database_Mar16.gdb
Hydrological_basins_P	polygon	hydrological basins and sub-basins	UPDATED_GEODATABASE_JAN17/ Lesotho_database_Mar16.gdb
RuralSettlements_Villages	point	location of rural settlements	UPDATED_GEODATABASE_JAN17/ Lesotho_database_Mar16.gdb
Major_Urban_Ares	line	outline of main urban areas	UPDATED_GEODATABASE_JAN17/ Lesotho_database_Mar16.gdb
Rivers_NEWUPDATE	line	rivers network	UPDATED_GEODATABASE_JAN17/ Lesotho_geological_map_updatedNEW_Jan17.gdb

Lesotho_Geology_LINE_updated NEW	line	geology boundaries	UPDATED_GEODATABASE_JAN17/ Lesotho_geological_map_updatedNEW _Jan17.gdb
Lesotho_Geology_LINE_updated NEW_P_withlabels	polygon	geology polygons	UPDATED_GEODATABASE_JAN17/ Lesotho_geological_map_updatedNEW _Jan17.gdb
geology_labels	point	labels of geology polygons	UPDATED_GEODATABASE_JAN17/ Lesotho_geological_map_updatedNEW _Jan17.gdb
Geology_Legend	table	table with codes and description of geology units	UPDATED_GEODATABASE_JAN17/ Lesotho_geological_map_updatedNEW _Jan17.gdb
fishnet_10000m_new	line	grid of lines generated for quality control	UPDATED_GEODATABASE_JAN17/ Lesotho_geological_map_updatedNEW _Jan17.gdb
fishnet_10000m_new_Poly	polygon	polygon feature generated from the grid of lines feature	UPDATED_GEODATABASE_JAN17/ Lesotho_geological_map_updatedNEW _Jan17.gdb



(Fig.2b) The Geology of Lesotho (layout compiled with updated/reviewed datasets stored in the GIS database – Jan. 2017)

The author of this paper is a Geologist with field experience gained in different Countries since 1980. He worked in Lesotho as Hydrogeologist in 1987-1988 with the Ground Water Project. From 1998 he expanded his knowledge in the fields of Computer Mapping, Geographical Information Systems and Remote Sensing. He works as Consultant in the private sector and with International Organizations (FAO, WFP, UNICEF). More info about his working history is available at: https://www.linkedin.com/in/luigisimeone
E-mail: luigisimeone@yahoo.it