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ESTIMATION OF GROUNDWATER RECHARGE IN BUGESERA REGION (BURUNDI) USING SOIL MOISTURE BUDGET APPROACH

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(6 figures, 8 tables)

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Abstract. Groundwater recharge for Bugesera region, a potable water-scarce area in northeastern Burundi, is computed using the soil moisture budget technique. Five evapotranspiration methods including Hamon, Hargreaves, Thornthwaite and two modifications of the original Thornthwaite method are evaluated in comparison to the reference evapotranspiration method, i.e. the FAO Penman-Monteith equation for years where complete climatic data is available. The evapotranspiration calculated by the aforementioned methods along with rainfall data are used to compute the soil moisture budget. The latter is calculated using the methodology devised by Thornthwaite & Mather (1955). Recharge calculation is performed using both the Thornthwaite Monthly Water-Balance Model (henceforth TMWB model) and excel sheets wherein each term of the soil moisture budget is computed separately**.** The results of evapotranspiration calculations show that, while the other evaporation methods slightly to moderately underestimate or overestimate the potential evapotranspiration in comparison to the FAO Penman-Monteith method, Hargreaves equation aberrantly overestimates this parameter. Likewise, groundwater recharge estimated using Hargreaves' evapotranspiration is dramatically reduced in comparison to the other evapotranspiration methods. Moreover, this study clearly shows that the time discretisation used in recharge calculations has important consequences, the use of smaller time steps leading to enhanced recharge. This better corresponds to reality. Compared to the recharge values obtained on a daily basis with Penman-Monteith evapotranspiration, the TMWB model which is on a monthly basis, using Hamon's evapotranspiration, gives the best approximations of reality, with the advantage of needing much less data. The distribution pattern of monthly recharge features a bimodal pattern somewhat similar to that of the monthly rainfall with an important peak in April.

Keywords: Bugesera region, Burundi, soil moisture budget, groundwater recharge, potential evapotranspiration.

1. Introduction

Groundwater recharge is to be understood in a broad sense as the downward flow of water reaching the water table, forming an addition to the groundwater reservoir. Four mechanisms of groundwater recharge can be distinguished (Xu & Beekman, 2003, Lerner et al., 1990): (1) downward flow of water (from precipitation, rivers, canals and lakes) through the unsaturated zone reaching the water table; (2) lateral and/or vertical inter-aquifer flow, (3) induced recharge from nearby surface water bodies resulting from groundwater abstraction, and (4) artificial recharge such as from borehole injection or man-made infiltration ponds. Natural recharge by downward flow of water through the unsaturated zone is generally the most important mode of groundwater recharge. Estimation of groundwater recharge is of critical importance for safe and efficient management of groundwater resources (Fitzsimons & Misstear, 2006). The amount of water abstracted from aquifers should imperatively take into account the rate of recharge to avoid resource depletion and adverse environmental impacts (Sharma, 1986). Indeed, groundwater overexploitation may cause substantial reduction of river discharge, ground subsidence due the compaction of compressible layers, urban flooding and saline water intrusion especially in coastal environments (Jusseret et al., 2010; Zhou, 2009; Stavric, 2004; Walraevens & Van Camp, 2005; Kalf & Woolley, 2004; Alley & Leake, 2004). Furthermore, infiltrating water can carry contaminants from the polluted ground surface or the vadose zone to the groundwater reservoir. The total recharge to groundwater encompasses three major components namely direct (or diffuse) recharge, indirect (non-diffuse) recharge and localized recharge (De Vries & Simmers, 2002; Maréchal et al., 2008). Direct or diffuse recharge occurs when the precipitation falling on the land surface percolates immediately below the point of impact of the precipitation. In other words, it is the rain water added to the groundwater reservoir in excess of soil-moisture deficits and evapotranspiration. Diffuse recharge is spatially distributed and results from widespread percolation through the entire vadose zone (Sophocleous, 2004). This mode of recharge is typical of the humid climate where regular precipitations maintain the soil water content to a value close to the field capacity (Dages et al., 2009). Indirect or non-diffuse recharge results from the percolation of a fraction of runoff water through joints, depressions, and surface water bodies. This mode of groundwater recharge can be further subdivided into two categories. The first category of indirect recharge consists

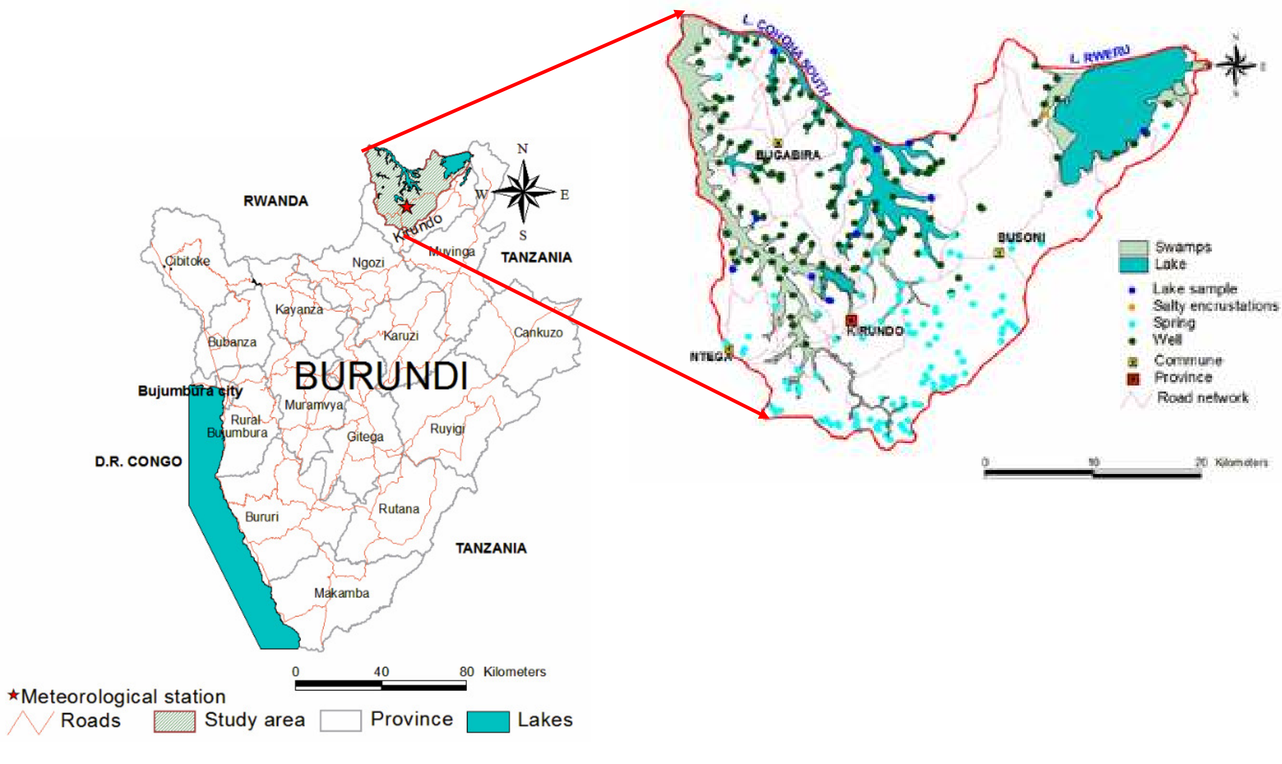


Figure 1. Location of the study area in Burundi

of percolation of water through the beds of surface water bodies (streams, rivers and lakes). The second category of indirect recharge, also called localized or focused, results from horizontal surface concentration of water in the absence of well-defined channels, such as recharge through sloughs, potholes, and playas (Sophocleous, 2004). The relative proportions of these components fluctuate according to climatic conditions, geomorphology and geology. In arid climatic regions, the most important mechanism of groundwater recharge is considered to be indirect recharge by infiltration from floods through the alluvial beds of ephemeral streams in wadi channels (Maréchal et al., 2008, Xu & Beekman, 2003, De Vries & Simmers, 2002).

Several methods for estimating groundwater recharge are nowadays in use. The use of one method or another depends on the temporal and spatial resolutions of the required estimates (Scanlon et al., 2002). These methods can be broadly separated into two groups, namely physical and chemical methods. Physical methods comprise: (1) direct method: lysimeters and seepage meters (Rushton et al., 2006; Sophocleous, 2004; Scanlon et al., 2002; Misstear, 2000); (2) the water table fluctuation method (Scanlon et al., 2002; Misstear, 2000); (3) the catchment water balance method (Chilton & Seiler, 2006, Sophocleous, 2004); (4) the zero flux plane method (Khalil et al., 2003; Scanlon et al., 2002); (5) the Darcy method (Sophocleous, 2004; Flint et al., 2002); (6) inverse modelling (Kendy et al., 2003; Prasad & Rastogi, 2001); (7) hybrid water fluctuation method (Sophocleous, 2004; Kommadath, 2000; Sophocleous, 1991); (8) empirical methods (Sophocleous, 2004; Kommadath, 2000), and (9) soil water balance models (Rushton et al., 2006; Misstear et al. 2008). Chemical methods consist of tracer methods (Sophocleous, 2004; Flint et al., 2002; Rushton et al. 2006; Misstear, 2000; Kommadath, 2000). However, although several methods are suggested for evaluation of groundwater recharge, this parameter is still the most difficult to measure as far as the evaluation of groundwater resources is concerned. Groundwater recharge is indeed a complex function of several factors and mechanisms, including meteorological conditions, soil types, land use, physiographic characteristics, depth to the water table, antecedent soil moisture, properties of the geological materials, interaction between surface and groundwater, available groundwater storage…, which may not be accurately appraised (Sophocleous, 2004). Hence, estimates of groundwater recharge are normally and almost inevitably sullied by considerable errors and uncertainties (Dages et al., 2009; Sophocleous, 2004; Fitzsimons & Misstear, 2006). The best way to minimize these uncertainties is to use a combination of several methods (Scanlon et al., 2002) as it would be time-consuming and expensive to envision a full water balance of the surface, unsaturated, and groundwater compartments (Cook et al., 1998).

In the present study, a preliminary estimate of groundwater recharge is computed using the soil moisture balance approach as a first step towards a proper evaluation as well as an efficient management of groundwater resources in Bugesera region (Burundi). This technique is recognized to be reliable and flexible for routine potential recharge estimation (Rushton et al., 2006). Indeed, direct measurements of groundwater recharge and evapotranspiration require sophisticated equipments and methodologies such as lysimeters or tracer experiments which were not available for this study. Hence, in the absence of field measurements of groundwater recharge, results from soil moisture balance calculations using five potential evapotranspiration methods (Hamon' equation in TMWB model, Hargreaves, Thornthwaite and two modifications of the original Thornthwaite equation) are compared to the recharge computed using the standard Penman-Monteith method in order to evaluate their performances. Likewise, the effectiveness of the above five PET methods is evaluated in comparison to the reference Penman-Monteith equation with a view to determining an alternative method for estimating PET which can be used when it is not possible to apply the reference evapotranspiration method due to the lack of relevant weather data. Indeed, the FAO recommends the use of the Penman-Monteith equation as the standard for estimating reference evapotranspiration and for evaluating other equations on the grounds that it better approximates direct measurements with lysimeter especially when used on a daily basis (Jabloun & Sahli, 2008, Trajkovic, 2007, Sentelhas et al., 2010).

2. Study area

2.1. Location

Bugesera is one of the numerous depressions known in the inter-lacustrine zone of East Africa. It covers an important part of northeastern Burundi and southeastern Rwanda. It is surrounded, to the North, East and South, by dissected plateaus whose quartzitic crests overhang the depression. To the West, the depression of Bugesera is bounded by the North-South trending valley of the Kanyaru river both in Burundi and Rwanda (Moeyersons, 1977). In Burundi, Bugesera region is one of the 11 natural regions and covers the northern extremity of the provinces of Muyinga and Kirundo (Fig. 1). According to local saying, this region is called "*mu Bugesera*" which literally means, "*a damned*", "*a cursed*" area, most probably due to the generalized scarcity of potable water in this area. Yet, one of the most striking features in this region is the presence of a complex of interconnected swamps in which lie several small shallow lakes, which form the head waters for the Kagera River. Apart from the swamps, the area is impressively marked by a lack of natural water springs. Hence, for domestic needs, the population heavily relies on groundwater resources which are tapped through several large diameter hand-dug wells scattered throughout the area. Moreover, the area is also remarkably marked by

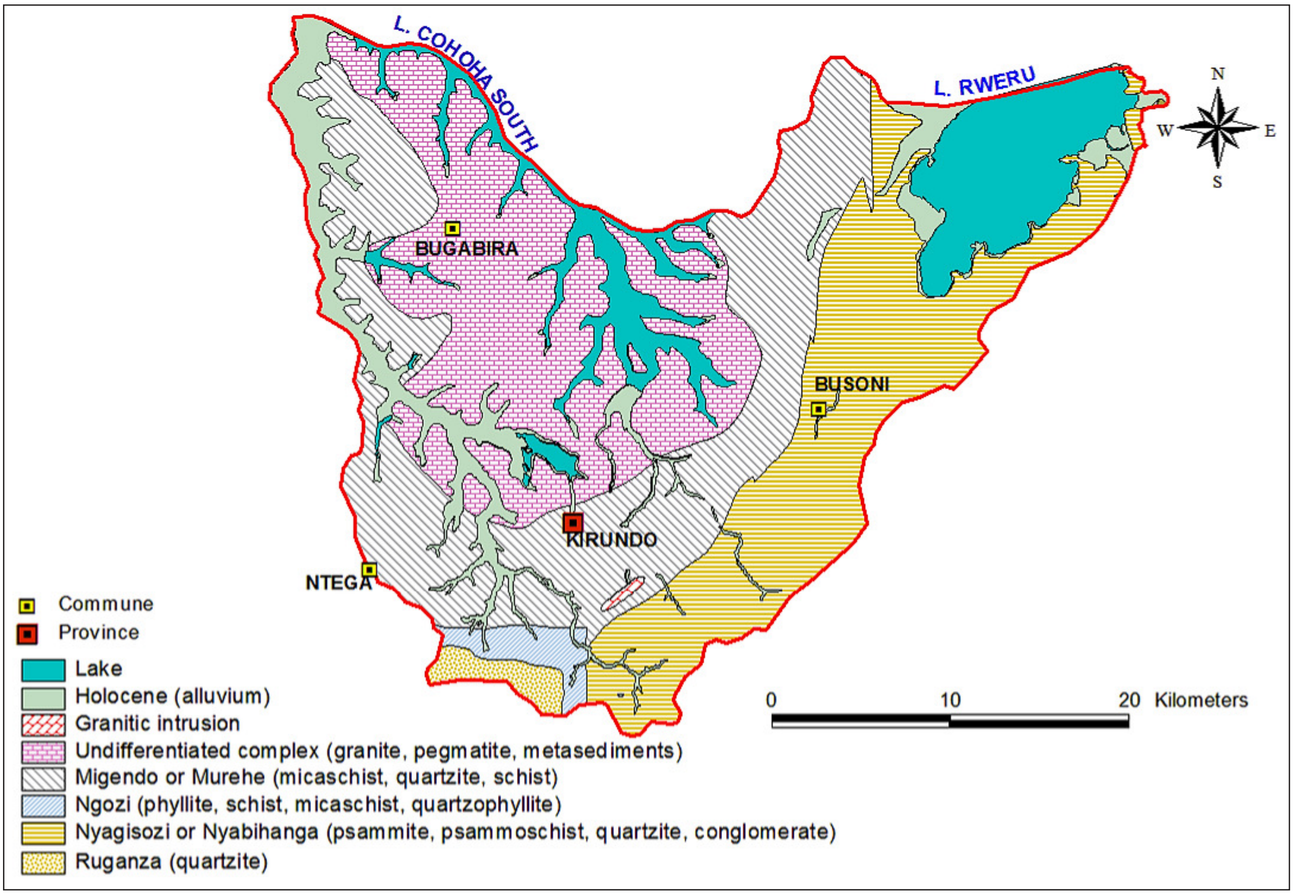


Figure 2. Geological setting of the study area (source: Cartes géologiques 1/100 000 publiées: feuilles Ngozi (1983), Muyinga (1986) and Busoni (1989))

dry conditions with a typical recurring drought, which negatively impact on the agricultural yield, thereby bringing about food shortage, which periodically compels the population to flee the region. The study area stretches between longitudes 29° 56’ 36.2’’E and 30° 23’ 38.9”E; latitudes 2° 19’ 45.2” S and 2° 41’ 37.4” S, with an area of approximately 1050.41 km^2 of which 152.80 km^2 are occupied by lakes.

2.2. Geological setting

Geologically, Bugesera region (as the major part of Burundi) belongs to the Kibaran belt, a mezoproterozoic orogenic belt in Central-Eastern Africa stretching from Katanga (Democratic Republic of Congo) to southwestern Uganda through Burundi, northwest Tanzania and Rwanda (Fernandez-Alonso et al., 2006). This prominent orogenic belt has a NE to NNE-trend from Katanga to Rwanda, where it swings to the NW before it terminates in Uganda and northern Democratic Republic of Congo. The Kibaran Belt is subdivided into two segments separated in the Democratic Republic of Congo by a palaeoproterozoic (Rusizian) basement rise in continuity with the Ubendian shear belt in western Tanzania. The two segments are defined as the “Kibaran Belt s.s.” (including the Kibara Mountains type area) and the “Northeastern Kibaran Belt (NKB)” (Tack et al., 2006; Tack et al., 2008). It is a continuous pelitic-arenaceous belt, more than 1500 km long, but which occupies a restricted fault bounded zone ranging from 100 to 500 km in width. Locally, the Kibaran belt is known as Burundi Supergroup. Rocks belonging to the Burundi Supergroup are dominated by pelitic rocks with quartzitic intercalations, which are mature and well sorted in lower levels, but progressively more immature and poorly sorted in upper levels. The Supergroup of Burundi is intruded by abundant peraluminous two micas granites and along a 350 km narrow zone by mafic and ultramafic intrusions including peridotites, norites and anorthosites (Buchwaldt et al., 2007).

Hence, apart from recent formations which consist of different soil types, widespread lateritic soils and crusts, the alluvium of valley bottoms and low terraces, all other geological formations in Bugesera region are Precambrian in age. The centre of the depression is geologically dominated by an undifferentiated complex which consists of profoundly weathered granites and pegmatites. Fresh outcrops of these lithologies are not observed and the granitic nature is only recognisable by the widespread typical granitic arena which is highly lateritised. At certain places, within this formation, quartzitic metasediments are still outcropping and may represent the relicts of the country rocks. The undifferentiated complex is girdled by metasediments which form high crests overhanging the depression. They comprise quartzites, phyllites, schists, quartzophyllites, psammites, psammoschists and conglomerates. They are grouped into six geological formations namely Migendo (or Murehe), Ngozi, Nyagisozi (or Nyabihanga) and Ruganza (Fig. 2). Where some rare rock exposures are observed, the metasediments display SW-NE trending bedding planes with high dipping angles towards the North (Kabundege, 1999). Sedimentary structures such as cross-bedding, mudcracks and tidal channels are equally observed reflecting a depositional environment of shallow water. These geological formations can be grouped into two distinct entities: (1) the western

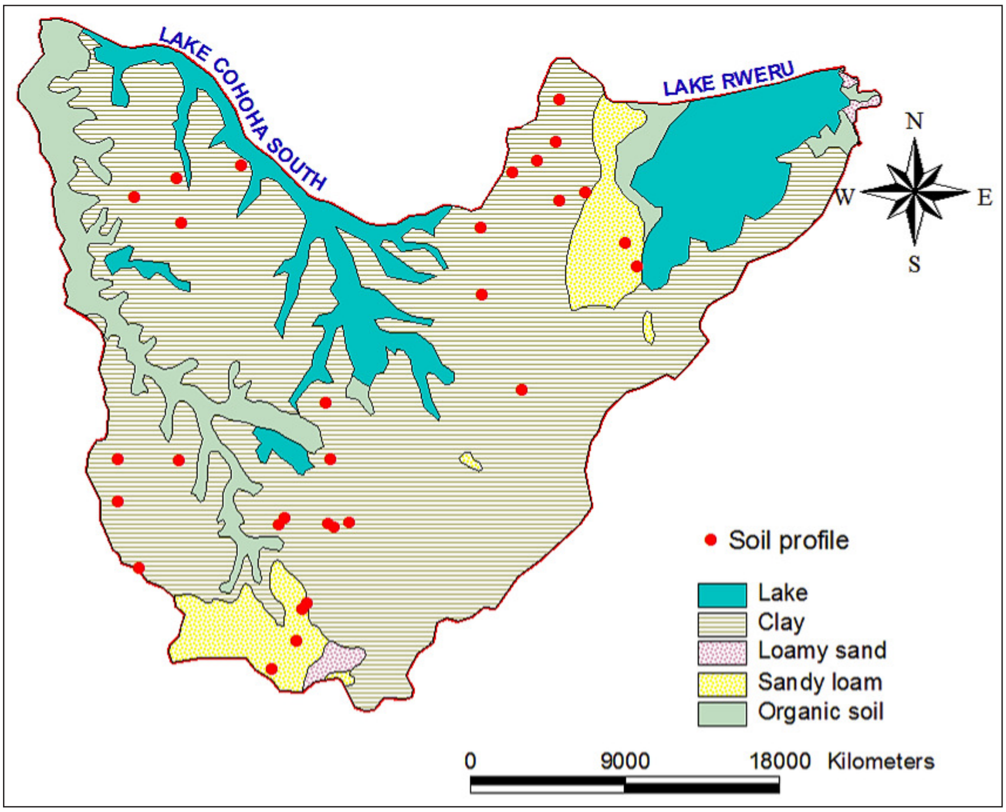


Figure 3. Soil map of the study area (source: Soil map of Burundi at 1/250000 by Sottiaux et al., 1988)

entity formed by the formations of Murehe, Ngozi, Ruganza is characterised by a complex of granitic intrusions associated with highly weathered pegmatite dikes. Some isolated outcrops of mafic rocks are observed within the formation of Ruganza. The formations belonging to this area are characterized by a high-grade metamorphism. (2) The eastern entity comprising the formation of Nyagisozi is marked by the absence of magmatic intrusions and a rather low-grade metamorphism, which increases towards the western entity.

Soils deriving from the weathering of Precambrian metasediments and magmatic intrusions are predominantly clayey as illustrated by the soil map of the study area extracted from the pedological map of Burundi (Carte des sols du Burundi au 1/250000) (Sottiaux et al., 1988) (Fig. 3). Other soil types such as loamy sand, sandy loam and organic soils are less important in terms of spatial extension. The soil classification utilised for this map is based on the principles of the INEAC (Institut National pour l'Etude Agronomique du Congo Belge) soil classification system as defined by Sys et al. (1961) and Tavernier & Sys (1965) (in Sottiaux et al., 1988 ; Tessens et al., 1991). In this soil classification system, the texture is represented by a symbol which relates to the parent materials and the proportion of the soil fraction smaller than 20 microns in size (Sottiaux et al., 1988; Tessens et al., 1991). In this study, the texture was adapted to the USDA textural classes using information from soil profiles described and sampled in the study area (Fig. 3).

2.3. Topography

According to the Africover project (FAO, 2003), four landform classes can distinguished within the study area: depression (53%), hills and mountain foot ridges (27%), alluvial plain (3%) and plateau (1%). Thus, geomorphologically, the study area mainly consists of a depression located around the so-called "*Lacs du Nord*" (northern lakes) which is characterized by a slightly undulating topography with elevations ranging between 1320 and 1500 m above mean sea level (a.m.s.l). However, some isolated peaks within the depression can reach an elevation exceeding 1600 m. This depression is surrounded, to the South and East, by a more rugged landscape, i.e. hills and mountain foot ridges, wherein crests peak up to 1800 m while the valley bottoms lie at about 1320 m a.m.s.l. This landform is dissected by numerous V-shaped valleys in which flow small perennial streams. It is important to note that most of water springs are located within this landform. The depression is dissected by an important network of large valleys where lie Holocene sediments, swamps and a number of shallow lakes. In some areas, this complex of swampy valleys and lakes is flanked by narrow alluvial plains where sediments from highlands are deposited. Underlined by the quartzitic formation of Ruganza, the small plateau is perched over the Mutumba Mountain, South-West of the study area. Overall, the elevation ranges between 1321 m and 1873 m above the mean sea level with a mean elevation of 1427 m. The highest elevations are observed to the South and East of the study area where a more rugged topography marks the transition from the Bugesera depression towards the highlands of Bweru. The percent slope varies from 0 % for flat areas including swampy valleys and lakes, to 64.06 % mostly for the steeply sloping topography to the South and East of the study area. The mean slope for the study area is 10.79 %.

2.4. Landuse

Land use in Bugesera region has tremendously changed over the last decades. What used to be natural vegetation and forests, erstwhile populated by several species of wildlife, have been progressively transformed into croplands and settled areas (Nzigidahera et al., 2005). This phenomenon has been accelerated by the arrival of populations from the densely populated provinces of Kayanza and Ngozi who, since the 1970's, came massively to seek agricultural land. Furthermore, the outbreak of the civil war in Burundi and Rwanda respectively in 1993 and 1994 has significantly contributed to the deforestation of the region. Nowadays, the land use in our study area is largely dominated by agricultural land (68.6 %) with sparse forest plantations and some relicts of natural vegetation comprising shrubs, savannah and marshy vegetation. Closed forest and natural vegetation represents respectively 0.8 % and 0.1 %, which underlines the continuing expansion of agricultural land to the detrimental of forest and natural vegetation. Water bodies and the surrounding marshland represent 15.3 % and 6.7 % of the study area. Human settlement is characterized by a dispersed pattern which is typical of most of the developing countries. The only urban settlement is the small city of Kirundo (0.1 %).

2.5. Climatological and meteorological conditions

The climatic regime for the area, as for the whole of Burundi, is characterised by distinct wet and dry seasons controlled by south-easterly and north-easterly monsoons. The longer south-easterly monsoon brings rain between about February and May while the shorter north-easterly monsoon is responsible for the rainfall occurring between September and November. There are equally two dry seasons namely the long and short dry seasons. The long dry season generally covers the months of June through August while the short dry season occurs between December and January. Average monthly rainfall for the period 1974 through 2008 shows that the long rainy season accounts for 49.40 % of the total yearly rainfall and the highest rainfall occurs in April. The short rainy season accounts for 28.13% of the total annual precipitations with the highest precipitation occurring in November. Thus, a hydrologic year in Burundi starts in September with the beginning of the short rainy season and ends in August, at the end of the long dry season. For the period 1974 through 2008, the annual precipitation varies between a minimum of 730 mm and a maximum of 1292 mm, respectively recorded in 2000 and 1985. The average annual precipitation for the whole period of records amounts to 1058.38 mm.

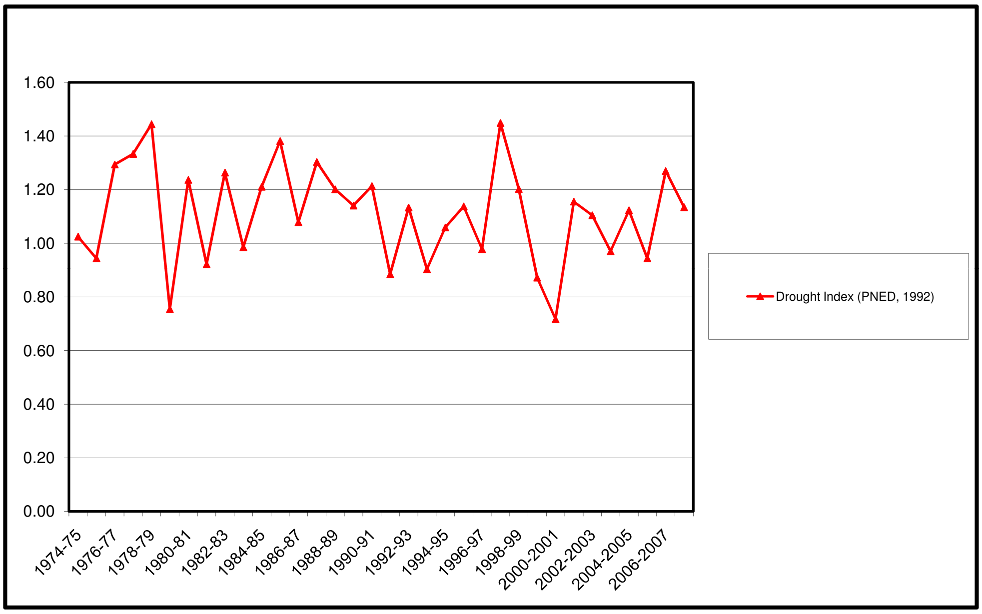


Figure 4. Annual aridity Index (PNED, 1992) for the period 1974/75-2007/2008

Air temperature in Bugesera region does not vary significantly throughout the year. The long term monthly mean varies between 20.75°C and 21.88 °C, whereas the annual average is 21.16°C.

The study area is characterized by relatively high values of relative humidity. Monthly average of maximum relative humidity varies between 96.72 % and 81.33 %. Monthly average of minimum relative humidity oscillates between 36.79 % and 59.17 %. The mean monthly relative humidity varies between a minimum of 59.48 % and a maximum of 77.20 %, with an annual average of 69.62 %.

Wind speed in our study area is rather low. The average monthly wind speed for a period of ten years (1999-2008) varies between 0.41 m/sec and 0.90 m/sec, with an average value of 0.67 m/sec. High wind speed occurs in the dry season (June-September) whereas low values of wind speed are recorded in the rainy season (November-May).

The average monthly solar radiation for a period of ten years (1999-2008) fluctuates between 15.13 MJm^2 and 12.38 MJm^2 with a mean value of 13.91 MJm^2. The maximum radiation is recorded during the long dry season (July-August) whereas two troughs are observed in April-May and in November.

Unlike to what has been always reported in literature in the last decades (e.g. UNEP/UNDP/Government of Rwanda, 2007), Bugesera region should not be classified as a semi-arid area because, with an aridity index (A.I.) of 1.10 (PNED, 1992), this region falls within the humid zone (A.I. > 0.65). On an annual basis, Fig. 4 shows that

Month	Rain (mm)	Tmax (°C)	Tmin (°C)	Max RH (%)	Min RH (%)	Wind speed (m/sec)	Radiation (MJm^2)
January	87.67	26.92	15.09	95.24	51,86	0.49	13.40
February	96.07	27.54	15.09	94.44	47,28	0.51	14.67
March	132.72	26.97	15.16	96.72	55.86	0.50	13.66
April	191.06	26.35	15.40	96.23	59.17	0.48	13.36
May	106.39	26.37	15.39	94.85	54.34	0.48	12.78
June	14.21	27.14	14.82	89.70	44.04	0.69	14.13
July	7.62	27.74	14.57	82.57	36.79	0.90	15.13
August	24.60	28.57	15.19	81.33	37.63	0.72	14.75
September	71.79	28.18	15.41	88.34	41.01	0.62	14.65
October	111.04	27.61	15.25	93.23	46.74	0.55	14.06
November	122.06	26.30	15.20	96.54	56.01	0.41	12.38
December	93.16	26.49	15.06	95.51	53.45	0.43	14.95

Table 1. Mean monthly weather parameters

aridity index for the whole period (1974/75-2007/2008) is systematically greater than 0.65, even for years of low precipitations like 1979/80 (A.I. = 0.75) and 2000/2001 (A.I. = 0.72).

3. Methodology

3.1. Data collection and processing

The climatic data used for this study come from the weather station of Kirundo, the only comprehensive meteorological station which is found within the study area, although it is slightly located at its southern periphery (Fig. 1). They were collected at the National Geographic Institute of Burundi, located in the city of Gitega, central Burundi. The meteorological parameters recorded at this station include precipitation, maximum and minimum temperature, maximum and minimum relative humidity, radiation and wind speed at 2m above the ground surface. Time series of meteorological data covering 35 calendar years, i.e. 1974-2008 were collected, although most of the time, air temperature and precipitations are the most complete time series. Time series of relative humidity, wind speed and solar radiation are only available for a period of 10 years (1999-2008). Missing data in time series were filled using arithmetic mean of adjacent days if only one record was missing. Larger gaps were filled using a linear correlation with data from the neighbouring meteorological station of Muyinga or by the long term daily means where satisfactory linear correlation could not be achieved. For the period 1999-2008, time series data including solar radiation, wind speed, maximum and minimum relative humidity are available and this enabled us to compute the potential evapotranspiration using the standard Penman-Monteith equation. Table 1 presents averages of monthly weather parameters computed for different time periods depending on the length of the time series. Averages of monthly precipitation and air temperature are calculated for a period of 35 years (1974-2008) whereas for wind speed, relative humidity and radiation, they were calculated for time periods of 10 years (1999-2008).

3.2. Potential evapotranspiration

Evapotranspiration is a key environmental parameter that deserves a lot of attention not only for efficient irrigation management but also for groundwater management schemes. Potential evapotranspiration is the amount of water that would be evaporated under an optimal set of conditions, among which is an unlimited supply of water. If the demand for water largely exceeds that which is actually available, soil moisture is depleted and plants eventually die (Ritter, 2006). There are several methods for estimating potential evapotranspiration. They are classified in five groups as: water budget (e.g. Guitjens, 1982), mass-transfer (e.g. Harbeck, 1962), temperature-based (e.g. Thornthwaite, 1957; Hargreaves & Sammani, 1982, 1985; Blaney & Criddle, 1950; Hamon, 1963), radiation-based (e.g. Priestley & Taylor, 1972; Makkink, 1957) and combination types. Penman-Monteith equation (Allen et al., 1998) is an example of methods where a combination of several weather parameters is used to estimate potential evapotranspiration. In this study, potential evapotranspiration is estimated using Hamon`s equation (Hamon, 1963) in the TMWB model (McCabe & Markstrom, 2007), Hargreaves equation (Hargreaves & Sammani, 1982, 1985), Thornthwaite equation (1957) and the *FAO Penman*-Monteith equation (Allen et al., 1998) for the years where a complete data set is available.

3.2.1. Penman-Monteith equation

The standard Penman-Monteith method for estimating evapotranspiration can be mathematically expressed as follows (Allen et al., 1998):

$$PET = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where PET = reference potential evapotranspiration (mm day^{-1}), R_n = net radiation at the crop surface (MJm^{-2}day^{-1}), G = solar heat density (MJm^{-2}day^{-1}), γ = psychrometric constant (kPa °C^{-1}), T= mean air temperature (°C), u_2 = wind speed at 2 m height (m s^{-1}), e_s= saturation vapour pressure (kPa), e_a = actual vapour pressure (kPa), e_s - e_a = saturation vapour pressure deficit (kPa), Δ= slope of the saturation vapour pressure curve (kPa °C^{-1}).

Computation of the standard Penman-Monteith equation on a monthly and daily basis was performed using the program written by Snyder & Eching (2003). Although the Penman-Monteith equation has proven to be the best method to estimate potential evapotranspiration worldwide, its major drawback is that it requires a wide variety of weather data which are not always available in many parts of the world especially in the developing world.

3.2.2. Hamon's equation

Hamon's formula for estimation of potential evapotranspiration requires only latitude, which is converted into daylength, and mean temperature, which is converted into saturated water vapor density. It can be mathematically expressed as follows:

$$PET = 13.97 * d * D^2 * W_t$$

where PET = potential evapotranspiration in mm per month, d = the number of days in a month, D = the mean monthly hours of daylight in units of 12 hours and W_t = saturated water vapour density (g m^{-3}), which is calculated based on temperature:

$$W_t = \frac{4.95e^{0.62T}}{100}$$

where T = the mean monthly temperature (°C).

In addition to its simplicity, Hamon's PET can be automatically generated through the computer-based

TMWB model developed by McCabe & Markstrom (2007).

3.2.3. Thornthwaite equation

Thornthwaite's method is a simple and empirical scheme for calculating potential evapotranspiration which requires only temperature as input data. The method is based on an exponential relationship between mean monthly temperature and mean monthly consumptive use. The Thornthwaite equation can be expressed as:

$$PET = 16\left(10\frac{T}{I}\right)^{a} \text{, 0 T} \leq 26° \leq °\text{C}$$

where I, the temperature-efficiency index or heat index, is the sum of 12 monthly values of the heat index i, and the parameter "a" is a function of I.

$$i = \left(\frac{T}{5}\right)^{1.514} \quad \text{where T = mean monthly temperature (°C)}$$

$$I = \sum_{i=1}^{12} i \quad \text{where i is the heat index per month}$$

$$a = 0.000000675I^3 - 0.0000771I^2 + 0.01792I + 0.49239$$

However, the estimates of potential evapotranspiration given by Thornthwaite equation have to be adjusted with a factor which takes into account the actual number of days in the month (28-31) and the number of daylight hours, the latter being a function of the altitude and the season. The major shortcoming of this method is that it overestimates potential evapotranspiration in humid climates while it underestimates the parameter in arid climates (Castaneda & Rao, 2005; Alkaeed et al. 2006; Pereira & Pruitt, 2004; Trajkovic & Kolakovic, 2009). Hence, several attempts have been undertaken to adjust the parameters or the constants of the empirical equation with a view to adapting the formulation to different geographical areas of interest (Castaneda & Rao, 2005; Pereira & Pruitt 2004, Trajkovic & Kolakovic, 2009). One of these modifications was introduced by Camargo et al. (1999) (in Pereira & Pruitt, 2004) who suggested to replace the monthly average temperature in Thornthwaite equation by an effective temperature empirically computed as a function of the average temperature and the daily amplitude (A= T_{max}-T_{min}). The effective temperature (T_{eff}) can be therefore mathematically expressed as:

$$T_{eff} = k(T_m + A) = 1/2k(3T_{\max} - T_{\min})$$

where T_m = mean air temperature

A value k = 0.72 was proposed as statistically the best value. However, in this study k = 0.69 and k = 0.67 have been adopted. The value k = 0.69 was found by Perreira & Pruitt, (2004) to give the best estimate of PET while k= 0.67 was determined by iteration in our study area and proved to give a good estimate of PET. In case there are two days with the same effective temperature but very different photoperiods, Camargo et al. (1999) (in Pereira & Pruitt, 2004) suggested to correct the T_{eff} parameter with the day-night length ratio as follow:

$$T^{*}_{eff} = T_{eff}\,\frac{N}{24 - N} \quad \text{with the following condition:}$$

$T_m \leq T^{*}_{eff} \leq T_{\max}$ with N = the photoperiod (daylight length) for a given day.

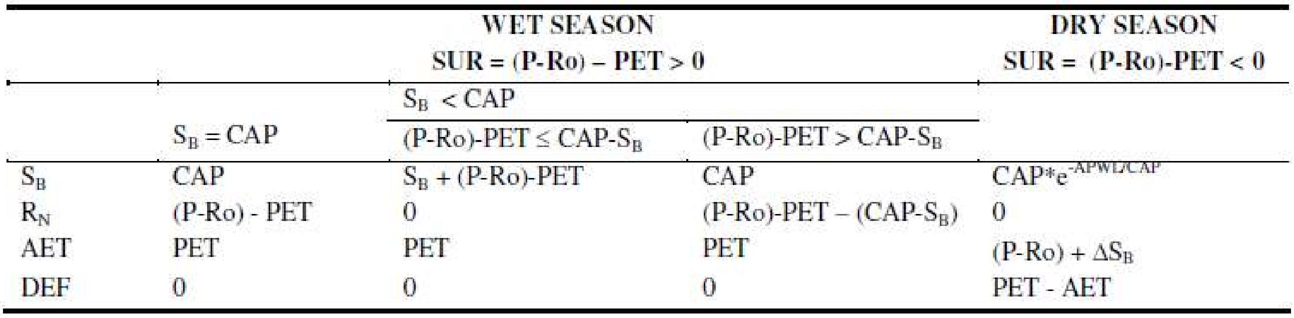
3.2.4. Hargreaves equation

Hargreaves equation is one of the simplest equations used to estimate potential evapotranspiration. It is expressed as (Hargreaves & Samani, 1985, Allen et al., 1998):

$$PET = 0.023(T_{mean} + 17.8)(T_{\max} - T_{\min})^{0.5} R_a$$

where PET = reference evapotranspiration (mm day^{-1}), T_{mean} = daily mean air temperature (ºC), T_{max} = the daily maximum air temperature, T_{min}= daily minimum air

Table 2: **Annual soil-water budget calculations** (Thornthwaite and Mather, 1957)



		WET SEASON SUR = (P-Ro) – PET > 0		DRY SEASON SUR = (P-Ro)-PET < 0
		S_B < CAP		
	S_B = CAP	(P-Ro)-PET ≤ CAP-S_B	(P-Ro)-PET > CAP-S_B	
S_B	CAP	S_B + (P-Ro)-PET	CAP	CAP*e$^{-APWL/CAP}$
R_N	(P-Ro) - PET	0	(P-Ro)-PET – (CAP-S_B)	0
AET	PET	PET	PET	(P-Ro) + ΔS_B
DEF	0	0	0	PET - AET

P = precipitation (mm); Ro = runoff (mm); PET = potential evapotranspiration (mm); APWL= accumulated potential water loss (mm) (PET – (P – RO)) accumulated for subsequent dry months; AET = actual evapotranspiration (mm); S_B = water stored in soil: S_B = CAP*e$^{-APWL/CAP}$; CAP = soil capacity (mm): maximum water content of soil, without gravitational water (= average rooting depth (mm) * water content at field capacity (in volume %)); ΔS_B = change in S_B; DEF = deficit (PET-AET) (mm); SUR = surplus ((P- Ro)-AET) (mm); R_N = natural groundwater recharge (SUR-ΔS_B) (mm).

Table 2. Annual soil-water budget calculations (Thornthwaite & Mather, 1957)

Table 3. Suggested values of water capacity for combinations of soil textures and vegetation types (Thornthwaite & Mather 1957)

Vegetation	Soil texture	Water holding capacity (% volume) = water content at field capacity	Rooting depth (m)	Water capacity of the root-zone (CAP) (mm)
Shallow rooted crops (spinach, peas, beans, beets, carrots etc.)	Fine sand	10	0.50	50
	Fine sandy loam	15	0.50	75
	Silt loam	20	0.62	125
	Clay loam	25	0.40	100
	Clay	30	0.25	75
Moderately rooted crops (corn, cereals, cotton, tobacco)	Fine sand	10	0.75	75
	Fine sandy loam	15	1.00	150
	Silt loam	20	1.00	200
	Clay loam	25	0.80	200
	Clay	30	0.50	150
Deep rooted crops (alfalfa, pasture, grass, shrubs)	Fine sand	10	1.00	100
	Fine sandy loam	15	1.00	150
	Silt loam	20	1.25	250
	Clay loam	25	1.00	250
	Clay	30	0.67	200
Orchards	Fine sand	10	1.50	150
	Fine sandy loam	15	1.67	250
	Silt loam	20	1.50	300
	Clay loam	25	1.00	250
	Clay	30	0.67	200
Mature forest	Fine sand	10	2.50	250
	Fine sandy loam	15	2.00	300
	Silt loam	20	2.00	400
	Clay loam	25	1.60	400
	Clay	30	1.17	350

temperature (º C), R_a = is the extraterrestrial radiation (MJ $m^{-2}day^{-1}$).

Many studies have pointed out the poor performances of the Hargreaves method in estimating potential evapotranspiration (Trajkovic & Kolakovic, 2009; Xu & Singh, 2002; Castaneda & Rao, 2005). This method was found to substantially overestimate the potential evapotranspiration. However, some few studies still present the method as the reliable alternative to the standard Penman-Monteith equation when there are not enough climatic data (Lopez-Urrea et al., 2006, Alkaeed et al., 2006; Allen et al., 1998)

3.3. Soil moisture balance

The different terms of the soil moisture budget are computed in two different manners: (1) automatically using the TMWB model program (McCabe & Markstrom, 2007); and (2) each term separately in an excel sheet. In both methods, the concept of water balance of the unsaturated zone (Thornthwaite & Mather, 1957) is applied. It consists of keeping track of the accumulated potential water loss (APWL) and the amount of water in the soil (S_B). Calculations to determine S_B and APWL are performed for each month or day using monthly or daily precipitation (P) and potential evapotranspiration (PET) (Table 2).

The monthly and daily climatic data, whenever available, were first rearranged into hydrologic years. As already mentioned above, a hydrologic year in Burundi starts with September, which is the beginning of the rainy season, and terminates at the end of August, i.e. the end of the dry season. This way of organizing data has the advantage of facilitating the computation of the change in soil moisture storage at the beginning of the hydrologic year, because the soil moisture storage at the end of the dry season, i.e. end of August, can be considered as completely depleted. Moreover, the concept of hydrologic year reflects the natural climatic reality in the sense that it commences with the start of the season of soil moisture recharge, includes the season of maximum groundwater recharge, if any, and terminates with the season of maximum soil moisture utilization (Ritter, 2006).

3.3.1. Actual evapotranspiration (AET)

Actual evapotranspiration (AET) is an output of water that is dependent on moisture availability, temperature and humidity. Actual evapotranspiration increases with temperature as long as there is water to evaporate and for plants to transpire. The amount of actual evapotranspiration also depends on the amount of water available which in turn depends on the water holding capacity of the soil (CAP). Practically, the concept utilised to compute the AET can be summarized in the following way: (1) in wet months, when there is enough rain, i.e. when P-Ro > PET, the AET is at its maximum value, which is equal to the PET. (2) In dry months, when there is not enough rain, i.e. when P-Ro < PET, the precipitation is no longer able to meet the evapotranspiration demand. Therefore, the unmet amount of water required by the evapotranspiration demand is progressively taken from the soil moisture storage until it is completely depleted. Hence, even if

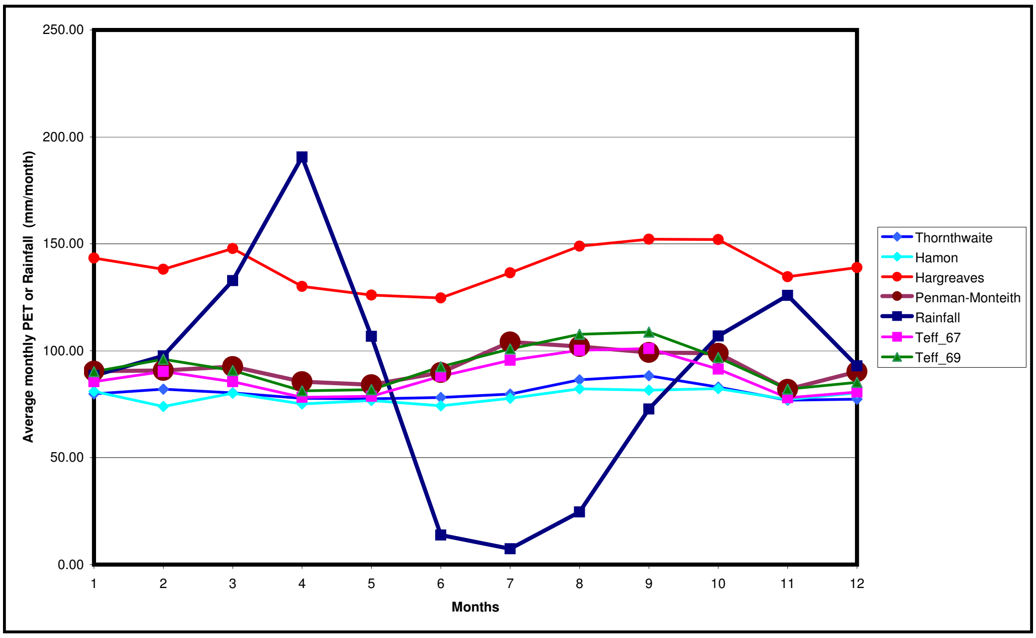


Figure 5. Comparison of PET computed using different methods

there is not enough precipitation, the AET can still approach the PET when there is still enough water within the soil moisture storage.

3.3.2. Soil moisture storage

Soil moisture storage represents the total amount of water which is held within the plants root zone. The soil texture and crop rooting depth are the main determinant factors for this parameter. A deeper rooting zone means that there is a larger volume of water stored in the soil zone and therefore a reduced amount of water going to the groundwater reservoir as recharge. The maximum amount of water that can be held within the soil zone is referred to as the field capacity. At field capacity the soil is holding all the water it can under the pull of gravity. This parameter is of capital importance in groundwater research as, conceptually, the recharge does not commence until when the moisture content exceeds field capacity. The soil water-holding capacity of the root zone is typically expressed in mm and can be obtained by multiplying the water content at field capacity by the effective depth of the root-zone. For instance, in our study area, soils deriving from the weathering of Precambrian metasediments and magmatic intrusions are predominantly clayey and the land cover is dominated by agricultural land with shallow rooted crops, mainly beans. Hence assuming a uniform water-holding capacity of 30 % over the entire the root-zone and a rooting depth of 0.25 m for shallow rooted crops, the water capacity of the root zone becomes 75 mm (Table 3). Previous studies have proposed a water holding capacity of 100 mm (TWB, Ingénieurs conseils, 1994) but no scientific explanation was given to substantiate the choice of this figure.

	PM (mm)	**TH (mm)**	**TH_Teff_69 (mm)**	**TH_Teff_67 (mm)**	**Hamon (mm)**	**Hargreaves (mm)**
January	90.43	79.84	89.85	89.56	81.09	143.79
February	90.76	82.04	96.37	90.31	73.97	138.70
March	92.60	80.28	90.90	85.51	80.00	147.04
April	85.52	77.75	81.53	78.25	75.09	130.14
May	84.10	77.53	82.08	78.69	76.69	125.42
June	89.79	78.13	92.45	88.05	74.17	123.95
July	104.14	79.74	100.77	95.53	77.70	135.70
August	101.95	86.37	107.71	100.23	82.05	148.30
September	99.15	88.27	108.64	100.99	81.40	151.41
October	98.77	83.00	96.89	91.44	82.19	151.98
November	81.92	76.87	81.99	77.99	77.03	134.62
December	90.24	77.35	85.31	80.72	80.23	139.42
RMSE	**0**	**12.83**	**4.32**	**5.77**	**15.13**	**47.33**

Table 4. Comparison of average monthly PET computed by different methods for the period 1974-2008 (PM: Penman-Monteith; Th: Thorthwaite; TH_Teff_69 and TH_Teff_67: modifications of Thornthwaite, with k = 0.69 and k = 0.67)

Calculation method	Annual average (mm)	Maximum (mm)	Minimum (mm)	Departure (%)
Penman-Monteith	1109.38	1045.50	863.35	0
Thornthwaite	967.17	1004.90	847.40	- 12.82
Thornthwaite_T_{eff}69	1114.48	1113.73	1012.03	0.46
Thornthwaite_T_{eff}67	1053.27	1206.47	1039.71	-5.06
Hamon	941.61	1131.36	989.21	-15.12
Hargreaves	1670.48	1748.48	1613.22	50.58

Table 5. Comparison of average annual PET computed by different methods for the period 1974-2008

3.3.3. *Runoff*

Surface runoff (overland flow) is the fraction of precipitation, in mm, that flows on impervious surfaces or over the land surface into surface water bodies when the infiltration capacity is exceeded and any depression has been filled with water. Surface runoff is subtracted from the precipitation to compute the amount of remaining precipitation which participates into the further steps of the soil water balance process. The runoff factor for this preliminary study was taken as 6% of the precipitation as suggested by previous studies (TBW Ingénieurs Conseils, 1994). This value is quite similar to the one proposed by Wolock & MacCabe (1999), i.e. 5 %, as the typical value of direct runoff to use in soil water balance calculations.

3.3.4. *Change in soil moisture storage*

The change in moisture storage is the amount of water which is added to or removed from what is stored. The change in soil moisture storage fluctuates between 0 and the field capacity (Ritter, 2006). The change in soil moisture storage is computed, depending on the time scale used, as the difference between the current soil moisture and the previous one. Withdrawals of water from the moisture storage take place during the dry months (PET>P-Ro) wherein a certain amount is taken to meet the evapotranspiration demand. Water is added to the soil moisture storage during the wet months (PET<P-Ro) until the water capacity of the root-zone, i.e. 75 mm in our study area, is reached. The excess moisture is drained to the groundwater reservoir in the form of groundwater recharge.

3.3.5. *Deficit*

A soil moisture deficit occurs when the demand for water exceeds the amount which is actually available. Deficits occur when potential evapotranspiration exceeds actual evapotranspitration (PET>AET). The amount of deficit is therefore calculated as the difference between potential and actual evapotranspiration *(*Ritter, 2006).

3.3.6. *Surplus (S)*

Surplus water occurs when P-Ro exceeds potential evapotranspiration, i.e. when there is more water than what is actually needed given the local environmental conditions. Surplus (SUR) is computed as the difference between P-Ro and the actual evapotranspiration (AET). The existence of surplus water indicates the possibility of groundwater recharge although the soil moisture storage must be brought to its field capacity at first.

3.3.7. *Groundwater recharge (R_N)*

Groundwater recharge occurs when there is a surplus and the soil moisture is at its field capacity. It is calculated as

Table 6: Example of the scheme used for the calculation of recharge in excel sheet for the hydrologic year 2007-2008

Month	P	P-R0	PET (PM)	(P-Ro)-PET	PET-(P-Ro)	APWL	S_B	ΔS_B	AET	DEF	SUR	R_N	Annual R_N
September 07	85.20	80.09	85.61	-5.52	5.52	211.87	4.45	0.34	80.43	5.18	-0.34	0.00	
October	115.90	108.95	88.73	20.22	-20.22	0.00	24.67	-20.22	88.73	0.00	20.22	0.00	
November	152.10	142.97	74.57	68.40	-68.40	0.00	75.00	-50.33	74.57	0.00	68.40	18.07	
December	26.20	24.63	90.58	-65.96	65.96	65.96	31.13	43.87	68.50	22.08	-43.87	0.00	
January 08	67.00	62.98	89.09	-26.11	26.11	92.07	21.98	9.15	72.13	16.96	-9.15	0.00	
February	144.00	135.36	85.39	49.97	-49.97	0.00	71.94	-49.97	85.39	0.00	49.97	0.00	
March	252.10	236.97	86.25	150.73	-150.73	0.00	75.00	-3.06	86.25	0.00	150.73	147.67	
April	143.30	134.70	81.31	53.39	-53.39	0.00	75.00	0.00	81.31	0.00	53.39	53.39	
May	58.05	54.57	89.73	-35.16	35.16	35.16	46.93	28.07	82.64	7.09	-28.07	0.00	
June	52.60	49.44	89.47	-40.03	40.03	75.19	27.52	19.41	68.85	20.62	-19.41	0.00	
July	2.40	2.26	100.82	-98.56	98.56	173.75	7.40	20.13	22.38	78.43	-20.13	0.00	
August	9.50	8.93	99.39	-90.46	90.46	264.21	2.21	5.18	14.11	85.28	-5.18	0.00	**219.13**

P = precipitation (mm), P-Ro = precipitation - runoff (mm), PET = potential evapotranspiration (mm), S_B = soil moisture storage (mm), ΔS_B = change in moisture storage (mm), AET = actual evapotranspiration (mm), DEF = deficit (mm); R_N = natural recharge (mm), APWL= accumulated potential water loss.

Table 6. Example of the scheme used for the calculation of recharge in excel sheet for the hydrologic year 2007-2008

Table 7. Scheme used for computation of groundwater recharge in TMWB model for the hydrologic year 2007-2008

Month	PET (mm)	Precipitation (mm)	Runoff Ro (mm)	(P-Ro)-PET (mm)	Soil moisture storage (mm)	AET (mm)	AET-PET (mm)	Snow storage (mm)	Surplus (mm)	Yearly Recharge (mm)
Sept-2007	81	85.20	5.11	-0.9	1.50	80.1	0.9	0	0	
Oct-2007	83.3	115.90	6.95	25.70	27.20	83.3	0	0	0	
Nov-2007	79	152.10	9.12	63.90	75	79	0	0	16.2	
Dec-2007	83.60	26.20	1.57	-59	16	83.6	0	0	0	
Jan-2008	83.20	67	4.02	-20.20	11.70	67.3	15.9	0	0	
Feb-2008	74.4	144	8.64	61	72.60	74.4	0	0	0	
Mar-2008	78.3	252.10	15.13	158.70	75	78.3	0	0	156.3	
Ap-2008	76.4	143.30	8.60	58.30	75	76.4	0	0	58.3	
May-2008	79.3	58	3.48	-24.70	50.3	79.3	0	0	0	
Jun-2008	73.7	52.60	3.16	-24.30	34	65.7	8	0	0	
Jul-2008	78.8	2.40	0.14	-76.50	0	36.3	42.5	0	0	
Aug-2008	86.1	9.50	0.57	-77.20	0	8.9	77.2	0	0	**230.8**

	Monthly basis						**Daily basis**	
Hydrologic year	**HS**	**TH**	**TH_69**	**TH_67**	**Hamon (TMWB)**	**PM**	**HS**	**PM**
1974-75	0.00	168.77	111.08	128.41	168.00			
1975-76	0.00	98.58	41.33	51.68	92.60			
1976-77	0.00	296.91	114.69	155.86	300.50			
1977-78	42.19	407.79	283.47	311.45	401.50			
1978-79	66.77	440.85	250.95	288.10	421.80			
1979-80	0.00	24.49	24.75	41.21	37.90			
1980-81	59.32	246.35	230.96	251.64	251.00			
1981-82	0.00	113.94	78.42	102.84	107.80			
1982-83	19.68	343.23	309.98	337.83	331.50			
1983-84	0.00	139.20	106.54	132.93	130.70			
1984-85	154.09	325.30	282.69	301.67	325.30			
1985-86	130.39	404.10	338.67	372.66	410.30			
1986-87	0.03	230.36	112.50	154.01	236.60			
1987-88	89.14	371.12	324.81	344.63	353.80			
1988-89	0.00	187.86	159.32	184.73	191.40			
1989-90	0.00	261.34	146.40	176.07	253.80			
1990-91	52.14	318.02	289.21	302.77	329.70			
1991-92	0.00	94.20	84.79	99.57	94.70			
1992-93	0.00	245.58	188.59	223.71	241.00			
1993-94	0.00	86.12	54.89	85.64	164.20			
1994-95	12.93	208.59	179.14	208.24	204.00			
1995-96	62.99	284.11	230.33	258.79	264.60			
1996-97	55.31	187.05	173.13	188.37	186.10			
1997-98	211.35	586.28	543.69	582.90	622.30			
1998-99	0.00	45.51	34.78	42.86	45.40			
1999-2000	0.00	85.16	29.01	50.27	69.40	28.72	18.87	128.61
2000-2001	0.00	2.45	0.00	1.67	0.00	0.00	13.45	107.04
2001-2002	20.12	280.69	222.91	265.72	293.80	248.25	200.18	428.81
2002-2003	63.37	215.79	160.31	187.81	230.90	210.26	205.40	376.31
2003-2004	22.05	184.12	208.61	226.90	211.70	185.04	136.02	288.29
2004-2005	0.01	241.32	218.76	252.24	260.60	213.62	132.57	373.04
2005-2006	35.68	174.44	157.37	172.97	176.20	144.15	141.81	261.31
2006-2007	72.74	348.08	349.69	372.06	355.20	305.91	263.50	455.90
2007-2008	42.35	245.53	224.45	248.58	230.80	219.13	153.78	336.33
Average all data	**35.67**	**232.15**	**184.30**	**209.02**	**235.15**	**172.79**	**140.62**	**306.18**
Average 1999/2000-2007/08	**28.48**	**197.51**	**174.57**	**197.58**	**203.18**	**172.79**	**140.62**	**306.18**

where HS = Hargreaves PET equation; TH = original Thornthwaite PET equation; TH_69 and TH_67 modifications of Thornthwaite PET equation with k = 69 and k = 67 respectively; Hamon = Hamon PET equation, PM = Penman-Monteith PET equation

Table 8. Results of annual groundwater recharge calculation using potential evapotranspiration estimated using different methods

the remaining surplus after the soil moisture has been brought to field capacity.

4. Results and discussion

4.1. Potential evapotranspiration

Fig. 4 represents the comparison between the monthly average values of potential evapotranspiration calculated using six methods namely Hamon, Thornthwaite, two modifications of the Thornthwaite method (k = 0.69 and k = 0.67), Hargreaves and Penman-Monteith for years where all required climatic parameters are available (Table 4). In absence of direct measurements of evapotranspiration, the Penman-Monteith equation was used as a criterion to evaluate the performances of the five other PET methods as recommended by FAO (Allen et al., 1998, Xu & Sing, 2002, Castaneda & Rao, 2005; Jabloun & Sahli, 2008, Gonzalez et al., 2009, Sentelhas et al., 2010). A visual inspection of Fig. 6 clearly shows that the Hargreaves method aberrantly overestimates the potential evapotranspiration whereas the Hamon and Thornthwaite methods slightly underestimate it with respect to the standard Penman-Monteith equation. It is also interesting to note that the modifications of the Thornthwaite method using k = 69 and k = 67, on the average, slightly overestimate and underestimate the potential evapotranspiration respectively as compared to the standard Penman-Monteith method. An evaluation of the performances of the different PET methods in comparison to the standard Penman-Monteith method was made through the computation of the Root Mean Square Error (RMSE) between the average monthly PET estimated by Penman-Monteith equation and other methods (Table 4). With a RMSE error of 47.33 mm/month, Hargreaves method appears to be the worst performing method for PET estimation in our study area, while the modification of the Thornthwaite equation with k = 0.69 gave the lowest RMSE (RMSE = 4.32 mm/month), thereby indicating a good performance of the method. It can also be noted that the Thornthwaite method performs slightly better (RMSE = 12.83 mm/month) as compared to Hamon`s method (RMSE = 15.13 mm/month). Fig. 5 also indicates that, when PET is calculated with Hargreaves method, surplus and eventually recharge occur only during the long rainy season (rainfall > PET only in April), while with the other PET methods, surplus can occur both in the short and the long rainy seasons, thereby leading to an enhanced recharge.

Table 5 shows the annual average of the potential evapotranspiration calculated using the different methods over the period 1974-2008. It can be observed that the Hargreaves method overestimates the potential evapotranspiration by more than 50 %, whereas Hamon and Thornthwaite methods underestimate it by 15.13 % and 12.82 % respectively, with respect to reference PET computed by the standard Penman-Monteith equation. On the other hand, it is also interesting to note that the modification of the original Thornthwaite method using the effective temperature instead of the mean air temperature seems to give good results. Indeed, by using these modifications with k= 0.69 and k = 0.67, the PET is respectively overestimated by 0.46 % and underestimated by 5.06 % with respect to the reference PET estimated by the Penman-Monteith method. These results confirm the poor performance of Hargreaves method in estimating PET as already reported by several previous studies (Trajkovic & Kolakovic, 2009; Xu & Singh, 2002; Castaneda & Rao, 2005; Jabloun & Sahli, 2008). Moreover, such aberrant PET results could be expected for our study area due to relatively high relative humidity (annual average 69.62%). Indeed, Allen et al. (1998) highlighted the tendency of Hargreaves equation to overpredict PET under conditions of high relative humidity.

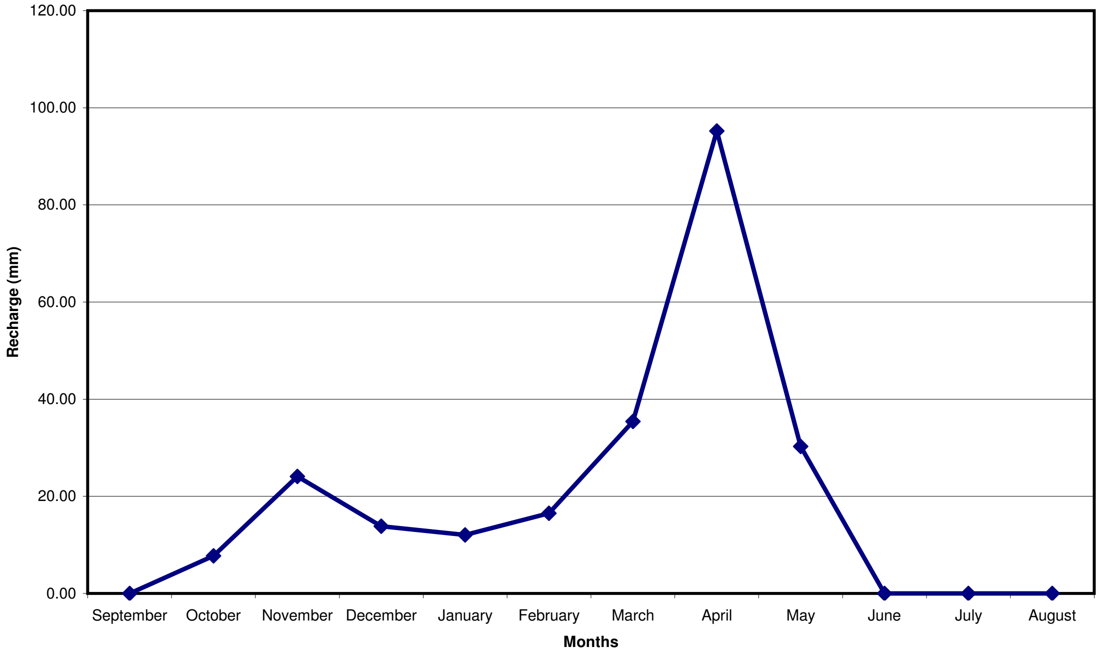


Figure 6. Monthly average recharge for the period 1974/75-2007/2008

4.2. Ground water recharge

Tables 6 and 7 present the concept utilised to compute the groundwater balance based on different PET methods. The Hamon equation for estimation of the PET is embedded into the TMWB model (McCabe & Markstrom, 2007). Thus, while the TMWB model program generates automatically the potential evapotranspiration and recharge (surplus), the computation of the soil moisture balance using other evapotranspiration methods through excel sheets is rather fastidious and time-consuming. Similarly to the evapotransipiration, groundwater recharge calculated using the Penman-Monteith evapotronsipiration is used as reference to evaluate the performances of the other five evapotranspiration methods in soil moisture balance. The results of calculations of annual groundwater recharge are given in Table 8. For the period 1999/2000-2007/2008, the average annual recharge computed on a monthly basis using the Penman-Monteith PET is equal to 172.79 mm. By using the evapotranspiration calculated using Hargreaves evapotranspiration, for the same period, the average annual groundwater recharge drastically drops to 28.48 mm; which represents only 16 % only of the one computed using Penman-Monteith PET. On the other hand, with the PET estimated by the modifications of Thornthwaite method with k = 0.69 and k = 0.67, the groundwater recharge is overestimated by ca. 1 % and 14 % respectively whereas, by applying the evapotranspiration calculated using the original equation of Thornthwaite and the equation of Hamon, the groundwater recharge is overestimated by 14 % and 17 % respectively.

Moreover, the time discretisation used in calculations has important consequences, the use of smaller time steps leading to enhanced recharge. Indeed, with recharge computation performed on a daily basis, precipitation sometimes greatly exceeds evapotranspiration on a single day, even in arid settings and this leads to increased recharge. On the other hand, averaging data over long time periods (monthly or annual) tends to overestimate evapotranspiration and thereby to deaden extreme precipitation events which are normally liable to recharge events (Walraevens & Van Camp, 2008; Scanlon et al., 2002; Giambelluca, 1987; Xu & Chen, 2005). Hence, computing recharge on a daily basis has the advantage of considering each of the individual small rainfall events which are actually the source of the groundwater recharge. On the contrary, in summing up all the precipitations of one month, it is wrongly considered that all the small daily rainfall events form one big event which might still be smaller than the total monthly evapotranspiration; thereby resulting in reduced groundwater recharge.

For the calendar years 1999 through 2008, daily values of meteorological parameters are available. Calculation of recharge on a daily basis using evapotranspiration computed by *FAO Penman*-Monteith equation gives 306.18 mm, which is 77 % higher than the recharge value obtained on a monthly time scale. Of even more spectacular significance is the increase of the recharge for PET calculated with Hargreaves equation, from 28.48 mm on a monthly, time scale to 140.62 mm on a daily time scale, which represents an increase of more than 390 %. In our study, groundwater recharge computed by the TMWB model using the Hamon equation for PET calculation was adopted. Compared to the recharge values obtained on a daily basis with Penman-Monteith PET (which represent the best approximation of reality), of all attempted methods, the TMWB method which is on a monthly basis, using Hamon's PET, performs best. The latter method presents the advantage of needing much less data.

For the period 1974/75-2007/2008, the average yearly recharge computed using the TMWB model amounts to 235.15 mm, which represents 211.17 Mm^3 per year for the whole study area. Annual recharge for the whole period of records (1974-2008) varies between a minimum value of 0 mm and a maximum of 622.3 mm respectively for the hydrologic years 2000/2001 and 1997/1998 which were exceptionally dry and wet. Fig. 5 shows the distribution of the average monthly recharge throughout the hydrologic year for the period 1974/75-2007/2008. It can be seen that the distribution pattern of monthly recharge features a bimodal pattern somewhat similar to that of the monthly rainfall. Indeed, groundwater recharge mainly occurs during the long rainy season (February to May) and to a lesser extent during the short rainy season, i.e. between September and November. Recharge during the long rainy season accounts for more than 75% of the total annual recharge with an important peak in April, whereas recharge occurring during the short rainy season contributes to only 13% of the total annual recharge with a small peak in November. There is always a time lag between the onset of the rainy season and the peak of groundwater recharge which must be expected from the fact that the soil moisture must be brought to its maximum water holding capacity, i.e. field capacity, before recharge can occur. It is also interesting to note that although the period December-January is considered as the short dry season due to the decrease of precipitations, groundwater recharge can still occur depending on the amount of precipitations and therefore the state of soil moisture during the short rainy season. This is not the case for the long dry season where groundwater recharge is systematically nil.

There is no contribution to recharge from return flow because there is nearly no irrigation practice in the study area. Indeed, in our study area as for the whole country, there are three agricultural seasons. Two agricultural seasons correspond to the two rainy seasons (September to November and February through May) whereas during the third one, which covers the months of June to September, crop production is concentrated on marshlands where there is no need for irrigation.

5. Conclusions

Bugesera region is a potable water-scarce area located in northeastern Burundi. The study area mainly consists of a depression surrounded by a more rugged landscape which forms the transition towards the highlands of Bweru region. The depression of Bugesera is impressively marked by a lack of natural water springs despite the presence of a complex of interconnected swamps wherein several shallow lakes lie. Groundwater recharge has been computed using the soil moisture technique as a first step towards a proper evaluation of the potential in groundwater resources in this region, which could be an alternative to the lack of natural water springs. To this effect, several methods for estimating potential evapotranspiration (Hargreaves, Thornthwaite, two modifications of Thornthwaite method, Hamon) have been tested and compared to the standard Penman-Monteith equation as recommended by FAO. This was done with a view to determining an alternative method for estimating potential evapotranspiration which could give acceptable estimates for this parameter in situations where it is not possible to use the reference evapotranspiration method due to the lack of relevant weather data. The findings of this study show that, while Thornthwaite and Hamon methods slightly underestimate the potential evapotranspiration by 12.82 % and 15.12 % respectively, Hargreaves method overestimates it by more than 50 % with a RMSE of 47.33 mm/month. Therefore, the latter method is not appropriate for our study area. Furthermore, the adaptation of Thornthwaite method with coefficients k = 0.69 and k = 0.67 was also tested and seems to generate reasonable estimates of potential evapotranspiration. Indeed, by using the modification of Thornthwaite method with k = 0.69, PET is overestimated by 0.46 % while with k = 0.67, the PET is underestimated by only 5.06 % with respect to the FAO reference PET. The RMSE is also significantly reduced to 5.77 mm/month when k = 0.67 and 4.32 mm/month for k = 0.69. It is important to recall that these empirical methods, like Thornthwaite equation, have been devised with coefficients which are most of the time site-specific. Hence, such encouraging results militate in favour of further research to be carried out so as to adapt these empirical methods to different geographic and climatic conditions.

Recharge was computed in two different ways using Thornthwaite Monthly Water-Balance (TMWB) model wherein Hamon equation for PET is embedded, and using excel sheets for other PET methods. The soil moisture capacity, an important term of the soil moisture budget, is estimated as 75 mm assuming a water-holding capacity of 30% over the entire root zone and a rooting depth of 25 cm. Indeed, soils in the study area result from the weathering of Precambrian metasediments and magmatic intrusions and are predominantly clayey while the land use is dominated by agricultural land (68.6% of the study area) where shallow rooted plants (subsistence crops) are predominantly grown. Depending on the method used to compute PET, recharge can occur only in the long rainy season (Hargreaves Method) or both in the long and short rainy seasons (other methods). Recharge computed using Hargreaves evapotranspiration gives dramatically reduced values. For this study the average annual recharge computed using the TMWB model (235.15 mm) has been adopted.

Moreover, the time discretisation used in calculations has important consequences, the use of smaller time steps leading to enhanced recharge even when computed using overestimated values of PET (Hargreaves method). This most likely corresponds to a better approximation of reality. For the calendar years 1999 through 2008, daily values of meteorological parameters are available and calculations of groundwater recharge on a daily basis, using evapotranspiration computed by Penman-Monteith and Hargreaves equations, give significantly higher values compared to the monthly basis, i.e. 306.18 mm and 140.62 mm respectively. The recharge values obtained on a daily basis with Penman-Monteith PET represents the best approximation of reality. Indeed, it should be understood that recharge occurs as a surplus fraction of each individual rainfall event rather that in function of a lump_important monthly rainfall amount. We can thus conclude that, of all attempted methods, the TMWB method, which is on a monthly basis, using Hamon's PET, performs best as it best approximates recharge values obtained on a daily basis with Penman-Monteith PET. The TMWB method presents the advantage of needing much less data.

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