Changes in landuse patterns in upland watersheds of Eastern Luangwa Valley, Zambia, and the potential impact on runoff and erosion

Victor Kayiwaze Wilford Nyirongo

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Conrad Heatwole (chair)

John McGee

Gene Yagow

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Abstract

Four small watersheds, Kamwamphula, Luelo, Kanyanga and Mphiri, near Emusa (Lundazi District) in Eastern Province, Zambia, were studied to document transitions in land use over time and to project the impacts of land use and topography on runoff, erosion and sediment delivery. Landuse was delineated from 2007 IKONOS image (one meter pixel), and Landsat imagery was used to depict the historic changes in landuse between the period of 1989 and 2007. The GWLF model was used to predict the impact of the landuses on the hydrology of the area. There had been an increase in clearing of forest area mainly due to the expansion of cropland area. The highest rate of clearing was predicted for the Kamwamphula watershed where the forest cover decreased from 95% to 71% over the 18 year period. The GWLF model was used to predict the impact of the landuse on the hydrology and sediment delivery. In comparison with the limited field data available from the four watersheds, the GWLF model gave poor prediction of streamflow, probably because the hydrology of the area is poorly understood and dambo function in the landscape is not well represented in the model. Highest runoff, erosion and sediment yields came from Luelo watershed which has steeper slopes and, less vegetative cover and poor permeability of soils. The GWLF gave poor prediction of streamflow, probably, because the hydrology of the area is poorly understood.

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1.0 Introduction

A watershed is the total land area that drains water to a common point within the landscape. It comprises a hydrologic network that links all living things including humans residing in it through a common water network into a single ecosystem. Every watershed has a set of unique features, processes, and a collection of plants and animals. Characterizing land use change, the conversion of one land use to another, as well as their associated impacts on hydrology, is of interest to planners and conservationists. One way of doing this is through the utilization of data from remote sensing satellites. Delineation of the watershed into its composite land uses using satellite imagery is one of the most effective ways of characterizing the watershed. Satellite imagery covers large areas which would otherwise be difficult to efficiently cover with conventional field surveying methods. Variations in the colors and coarseness of the imagery give explicit details of land use/land cover in different levels. The quality of the landuse maps produced, however, will depend on the resolution of the satellite imagery, among other factors. In general, high resolution satellite imagery produces clearer base-maps upon which accurate landuse maps can be drawn.

The hydrology of a catchment is affected by not only climatic factors and landuse but also landuse changes. However, landuse activities such as deforestation, urbanization, and agricultural development have a more significant effect on seasonal distribution of runoff, streamflow and sedimentation of a watershed than does climate (Alansi et. al., 2009). Changes in landuse that cause marked differences in runoff, streamflow and erosion include a reduction in ground cover or an increase in imperviousness. Bare or impervious areas result in less infiltration taking place and, therefore, greater volumes of high-energy runoff and streamflow, and reduced base-flow in a stream (Landers et. al, 2002). Increased runoff accelerates erosion of the land surface. The situation is worsened in areas where the soil does not support vegetative cover. Greater streamflow causes the scouring of stream channels which in turn results in higher yields of stream sediment in areas when vegetation cover has been removed due to agriculture, settlement or other development. High sediment deposition into a stream channel degrades the aquatic environment.

In most parts of tropical Africa, metrological and hydrological data is scanty both in space and time, a factor that makes climatic and hydrologic predictions difficult (Leggesse et. al, 2003). In addition, the hydrology of a watershed is very complex to be accurately understood by scientists. Hydrologic models are tools that are meant to conceptualize and represent real world relationships using mathematical relationships. Hydrological models that can estimate the impact of landuse at a watershed level are more appropriate than regional predictions because they have higher accuracies (Legesse et. al., 2003). There many different models that can be utilized depending on the objective, scale, and availability of resources. This study utilized the Generalized Watershed Loading Functions (GWLF) model to predict hydrologic responses to changes in land landuses (Haith et al, 2002).

Traditional agricultural practices in the Eastern plateau region of the Luangwa Valley result in abandonment ("fallow") of non-productive cropland and continued expansion of communities and new cropland in the neighboring national forest. Four small watersheds near Emusa (Lundazi District) were studied to document transitions in land use over time and to estimate the potential productivity of the region, and to project the impacts of land use and topography on runoff, erosion and sediment delivery. Answers to the following questions will provide direction and tools to assist in land use management in the region.

- What is the area and percentage distribution of each landuse class in the plateau watersheds when compared to dambo watersheds?

- What are the patterns of land use transition for the different watersheds, in particular, the transitions of land into and out of cropland?

- Are there differences in hydrological response between watersheds existing at different elevations?

- Can the GWLF model be applied to predict runoff and stream flow in dambo-imfluenced watersheds?

1.1 Objectives

The specific objectives of this research were:

1. To determine the distribution of land use in four upland watersheds that represent different histories of settlement (old vs recent) and different physiographic characteristics.

2. To characterize the change in landuse over time in terms of the fraction of cropland that is abandoned, and the rate of land clearing in the 'frontier' Kamwamphula watershed.

3. To compare rates of runoff and sediment loss from Kamwamphula, Luelo, Kanyanga and Mphiri using GWLF simulations.

4. To evaluate the use of the Generalized Watershed Loading Functions (GWLF) model as a tool for representing the hydrology and erosion of dambo-influenced watersheds in Eastern Province of Zambia.

2.0 Literature Review

2.1 Description of study area

Magodi is situated in Lundazi District in the Eastern Province of Zambia. The geographical coordinates of Magodi are Latitude 11° 59' 0" South and longitude 33° 7' 0" East. The average altitude of the area is 1151 m above sea level. The area is in South Eastern Luangwa Valley region.

Figure 2.1. Location of the study area in the Luangwa Valley

Astle et. al. (1969) describe the landscape of the Luangwa Valley which covers an area of approximately 40,000 km^2 of North-East Zambia (figure 2.1). The valley has a flat floor which is between 400m and 700m above sea level (figure. 2.2).

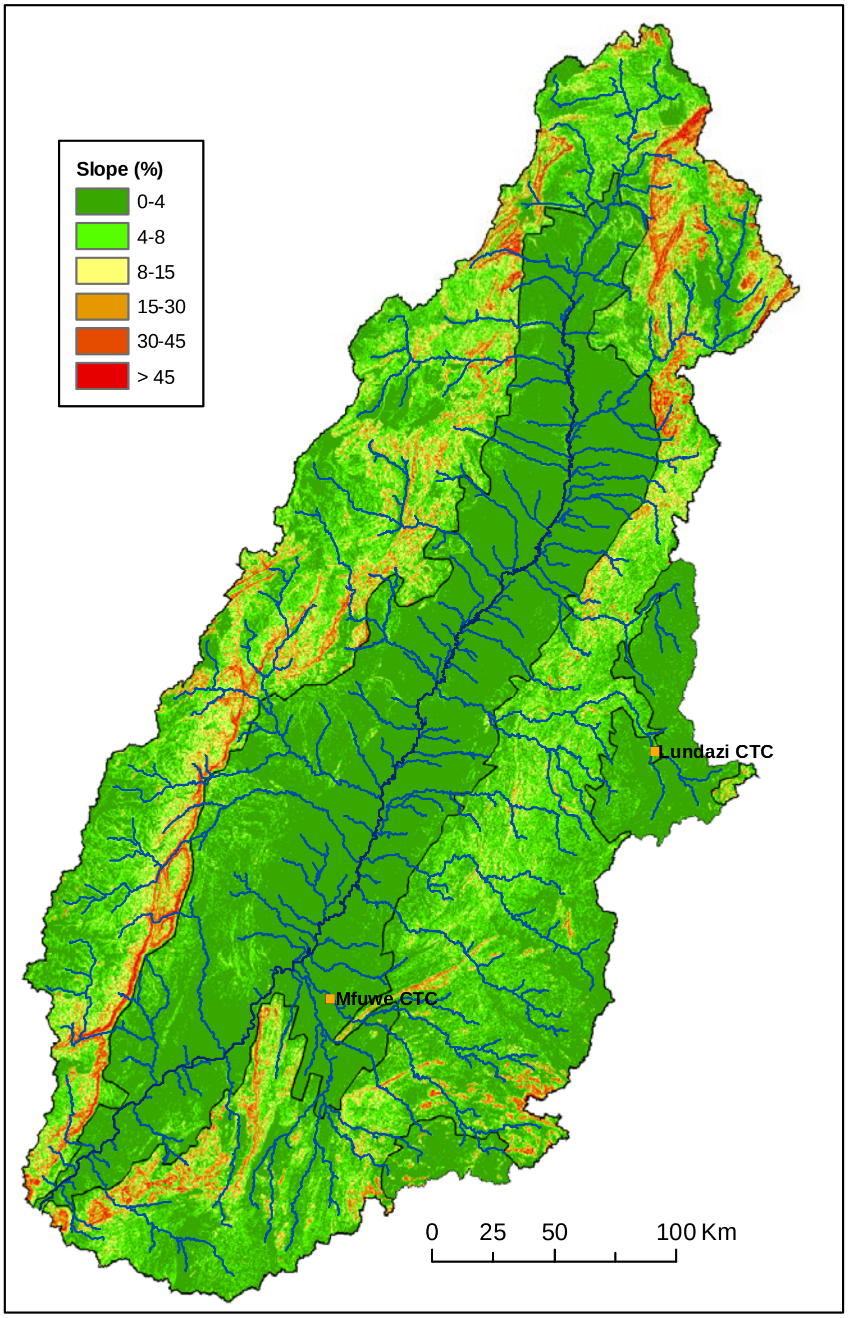

Figure 2.2. Map showing the landscape of Luangwa Valley

The Luangwa valley is part of the great African rift valley. The underlying rocks of the Luangwa Valley are Precambrian igneous and metamorphic rocks and Karoo sedimentary rocks (Gilvear et. al, 2000). Sichingambula (1998) distinguishes three groups of soils in Luangwa valley: acrisols which are deep, fine textured and are well drained soils; lithosol-cambisols, which are shallow and generally poor in nutrients; and fluvial-vertisols.

The Luangwa valley has two marked seasons: wet and dry. The wet season starts in November and ends in April and has average rainfall between 400 and 800 mm. The dry season begins in May and continues through October with virtually no rainfall. The mean temperature of the area is 25^{o}C (Astle et. al., 1969). The maximum temperature reaches 36^{o}C in October and the decreases to 15^{o}C in June. Total evaporation potential of the Luangwa area is about 2032 mm/year (Sichingabula, 1998).

The bedrock of consists of alternating layers of grits, sandstones, siltstones and mudstones (Astle, et. al., 1969). The vegetation consists of what is generally referred to 'Miombo' woodlands comprised of *Brachystegia, Isoberlinia*, *Colophospermum mopane*, *Julbernardia*, *Acacia* and *Combretum* species. Grass species prevalent in the area are *Hyparrhania rufa*, *Setaria eylesii* and *Andropogon* species. The soils of the area vary from area to area. Cracking calcareous clays are found on old alluvium while in the recent alluvium the soils range from deep, sandy to seasonally waterlogged or expansive clays (Astle et. al., 1969). Magodi area suffers from deforestation due to shifting cultivation which is a threat to Miombo woodlands (Chidumayo, 2002). The shifting cultivation results in the abandonment of productive lands for a period ranging from one to three years. There is a lack of documentation associated with the effects that deforestation has on the runoff, hydrology of streams and the effect on soil erosion in the area.

Figure 2.3 shows the two sets of paired watersheds that were studied in Magodi area. Four watersheds were chosen and these included Kamwamphula and Luelo in Western Magodi and Mphiri and Kanyanga in Eastern Magodi. Kamwamphula has a total area of approximately 2800 ha while Luelo has an area of about 3300 hectares. Among the four watersheds studied, Kamwamphula has the largest area with forest. Mphiri and

Kanyanga are, respectively, about 1800 and 1100 hectares in area. Mphiri and Kanyanga are found in the plateau area of the Luangwa valley whereas Kamwamphula and Luelo are in the hilly transition zone between the plateau and the river valley floor. These sites were chosen because they were good candidates for comparison on the effect of landuse and topography on the hydrology of a watershed in this region. Among the hilly/no-plateau watersheds, Kamwamphula has a high proportion of forest area while Luelo has less forest cover. On the other hand, among the plateau watersheds, Mphiri has more forest cover than Kanyanga.

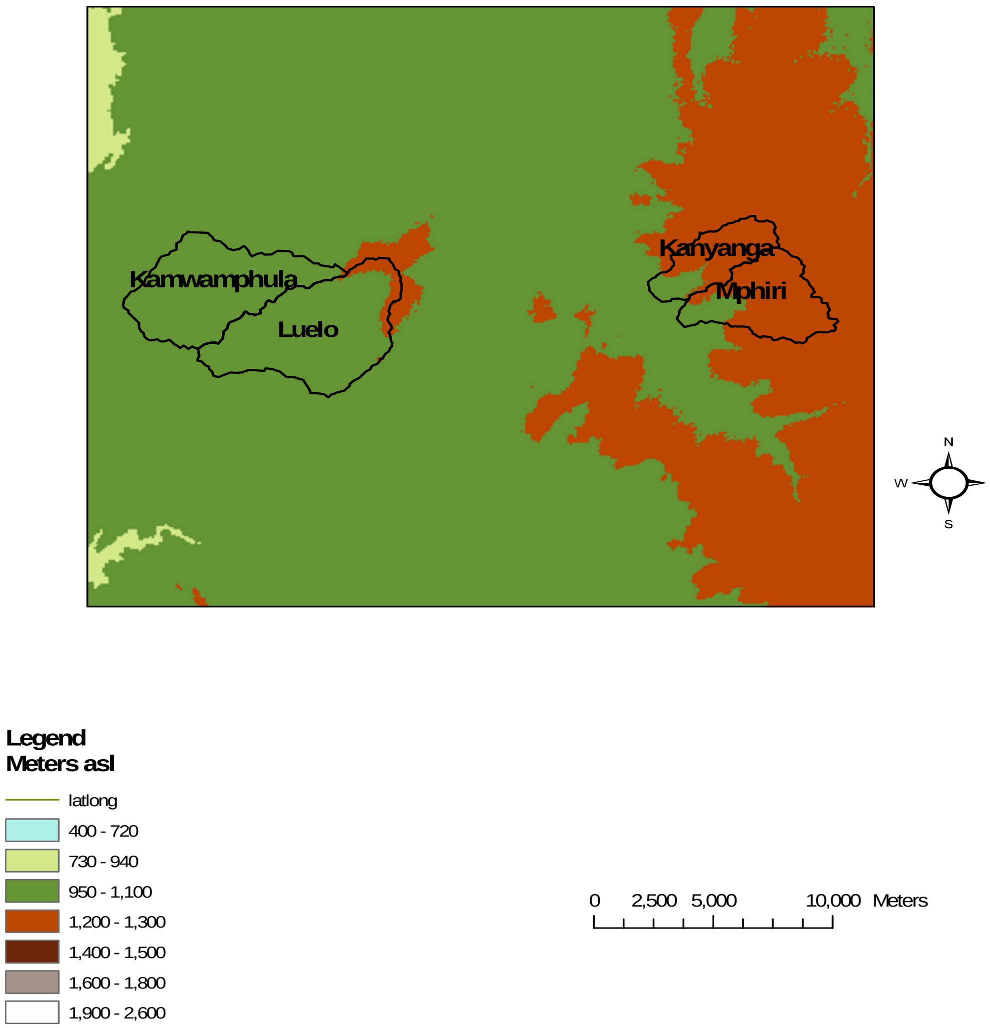

Figure 2.3. Map showing the position of Kamwamphula, Luelo, Kanyanga and Mphiri watersheds and their elevation

2.2 Changes in land use in Eastern Zambia

Agricultural expansion, abandonment of cropland, and wildlife are some of the major dynamic factors that cause changes in landuse in sub-Saharan Africa (Kamusoko and Ania, 2009). Shifting cultivation is very common in Magodi area and many parts of Zambia. Shifting and semi-permanent cultivation accounted for 66% and 29% of the total amount of 0.9 million ha of land deforestated in Zambia in 1990 (Chidumayo, 1990). Farmers began to integrate fertilizer applications in their agricultural practices soon after Zambia independence in 1964. The goal of the Zambian government at that time was to increase maize production, the staple food for the country (Kwesiga et. al., 2003). To this end, the government introduced a fertilizer subsidies in 1971. By 1986 the subsidies averaged 60% of the total costs and by mid 1980's fertilizer was used by most farmers in Eastern Zambia. However, the subsidies were removed in the late 1980's. After the state agricultural subsidy and credit programs ended, fertilizer use reduced substantially but the farmers still saw the need for improved soil fertility. Due to the abundance of uncultivated land, farmers began to abandon their fields their land for 1-3 years (Kwesiga et. al., 2003). This practice is continuing up to the present. Some of the fallowed areas are replanted while some are abandoned permanently.

The effectiveness of the fallows in contributing to soil fertility is questionable. A survey conducted in Katete and Chipata Districts of Eastern Province (Ajayi et. al., 2003) showed that the fallows have not resulted in substantial increases in yield. Similar studies conducted elsewhere in Zambia have revealed a general decrease in soil fertility levels that are attributed to this agricultural practice. (Kwesiga and Coe, 1994). Further Eastern Luangwa region experiences a lot of deforestation. A study conducted by Yang and Prince (2000) showed that there was a significant amount of deforestation in Eastern Zambia accounting for up to 40% in canopy loss in South Luangwa National Park Region. Much of the deforestation was attributed to browsing by wild animals.

2.3 Effects of landuse on Stream flows

Landuse changes affect the hydrological cycle of a watershed by altering the balance between rainfall, evaporation, and the runoff response of the area (Sahin and Hall, 1996). A study conducted by Mumeka (1986) showed that streamflow increases as a result of deforestation due subsistence agriculture and that the shape of the hydrograph changes as a result of changes in landuse. In a study of streamflows from a basin in the Rhine it was shown that runoff from a catchment with good vegetation cover was 30-36 % lower than from cultivated catchments, with the largest difference occurring in the dry season. Pilgrim et. al. (1982) observed that clearing of forests and replacing them by shallow-rooted pasture and crops increased runoff while reestablishment of forest cover reduced runoff. However, the impacts of changes in landuse on runoff and streamflow will vary according to the size of the watershed, with the effects being more pronounced in the smaller watersheds. For large watersheds, averaging the effects of areas of different land use masks any changes in large catchments.

The effect of forests on runoff and streamflows has been a subject of debate for several decades. One such debate concerns the effect of deforestation on extreme hydrological events. Forests have the effect of augmenting low flows by the encouraging the infiltration of water. Since trees transpire more water than agricultural crops (McCulloch and Robinson, 1993) most of the rain water that is intercepted by the canopies is lost through evapotranspiration. Therefore, with more infiltration and transpiration, less water runs off the land. Generally, cutting forest results in increased streamflows (Bosch and Hewlett, 1982). Forests are thought to reduce runoff and erosion due to their canopy with their underlying litter slowing down the force of rainwater and therefore encouraging infiltration. However, the impact of change in canopy on extreme hydrological events is very small and difficult to detect (McCulloch and Robinson, 1993). Rather, what causes increased flows is the compaction that accompanies forest clearing and not the clearing itself (McCulloch and Robinson, 1993).

Faulkenmark (1997) divides water into two phases: “green water” and “blue water”. According to Faulkenmark, “green water” is the water that is returns to the atmosphere from soil, tree canopies and water bodies. On the other hand, “blue water” is that which contributes to ground water level and streamflow. There is a difference in terms of water partitioning between old forest and regenerating forests and afforestation. Old forests tend to partition water more to “blue water” because they tend to have higher accumulation of litter and soil protection (Bruijnzeel 1990). Thus old forests will accumulate more water during the rainy season and release it slowly during the dry season thereby maintaining streamflows longer than newer forests. On the other hand, regenerating forests and afforestation are shown to partition more of the rainfall to green water, reducing availability of blue water (Farley et al. 2005, Scott et al. 2005). However, increasing surface runoff after deforestation and possible soil deterioration leads to more “blue water” in streams momentarily (Malmer and Nyberg, 2008).

In conclusion, landuse changes have the impact of altering runoff and streamflows as well as increasing streamflows. Deforestation and agricultural expansion have the impact of increasing runoff, streamflows and erosion. Where there is more land cover, more infiltration will take place with the result effect of having longer streamflow time. Deforestation increases runoff and, therefore, results in increase in streamflows for a short period but lesser streamflow in the long term. However, the impact of landuse changes is more pronounced in smaller watersheds than in larger watersheds.

2.4 Use of IKONOS and Landsat remote sensing in monitoring landuse changes

Remote sensing technology is increasingly being used to study land use and vegetation cover changes and to identify changes that have occurred through different land use activities. Traditional ground-based vegetation survey combined with aerial surveys have been useful tools is monitoring landuse changes (Young and Prince, 2000). The disadvantage of these methods are that they can only be effectively applied over small areas. Remote sensing technology, on the other hand, has the capability of covering a large area and has the power to depict the changes in vegetation using the differences in reflectance by different land objects.

Two types of imagery were utilized in this study, namely, IKONOS and Landsat ETM+. The observatories of the IKONOS and Landsat ETM+ share two similar measurement characteristics, that is, they have the same nominal descending orbit of 10:00 AM local solar equatorial crossing time on the sunlit side of the Earth. In addition, some multi-spectral bandwidths of the IKONOS are similar to the four shortest wavelengths of Landsat ETM+ (Goward et. al, 2003). However, there are several differences in the two observatories. Some of the differences between the two observatories are in terms of spatial resolution, quality of the image and the viewing angle (Goward et. al., 2003). The IKONOS sensor provides a finer spatial resolution at 4 m (multispectral) while the Landsat ETM+ produces a resolution of 30 m. The Landsat platform is fixed at ±7.5° scan angles viewing position, whereas the IKONOS platform may be positioned over a wide range of viewing positions, including looking quite close to the Earth's horizon (Goward et. al., 2003). Furthermore, the picture of the IKONOS is enhanced in that the IKONOS sensor acquires 11-bit images while the Landsat ETM+ acquires up to 8 bit images (Goward et. al., 2003).

Both the IKONOS and Landsat imagery can be used in assessing landuse changes with reasonable degree of accuracy. For example Capolsini et. al. (2003) observed that the accuracies of Landsat-7 ETM+ compared well to sensors with higher spatial (IKONOS) or spectral (MASTER) resolution for low or moderate habitat complexity mapping while IKONOS was suited best to high-complexity mapping.

2.5 Definition of dambo and their characteristics

Dambos are wetlands found in flatter lower-lying parts of the miombo landscape (Mapaure and McCartney 2001). The name *dambo* has been adopted from Chewa language which is extensively used in Zambia, Malawi and parts of Mozambique. Elsewhere, a dambo is called by different names. It is called “vlei” in South Africa, “mbuga” in East Africa, “bolis” in Sierra Leone and “bas fundus” in Nigeria and central West Africa (Acres et al, 1985). Boast (1990) also observed that dambos may also exist in southern India and in South America.

Dambos are mainly concentrated in southern central Africa with some few occurring in the northern hemisphere south of the Sahara (Acres et al., 1985). They occupy a sizeable area of land in Africa. The total number of dambos in Africa is estimated to be between 10,000 and 100,000 (Balek, 2006). In Zambia dambos occupy approximately 35,000 km^2 or 4.6% of the national area (Ferreira, 1981). The commonest types found in Africa are 'headwater' and 'river' dambos. Headwater dambos tend to be broad and are found near the headwaters (Bell and Roberts, 1991). River dambos are the extensions of headwater dambos downstream (Matiza, 1991). Other forms of dambos have been identified in Zimbabwe and these include 'stream' dambos and 'residual' dambos. Stream dambos are adjacent to second or third order streams. Residual dambos are narrow and linear and tend to follow first order side streams. Dambos are generally located in areas with rocks of basement complex including gneisses, schists, and quartzites (Bullock, 1992b).

The term *dambo* was introduced into the scientific literature by Ackerman (1936) who defined it as 'a stream-less grassy depression periodically inundated and at the headwater of a drainage system in a region of dry forest or bush vegetation'. This definition is consistent with the definition of later authors. For example, Hindson (1962) defined a dambo as 'seasonally waterlogged, grass covered treeless area bordering a drainage line'. However, dambos may sometimes remain wet in the dry season (Hindson, 1962) mainly due to a heavy rainy season preceding a dry season and because the high storage capacity of the dambo enables them to absorb a lot of water (Balek and Perry, 1973). In addition, the term dambo is not restricted to the headwaters only but includes grasslands below the headwaters (Garlick, 1961).

Dambos play significant roles in the livelihoods of the surrounding human communities where they exist. Some dambos remain wet during the dry season, and the availability of water makes them useful for agriculture in the semi-arid regions (Scoones, 1991). This importance cannot be overemphasized, especially, in rural communities of Africa where hunger is rampant. Dambo farming provides a safety net by supplementing the upland farming where the yields are low due to inadequate inputs and poor soils. In many parts of Africa small-scale farmers depend on dambos for crop production. At the same time, there are communities that survive exclusively on dambos. For example, Jansen and Schuyt (1998) report that the survival of people surrounding Yala Camp dambo depended exclusively on water extracted from the dambo for drinking, cooking, washing, and building materials.

Dambos have been known to influence the stream network below them and the hydrological cycle in different ways but how this influence is exerted is a subject that is contentious. Dambos are also known to be natural ‘sponges’, absorbing water during the wet season and slowly releasing the water to streams below them during the dry season thereby attenuating floods and maintaining dry season river flows (Balek and Perry, 1973). This observation, however, has not been scientifically proven and has been challenged by many authors on dambo hydrology (e.g. Bullock, 1992a, McCartney, 2000). In addition, a number of studies have shown that dambos can influence the hydrological cycle by decreasing or increasing a particular component of the hydrological cycle, e.g. transpiration, runoff and infiltration (Bullock and Acreman, 2003).

Research on hydrology of dambos is in its infancy (Bullock, 1988) and much that is written on this subject is based on guesses rather than on founded scientific evidence through research (McCartney, 1998). There is, therefore, need to do more research on dambos in order to understand the processes and to manage the dambo environments properly.

A dambo, like any other wetland, forms where topographic, geological and hydrological conditions are favorable. Typically, the drainage basin must have sufficient and a long-term source of water, land-surface depressions, fine textured surface soils with low hydraulic conductivity and sufficient thickness to store water, and impermeable bedrock near the land surface (Michigan Department of Environmental Quality, 2001). Similarly, Rattray et. al. (1953) observed that the necessary conditions for dambo formation are: surface soils with high infiltration and low field capacity; subsoil that allows the accumulation of more and more clay to the point where it becomes impermeable clay soil layer or rock; a shallow depth of permeable soil; and finally, topography which is broad, gentle and undulating.

Models relating to the formation of dambos have been anchored on two contrasting hypothesis of on causes of African soil erosion, namely, *prediplanation* and *etchplanation*. The theory of *prediplanation* (King, 1963) states that runoff strips off the regolith thereby causing low relief in the dambos. However, the validity of King's approach has been challenged by a number of authors on grounds that current geomophological theories and data are not in line with King's arguments (Bezerra et. al., 2007). On the other hand, under *etchplanation*, parent material is weakened through differential leaching of the minerals caused by rainwater infiltrating the parent material. The weakened rock disintegrates and forms a more stable colluvial material that migrates downslope to fill the depressions, thereby forming dambos (von der Heyden, 2003).

Recently, the above hypotheses have been challenged by the *fluviatile* and *in situ* weathering models, which essentially are built on the same hypotheses but have expounded on the distribution of the particles across the soil catena. Similar to prediplanation, the *fluavitile* model views dambos as initially low areas which are excavated by the high energy of runoff water coming from the higher areas. As time progresses, the excavations are filled by the colluvial material and the landscape slopes and the kinetic energy of the runoff are reduced. Under these circumstances, the particles become finer as one moves from the dambo going upwards. In contrast, the *in situ* model proposes that the low depressions forming dambos are produced as a result of collapsing of the 'preferential leaching' of the parent material due to leaching (McFarlane, 1989).

2.6 Characteristics of dambo soils

According to Acres et al. (1985), there are six main types of soils found in dambos, namely, peat, sandy clays, sandy soils, black cracking clays, grey clays, and termite soils. The soils have a mixture of smectite (montimorillonite), kaolinite and sand (Whitlow and McFarlane, 1991). Smectites they are prone to cracking and drying out (Whitlow and McFarlane, 1991). Boast (1990) found out that dambo soils have higher clay content than interfluves, with the clay content increasing towards the center. Dambo soils are generally fertile owing to their having a high cation exchange capacity (CEC) and high water holding capacity (Whitlow and McFarlane, 1991). At the same time, dambo soils are shallow, have low hydraulic conductivity with permeability decreasing with depth, and are, thus, poorly drained (Bullock, 1992). Studies conducted in Malawi by The British Geological Survey (1989) reported measured hydraulic conductivity values of 0.1 to 10 cm/day. Similar studies done on Chizengeni catchment in Zimbabwe (Faulkner and Lambert, 1991) and Aguima catchment in Benin, West Africa (Giertz and Diekkrüger, 2003) gave hydraulic conductivities of 0.1 to 1000 and 6 to 347 cm/day, respectively. Low conductivity of the dambo soils allow the dambo soil to easily become water logged under conditions of high moisture.

Typically, dambo soil moisture will tend to rapidly rise in response to early rains to reach saturation (Bullock, 1992). Further, where the soils have high clay content, saturation takes longer than soils which have higher sand content. Results from studies conducted in several Zambia valleys showed that there is an initial rise in the saturated zone within the first month of rain at Luano (Balek and Perry, 1973), saturation being reached after 200-250 mm of rainfall (Kanthack, 1945). Once soils have become saturated, the groundwater level remains constant until the dry season (Balek and Perry, 1973).

2.7 Vegetation of dambos

The most common vegetation in the Southern African region where dambos are prevalent is the *miombo* woodland, comprised mainly of *Brachystegia* and *Julbernadia* species (Hough, 1986, Millington and Townshend, 1989). Dambo vegetation is comprised of different species of plants which are distributed according to hydrological conditions. Mackel (1985) observed that the grasses display a pattern in which four zones can be distinguished depending on their position in the slope catena. Mackel (1995) identifies the zones as upper dambo margin, upper dambo zone, lower dambo zone and the dry dambo bottom. The upper dambo margin is comprised of unfertile soils where most of the nutrients have been washed to the lower zones of the landscape. This zone supports shrubs such as *Syzygium huillense*. The upper dambo zone comprises of a more moist soil and is dominated by grasses such as *Andropogon*, *Eragrostis*, and *Drosera* species. The lower dambo zone, which is saturated during the wet season but dries out by the end of the dry season, is dominated by sedges. However, this categorization is an oversimplified way of understanding the occurrence of dambo vegetation, as noted by Bell and Roberts (1991). They observed that plant-water relationships of dambos are poorly established and not all dambos exhibit distinct zones (Bell and Roberts, 1991).

Dambo vegetation plays an important role in hydrological processes. Balek (2006) observed that grass cover in the dambos delay surface runoff and stabilize the hydrological regimes. Dambos also help in the integrity of the landscape. Bullock and McCartney (1996) established that where there are dambos, there is greater evapotranspiration than the non-dambo containing *miombo* woodland, because more water is available for transpiration as it is kept close to the surface in close to the surface in the grass-covered dambo. Similarly, Benham (1948) noted that the dambo plants have high evaporation coefficients**.**

2.8 Dambo hydrology

Hydrology considers the occurrence, distribution, movement and properties of the waters of the earth and their relationship with the environment. Understanding African hydrology is difficult because of inadequate data or the complete absence of data (Ayibotere, 1993; Bullock, 1993). In addition, there is a lot of diversity in the ecology of the dambos such that experiments conducted on dambos have given conflicting results and conclusions. Another area of contention has been the influence of dambos on the hydrology of the catchment and the stream/river network downstream. In general the discussion on hydrology has centered on four main areas (Von der Heyden, 2003), namely: 1) sources of water to the dambo; 2) soil moisture regimes; 3) effect of dambos on dry season water flow and 4) the role of dambos on the hydrological cycle.

2.9 Sources of water to the dambo

Bullock (1993) identifies four potential sources of water in the dambo: direct precipitation; surface runoff from upslope; subsurface runoff from upslope; contributions from channels upslope. These contributions can also be summarized as direct precipitation or “meteoric” water and water from upstream land or “telluric” water Bullock (1992). Balek and Perry (1973) concluded that direct precipitation was the main contributor of water to the dambo with the contributions from the surrounding non-dambo areas being minimal. They further observed that base flow contributed less than one-third of the total flow (Balek and Perry, 1973). They observed that the response of the dambo to precipitation events depends on the type of soil and the size of the dambo. Where the soil has a high water holding capacity it takes longer for it to become saturated and for runoff to take place and vise versa. According to the same study, where you have a higher total area of dambo, there is a higher total amount of runoff generated. However, the contribution of precipitation will vary depending on the area of the dambo in relation to that of the catchment area (Bullock, 1993).

The volume of runoff into the dambo resulting from precipitation does not depend on the catchment area only. For example, studies done on Luano dambo demonstrated that despite the dambo being smaller in area (about 5% of the catchment area) direct precipitation onto the dambo was important because the surrounding woodland area had high evapotranspiration losses (Balek and Perry, 1973). Precipitation is the main source of water for headwater dambos because they are surrounded by a small catchment upstream (Bullock, 1993). On the other hand flood plain dambos receive less water from precipitation because the contributing upstream catchment is larger and as such they receive most of the water from the channels upslope flow (Bullock, 1993). McFarlane and Bowden (1992) and Whitlow and McFarlane (1990) showed that base flow is a very important component of dambo hydrology based on the observations from Malawi dambos.

2.10 Dambo soil moisture regime

Dambo soils tend to become saturated rapidly soon after early rains, remain almost constant during the rainy season, and gradually get depleted during the dry season (Von Der Heyden, 2003). However, the time it takes for the soil to become saturated depends on soil type. Where the soils are predominantly clay, it takes longer for the soil to become saturated than where the soils are predominately sand (Acres et al., 1985). This is obviously due to differences in the sizes of pore spaces between the two soil types. Also, predominantly sandy soils display larger fluctuations in water level than predominantly clay soils (Acres et al., 1985). In general, dambos will tend to have high water table throughout the year and thus have higher moisture storage potential than other soils (Von der Heyden, 2003). Small-scale farmers tend to take advantage of this moisture for dambo cultivation during the dry season.

2.11 Dry season dambo flow maintenance

Contrary to the early view that dambos function as ‘sponges’ of water, absorbing it during the rainy season and releasing it during the entire dry season (Acres et. al, 1962), there is abundant literature that suggests that dambos only sustain flow of the downstream stream for a few months after the end of the rain season (e.g. Von der Heyden and New, 2003; Von der Heyden, 1998; and McCartney et. al., 1998). Balek and Perry (1973) and Kanthack (1945) observed that where the dambos occupied a higher percentage of the catchment area, they tended to have a higher volume of storage and maintained streamflow longer during the dry season. The maintenance of flow results from a lot of water being stored in the dambo aquifer (Balek, 2006). On the contrary, Bullock (1992b), based on studies conducted in Zimbabwe, concluded that dambos do not play a significant role in maintaining dry season flows, regardless of their densities. Studies done by Bullock (1992) on Zimbabwean dambos established that dry-season flows are reduced in areas where dambos are found on soil profiles that have a granitic basement complex. Bullock (1992a) further argues that sustained dry season flows occurring in the dambos are not the result of large storage volumes from the soil profile but rather the result of groundwater discharge. Additionally, Von Heyden and New (1998) observed that dambos contribute more water during the rainy season and early dry season but their contribution ceases by mid dry season. Further, earlier studies conducted in Malawi by Hindson (1962) also concluded that dambo storage does not support flows of streams throughout the dry season. However, von der Heyden (2003) concluded that although the arguments advanced by Bullock (1992b) and Hindson (1962) may be true, shrinkage of the dambo and seepage from dambo may play significant role in dambo contributing to streamflow.

2.11 Effect of dambos on flood flow

No consensus has been reached amongst researchers on the impact of dambos on flood flow (Von der Heyden, 2003). The widely accepted belief is that dambos reduce runoff by reducing the speed of the water through roughness provided by the vegetation and by absorbing and storing the water (Kanthack, 1945). Balek and Perry (1973) observed that surface runoff was delayed in the Luano dambo experiments due to resistance by dambo grasses. However, in the same study, catchments with greater dambo area were found to generate more runoff than non-dambo catchments. Giertz and Diekkruger (2003) also found higher runoff from areas which had larger dambo areas in their studies done on a catchment in Benin. McCartney et al. (1998) observed that dambos play contrasting roles of storing a lot of water prior to saturation and rapidly dispensing a lot of water once saturation has been reached. Similar results were obtained by Von der Heyden and New (2003) from experiments conducted in north-western Zambia. However, Bullock (1992a) noted that there is no evidence to support the notion that dambos play any significant influence on the magnitude and frequency of floods in the streams downstream. Except from the stand taken by Bullock, there seems to be a general agreement that dambos do delay flood flow (Von der Heyden, 2003).

2.12 Evapotranspiration (ET) from dambos

Results from studies in Zambia dambos have shown that ET from the dambos will likely be greater than that from the interfluve when the interfluve is vegetated by short grasses and shrubs, and less than that from the interfluve when miombo woodland predominates (von Heyden, 2004). Lower root density of dambo grasses reduces evapotranspiration in dry season compared with woodland, (Balek and Perry, 1973). However, the water balance calculation for African swampy areas is difficult because evapotranspiration from papyrus can exceed evaporation from free water surfaces (Balek, 2006).

Evapotranspiration rates for Luano dambo catchments were 0.13 mm - 4.13 mm per day (Balek and Perry, 1973) while values for another dambo in Chambishi area in Northwestern Zambia gave a range of 2.37- 5.63 mm per day (Von der Heyden and New, 2003).

2.13 Water Budget of a catchment containing a dambo

According to McCartney (2000), in order to model a water budget for a dambo one can use the same equation that is applied to any wetland, which is

$$Q_{in} = Q_{out} + \Delta E + D - P - \Delta S$$

Where:

P = precipitation (m^3),

ΔE = actual evaporation (m^3),

Q_{in} = lateral drainage into the segment (m^3),

Q_{out} = lateral drainage out of the segment (m^3),

ΔS = change in storage (m^3),

D = "deep drainage" (m^3).

In a study conducted by McCartney (2000) on a small Zimbabwean catchment containing a single dambo, it was shown that rainfall has the highest input (80%) while the surrounding catchment gave a small proportion (12%) of the total amount of water in the dambo. The study also observed that the evapotranspiration from the dambo (50%) was greater than that from the interfluve (41%). Water from the interfluve accounts for 23% and 10%, respectively, of the water lost from the dambo through evaporation (McCartney, 2000). Further, Bullock and McCartney (1996) observed that the type of vegetation plays an important role in determining whether more or less evapotranspiration takes place from dambo than the interfluve. They observed that where the interfluve is comprised primarily of Miombo and grass, ET was 8% greater.

In their investigation of water balances of four major African wetlands — Senegal, Niger, Sudd, and Okavango — Sutcliffe and Parks (1989) found that annual and seasonal inflows showed big differences. It was observed in their later study that the presence of perennial swamps increased the flows.

2.14 A hydrogeological model of a dambo

A good summary on the hydrogeological models of dambos is given by von der Heyden (2003). The author discusses in detail three hydrogeological models: the ‘Dambo Research Unit Model’; the 'McFarlane Model’; and the 'McCartney-Neal Model'. The common feature among all the models is that a dambo is represented as an impermeable layer that obstructs vertical movement of water upward or downward (Von der Heyden, 2003). The extent of ground water discharged into the dambo depends on the nature and thickness of the impermeable layer.

2.15 Effect of human activities on dambo gullying

The impact of human activities on the geomorphology of the dambo has been a concern for the past four decades. Overgrazing and the lack of conservation measures on the cultivated plots were reported as the major causes of soil erosion in the dambos as early as 1964 (Hindson, 1964). Smith (1966) emphasizes the importance of tracks which concentrate flow into and within dambos and as a result, often turn into gullies. Mackel (1974) reported that the problem of soil erosion is prevalent in densely settled areas, particularly where peasant farming occurs. Mumeka (1986) suggested that that deforestation and subsistence agriculture were responsible for increased streamflow in Zambia.

2.16 Classification of hydrological models

A model is defined as a representation of reality. A hydrologic model can be defined as 'a mathematical representation of the transport of water and its constituents on some part of the land surface or subsurface environment' (Fraisse et. al., 1996 p.155). Several criteria can be used to classify models depending on the interests and needs of a discipline (Woolhiser and Brakensiek, 1982). One way of classifying models is by using the model structure and spatial discretization criteria (Leavesley, 1994). Using this approach models can be classified as Empirical Models, Water Balance Models, Conceptual Lumped-Parameter Models, and Process-Based Distributed-Parameter Models

2.16.1 Empirical Models

An empirical representation considers only the statistical relations among the components of the water balance. Empirical models do not explicitly consider the governing physical laws of the processes involved, but only relate input to output through some transform function. As such, empirical models reflect only the relations between input and output (Woolhiser and Brakensiek, 1982).

2.16.2 Water balance models

Water balance models were introduced through the work by Thornthwaite (1948) and Thornthwaite and Mather (1955). These models account for the movement of water from the time it enters a basin as precipitation to the time it leaves the basin as runoff (Leavesley, 1994). Most water balance models calculate direct runoff from rainfall. ET is calculated as a function of potential *ET* and the water available in storage.

2.16.3 Conceptual Lumped-Parameter Models

Conceptual lumped-parameter models are based on fundamental physical laws and may include some amount of empiricism (Woolhiser and Brakensiek, 1982). These models rely heavily on the use of parameters to represent a hydrologic response unit (HRU) which has a unique heterogeneous mix of vegetation, soils, and land use. Some models attempt to account for spatial variability in watershed characteristics by dividing the watershed into smaller areas or sub-basins.

2.16.4 Process-Based Distributed-Parameter Models

These models are firmly based in the understanding of the physics of the processes that control basin response. The basin can divided into smaller units using a grid-based approach or a topographically based delineation. Process parameters are determined for each grid cell (Woolhisser and Brakensiek, 1982).

2.17 Description of the GWLF Model Structure and Approach

GWLF simulates runoff, streamflow, erosion and nutrient loads, with primary inputs to the model being daily precipitation, and average daily temperature. The model uses a form of the Natural Resources Conservation Service's (NRCS) Curve Number method (SCS, 1986) to partition precipitation into direct runoff and infiltration. The Curve Number determines the amount of precipitation that runs off. The amount of runoff is adjusted according to the amount of 'antecedent soil moisture' that is already present in the soil as a result of total precipitation in the preceding 5 days. Each landuse is assigned a hydrologic group and, in turn the model user has to assign a Curve Number to the landuse.

In terms of spatial representation, the soil profile of the watershed is divided into unsaturated, saturated and ground water zones. Infiltrated water is first assigned to unsaturated zone storage where it may be lost through evapotranspiration. When storage in the unsaturated zone exceeds soil water capacity, the excess percolates to the shallow saturated zone. This zone is treated as a reservoir that discharges to the stream or looses moisture to deep seepage, at a rate described by the product of the zone's moisture storage and a constant rate coefficient (Haith et al., 1992). Flow in streams comes from surface runoff during precipitation events or from ground water pathways. In GWLF, potential evapotranspiration is estimated from a relationship with mean daily temperature and the number of daylight hours.

In order to use the GWLF model, landuses are divided into “rural” and “urban” landuses. The model calculates loading of sediment and nutrients following this categorization of landuses. “Rural” land uses are those with predominantly pervious surfaces, while “urban” land uses are those with predominantly impervious surfaces. Monthly sediment delivery from each “rural” land use is computed from erosion and the transport capacity of runoff (Haith and Merrill, 1987). Total amount of soil erosion is calculated based on the universal soil loss equation (USLE) (Wischmeier and Smith, 1978). A rainfall erosivity coefficient is required to calculate the rainfall energy to detach soil particles from daily precipitation (Haith and Merrill, 1987).

3.0 Materials and methods

3.1 Metrological and streamflow data collection

Historical records of daily rainfall and temperature totals for Lundazi metrology station were collected from the Meteorological Department in the Ministry of Transport and Communications in Zambia. The length of the rainfall and temperature series was for 10 years (1985 to 1995). The missing data of temperature for the period were replaced with monthly average values of the other years with complete data. Records of daily river flows over a period of 2 years were obtained from pressure sensors located on Kamwamphula, Luelo, Mphiri and Kanyanga streams. Site visits were made to observe the situation on the ground. Members of the general public also provided valuable information on the actual experiences that they have witnessed taking place in terms the changes in landuses and streamflow over the years.

3.2 Delineation and classification of landuses

Land classification was achieved through digitizing Landsat imagery of 1989, 1994, 2002 and IKONOS imagery of 2007 (Table 3.1) in ArcGIS. Polygons were initially created using the 2007 IKONOS imagery and codes were assigned to each polygon depending on the landuse. This parcel layer was then overlayed on the Landsat imagery and a code assigned for each parcel. As needed, parcels were further subdivided based on the Landsat imagery. This was usually needed to reflect the progression of clearing that would not be evident in the 2007 image alone. This procedure produced a parcel map with an attribute table with four sets of landuse classes corresponding to the four years of imagery. A total of twelve landuse classes were created from the IKONOS 2007 imagery. Areas of each polygon were calculated and added as a separate column in the attribute table using the "calculate geometry" in ArcGIS.

Table 3.1. Type and characteristics of imagery used in land classification of the Magodi watersheds

Data used	Acquisition date	Pixel size
IKONOS-2	05/31/2007	1.0m
Landsat-5	05/12/1989	28.5m
Landsat-5	05/26/1994	28.5m
Landsat-7	05/08/2002	28.5m

Table 3.2 shows the landuses that were demarcated from the IKONOS imagery, their codes and description. Due to poor resolution of the Landsat imagery only three areas were distinguished: forest land, cropland and dambo grasslands. The intent was to separate between cleared versus uncleared land in each watershed at the different dates, and in addition, the dambo could also be clearly distinguished in the Landsat imagery as well. A false-color image was used for the visual classification, and for the Ikonos image, the 4m multispectral image was pan-sharpened to 1m resolution for the parcel delineation and classification.

Table 3.2. Landuses classes assigned from the IKONOS image

Code	Name	Description
21	human settlement	rural villages mostly with bare and compacted soil
22	playground	treeless bare grounds with scanty grass
23	road	compacted earth roads
41	forest undisturbed	forest providing good ground cover with minimal human interference
42	forest sparse	forest with sparse vegetation
49	burnt area	burnt forest areas
51	fallow 1	abandoned cropland with vegetation about 1m tall or less
52	fallow 2	abandoned cropland containing trees about 2m tall or less
55	fallow 5	abandoned cropland with bigger trees that are re-establishing into mature forest
82	cropland	croplands grown to soy bean, corn, cotton etc.
91	stream channel	areas containing stream water
92	dambo	treeless grasslands along seasonal tropical wetlands (dambos)
93	transitional vegetation	vegetation containing scattered trees connecting upland areas and dambos

3.3 Determination of parameters used in GWLF

3.3.1. Land uses

Landuses were determined from satellite imagery as described above. All the landuses were categorized as “rural” because the study area is in a rural setting containing all pervious areas.

3.3.2. Runoff curve numbers

Based on the FAO soil classification system, soils in Magodi area are categorized into two categories of Lithosols and Ferralisols. These soils are known to possess a combination of sandy clay loam and clay soils according to FAO classification (FAO, 1995). Therefore, a hydrologic soil group ‘B’ was chosen to be appropriate for all land uses except for dambo areas and sparse forest areas, which were assigned soil hydrologic group D because they are clearly known to contain clay and, therefore have poor drainage. Table 4.3 shows the curve numbers that were assigned to western and eastern Magodi watersheds.

Table 3.3. Areas and curve numbers for landuses in Magodi watersheds

Code	Landuse	CN	HSG*	Comment
21	settlement	89	D	dirt road
22	playground	89	B	open space poor condition
23	roads	93	D	hard surface
41	dense forest	66	B	woods poor
42	sparse forest	66	B	woods poor
51	fallow 1	86	B	straight row, fallow
52	fallow 2	79	B	pasture range, poor
55	regrowing vegetation	66	B	woods poor
82	cropland	81	B	straight row, poor condition
91	stream channel	100		open water
92	dambo	92	B	clay soil
93	transitional forest	92	D	trees and grass under-storey

* HSG – Hydrologic soil group

3.3.3 Erosion and sediment parameters

Data required for estimation of soil loss were obtained from the GIS analysis, GWLF manual and field observations. Areas of each land use were calculated automatically in GIS.

3.3.3.1. Soil erodibility factors (K)

Soil erodibility depends on the nature of soil and the amount of organic matter present. For Magodi, there are two distinct soil types. Since the Magodi watersheds have primarily a combination of sandy clay loam soil and clay soils according to FAO classification, K-factor values of 0.27 and 0.29 (Haith et al., 1992) were assigned to the landuses. Dambo areas and transitional forest areas were assigned a K-factor value of 0.29 and all other values a value of 0.27 (Haith et al., 1992).

3.3.3.2. Evapotranspiration cover coefficients

The growing season was assumed to coincide with the rainy season which starts from November and ends in April. Cover coefficients were evaluated based on information from Table B-8 of the GWLF manual and are listed in Table 3.4 below:

Table 3.4. Evapotranspiration cover coefficients for Magodi

Code	Landuse	Cover coefficient			
		Growing season	Comment	Off-season	Comment
21	Settlement	0.3	little or no ground cover	0.3	no cover
22	Playground	0.6	60% grass cover	0.3	little cover
23	Roads	0.3	no cover	0.3	no cover
41	dense Forest	1	100% cover	1	year round foliage
42	sparse forest	1	100% cover	1	year round foliage
51	fallow 1	1	100% cover	0.3	dry during off-season
52	fallow 2	1	100% cover	0.6	has 50% shrubs
55	regrowing vegetation	1	100% cover	1	year round foliage
82	Cropland	1	100% cover	0.3	annual crops
91	Stream channel	0.3	no cover	0.3	no cover, minimum value
92	Dambo	1	100% cover	0.8	year round foliage
93	Transitional forest	1	100% cover	0.9	year round foliage

For each watershed the cover coefficients were area-weighted as explained in the GWLF manual (Haith et al., 1992). Table 3.5 shows the area-weighted values by watershed.

Table 3.5. Evapotranspiration cover coefficients by watershed

Watershed	Growing season	Dormant season
Kamwamphula	1.000	0.816
Luelo	1.000	0.546
Kanyanga	1.000	0.595
Mphiri	1.000	0.674

3.3.3.3. Erosivity factors and day hours

Soil erosivity factors, a_t, for the entire Magodi area were calculated using erosivity indices data obtained from Pauwelyn et. al. (1988) and the equation developed by Richardson et. al. (1983) which is given in the GWLF manual (p9) as follows:

$$RE = 64.6 * a * R^{1.81}$$

where RE is the rainfall erosivity (MJ-mm/ha-h) for the month and R is the average daily rainfall for the month.

Erosivity values and hours/day are given in the Table 3.6 below. The determination of the values also took into account the maximum and minimum values allowed in the GWLF. The minimum and maximum values for the cool (dry) season are 0.3 and 0.6, respectively, while in the warm (rainy) season the range is 0.6 and 0.42 (Haith et. al, 1992).

Table 3.6. Erosivity factors for Magodi area

Month	Day Hrs	Erosivity
Apr	11.9	0.13
May	11.5	0.06
Jun	11.3	0.06
Jul	11.4	0.06
Aug	11.7	0.06
Sep	12.1	0.06
Oct	12.5	0.06
Nov	12.9	0.42
Dec	13.1	0.42
Jan	13.1	0.42
Feb	12.7	0.42
Mar	12.3	0.42

3.3.3.4 LS factor

The LS factor was calculated according to metric conversion of USLE (Wischmeir and Smith, 1978) as

$$LS = 5.8 * (L / 22.13)^m * (0.065 + 0.043 * S + 0.0065 * S^2)$$

Where m = 0.2 for $S \leq 1.0$; m = 0.3, $1.0 < S \leq 3.5$; m = 0.4, $3.5 < S \leq 4.5$; and m = 0.5, for $S > 4.5$

S = slope (%)

Slope was evaluated from 30m DEM as average slope within each landuse using the ‘zonal statistics’ function of ArcGIS.

L = slope length (m)

The slope length was assumed to be 100 m based on observation of the study area.

3.3.3.5. P-factor

P factor was assigned a value of 1.000 except for cropland and fallow areas which were assigned a value of 0.3. The 0.3 was based on GWLF manual value for stripped contour crops and terraced crops.

3.4 Data analysis

Calculation for areas of each polygon as well as average slope for each land use was done in ArcGIS. Calculation of the KLSCP formula was done in Excel. Landuse distribution data was exported into Excel and pivot tables were created to compare the landuse changes that have taken place from the period 1989 and 2007. Tables 3.7 to 3.10 show KLSCP factors for Kamwamphula, Luelo, Kanyanga and Mphiri watersheds. Table 3.11 shows non-landuse dependent parameter values by watershed

Table 3.7 KLSCP factors used for Kamwamphula watershed

Landuse	CN	K	L	S	LS	C	P	KLSCP
settlement	89	0.27	100	3.77	2.67	1.000	1	0.722
roads	93	0.27	100	3.79	2.69	1.000	1	0.726
dense forest	66	0.27	100	4.76	3.40	0.001	1	0.000919
sparse forest	66	0.27	100	4.46	3.18	0.003	1	0.00257
fallow 1	86	0.27	100	4.71	3.37	0.010	0.3	0.00273
fallow 2	79	0.27	100	3.27	2.33	0.040	0.3	0.00756
cropland	81	0.27	100	4.35	3.09	0.620	0.3	0.155
dambo	92	0.29	100	3.58	2.54	0.003	1	0.00221

Table 3.8. KLSCP factors used for Luelo watershed

Landuse	CN	K	L	S	LS	C	P	KLSCP
Settlement	89	0.27	100	3.14	2.25	1.000	1	0.607
Playground	89	0.27	100	1.39	1.22	0.040	1	0.0132
dense Forest	66	0.27	100	4.50	3.21	0.001	1	0.000866
sparse forest	66	0.27	100	4.16	2.95	0.003	1	0.00239
fallow 1	86	0.27	100	3.83	2.72	0.010	0.3	0.00220
fallow 2	79	0.27	100	3.69	2.62	0.040	0.3	0.00849
regrowing forest	66	0.27	100	3.10	2.22	0.007	1	0.00420
Cropland	81	0.27	100	3.85	2.73	0.620	0.3	0.137
Dambo	92	0.29	100	3.24	2.31	0.003	1	0.00201

Table 3.9. KLSCP factors used for Kanyanga watershed

Landuse	CN	K	L	S	LS	C	P	KLSCP
Settlement	89	0.29	100	1.95	1.52	1.000	1	0.442
play grounds	89	0.29	100	2.83	2.05	0.040	1	0.0237
Roads	93	0.29	100	2.17	1.65	1.000	1	0.478
forest dense	66	0.29	100	2.18	1.65	0.001	1	0.000480
forest sparse	66	0.29	100	1.87	1.48	0.003	1	0.00129
fallow 1	86	0.29	100	2.06	1.58	0.010	0.3	0.00138
fallow 2	79	0.29	100	0.79	0.93	0.040	0.3	0.00324
regrowing forest	66	0.29	100	2.08	1.60	0.007	1	0.00324
Cropland	81	0.29	100	2.03	1.57	0.620	0.3	0.0844
stream channel	100	0.29	100	2.66	1.94	1.000	1	0.563
Dambo	92	0.29	100	2.01	1.56	0.003	1	0.00136
transitional vegetation	92	0.29	100	2.14	1.63	0.003	1	0.00142

Table 3.10 KLSCP factors used for Mphiri watershed

Landuse	CN	K	L	S	LS	C	P	KLSCP
Settlement	89	0.29	100	1.83	1.46	1.000	1	0.422
burnt areas	93	0.29	100	1.94	1.52	1.000	1	0.440
forest dense	66	0.29	100	2.10	1.61	0.001	1	0.000466
forest sparse	66	0.29	100	1.82	1.45	0.003	1	0.00126
fallow 1	86	0.29	100	1.99	1.55	0.010	0.3	0.00135
fallow 2	79	0.29	100	0.72	0.78	0.040	0.3	0.00270
regrowing forest	66	0.29	100	2.13	1.62	0.007	1	0.00330
Cropland	81	0.29	100	1.96	1.53	0.620	0.3	0.0823
Stream channel	100	0.29	100	2.77	2.01	1.000	1	0.582
Dambo	92	0.29	100	2.08	1.59	0.003	1	0.00139
transitional vegetation	92	0.29	100	2.18	1.65	0.003	1	0.00144

Table 3.11. Non-landuse dependent parameters by watershed

Parameter	Value			
	Kamwamphula	Luelo	Kanyanga	Mphiri
recession coefficient	0.21	0.11	0.06	0.05
seepage coefficient (day^{-1})	0.00	0.00	0.00	0.00
initial unsaturated storage (cm)	10.00	10.00	10.00	10.00
initial snow (cm)	0.00	0.00	0.00	0.00
initial saturated storage (cm)	0.00	0.00	0.00	0.00
sediment delivery ratio	0.15	0.15	0.18	0.18
unsaturated available water capacity (cm)	10.00	10.00	10.00	10.00

4.0 Results and Discussion

4.1 Landuse changes in Magodi

4.1.1 Introduction

In this section, the landuse changes between the period 1989 and 2007 for Kamwamphula and Luelo in West Magodi and Mphiri and Kanyanga in East Magodi are considered. The results were arrived at by digitizing Landsat (30mx30m) and Ikonos (4mX4m) imagery. The Ikonos imagery of 2007 was used as a basis for delineating the landuses for the "Eastern" and "Western" watersheds. It was important that the trends in landuses changes over the years be documented. As such an additional three Landsat imageries were utilized to provide the contrast with the period prior to 2007. In general, the high resolution Ikonos imagery gave a better view of the landuses and therefore more landuses were delineated from this imagery. In contrast, it was difficult to delineate many landuses using the Landsat imagery because it did not give a lot of contrasts between landuses. For this reason only three landuses were delineated from Landsat imageries: dambo, forest and cropland. It was evident from both imageries that western Magodi has more vegetation cover than Eastern Magodi. Also, it was apparent that Western Magodi, especially Kamwamphula, has had more land cleared and converted to cropland than Eastern Magodi. This research, therefore, sought to find the trends in conversion from forest to cropland and vise versa over the said period. In this regard three imageries in addition to the 2007 Ikonos imagery were studied for West Magodi, that is, Landsat imageries of 1989, 1994, and 2002. For Eastern Magodi, on the other hand, an eyeball observation showed that there was not much change between landuses over the period under consideration. This research, therefore, considered comparing the land uses in 1989 and 2007 for Kanyanga and Mphiri watersheds.

4.1.2 Landuse characteristics of the four watersheds.

Table 4.1 below summarizes the distribution of landuses from the 2007 IKONOS imagery in acreage and percentage (given in parentheses) of the land uses in the four watersheds. It is evident from this table that Kamwamphula watershed had more dense forest (55%) than all the watersheds. The total amount of forest cover (from dense forest and sparse forest) accounted for 71% of the total area of Kamwamphula watershed. Only 3% of Kamwamphula watershed was covered by dambos. This watershed had the least area allocated to human settlement (0.2%) and cropland (24%) when compared to the other three watersheds. This area also had the least abandoned land existing as fallow 1 (1 %) and fallow 2 (0.07 %). This is probably due to the fact that the area had just been opened up to agriculture and croplands are still fertile.

Luelo watershed had the least dense forest at 13% and the highest amount of land utilized for cropland (58%). Total percentage area for Luelo watershed is 29%. Human settlement accounted for 1% of the total area, while dambo area constituted 8%.

Kanyanga had 20% of dense forest. The total area under forestry in Kanyanga was 34%. Fifty one percent of the area was used for cropland while dambo and stream constituted 11% of the total watershed area.

Mphiri came next to Kamwamphula in terms of percentage of total area with forest cover. The watershed had 34% forest cover. Cropland occupied 41% of the watershed area while dambo percent area was 10%.

Table 4.1. Landuse distribution in the four watersheds in 2007 as delineated from Ikonos imagery

landuse code	name	description	area and % area			
			Kamwamphula	Luelo	Kanyanga	Mphiri
21	human Settlement	villages, bare with compacted soil	6.06* (0.22)#	44.54 (1.34)	7.29 (0.64)	14.31 (0.80)
22	playground	treeless bare grounds with scanty grass	0.75 (0.03)	1.11 (0.03)	3.90 (0.34)	0.33 (0.02)
23	roads	compacted earth roads	6.81 (0.25)		0.52 (0.05)	5.41 (0.30)
41	forest dense	forest providing good ground cover with minimal human interference	1527.03 (55.01)	423.63 (12.75)	224.71 (19.74)	424.64 (23.77)
42	forest sparse	forest with sparse vegetation	440.41 (15.86)	417.06 (12.55)	82.87 (7.28)	110.62 (6.19)
51	fallow 1	abandoned cropland with vegetation about 1m tall or less	34.19 (1.23)	69.36 (2.09)	28.17 (2.47)	38.01 (2.13)
52	fallow 2	abandoned cropland containing trees about 2m tall or less	1.871 (0.07)	36.21 (1.09)	2.37 (0.21)	3.18 (0.18)
55	regrowing forest	abandoned with bigger trees that are establishing into a forest	0.82 (0.03)	116.91 (3.52)	83.20 (7.31)	255.25 (14.29)
82	cropland	croplands grown to soy bean, corn, cotton etc.	667.27 (24.04)	1930.56 (58.11)	576.60 (50.64)	731.19 (40.94)
91	stream channel	areas containing stream water			3.08 (0.27)	4.16 (0.23)
92	dambo grassland	treeless grasslands in seasonal tropical wetlands (dambos)	90.77 (3.27)	280.13 (8.43)	90.76 (7.97)	175.41 (9.82)
93	transitional forest	scattered trees on the fringes of dambos		2.52 (0.08)	35.10 (3.08)	23.55 (1.32)
Total			2775.97 (100.00)	3322.03 (100)	1138.56 (100.00)	1786.07 (100.00)

*Landuse area in ha # percentage of total watershed area

4.1.3. Landuse changes between Landsat 1989 and IKONOS 2007 in Kamwamphula, Luelo, Kanyanga and Mphiri

4.1.3.1 Landuse changes in Kamwamphula watershed

Table 4.2 is a cross-tabulation showing changes in landuses that have occurred in Kamwamphula watershed. Columns are percentages of areas by landuse code for the watershed in the year 1989. Rows represent percentages for the year 2007. The table also depicts how each landuse in 1989 had been re-allocated in 2007. For more convenient comparison three land classes were considered: cleared, not cleared and dambo.

It can be seen from the table that almost the whole (95%) Kamwamphula watershed was under forest cover in 1989. Four percent of the land was cleared in 1989 while dambo occupied 2% of the total area. However, by 2007 the amount of forest decreased to 71%. In the same year, the amount of land cleared for cropland, human settlement and other construction work was at 26%.

Table 4.2. Comparison of landuses in Kamwamphula between 1989 and 2007

Year	1989				
2007	landuse	not cleared	cleared	dambo	total
	cleared	23.54	2.29		25.83
	not cleared	69.54	1.36		70.90
	dambo	1.59		1.68	3.27
	Total	94.67	3.65	1.68	100.00

4.1.3.2 Landuse changes in Luelo watershed between 1989 and 2007

Table 4.3 shows the changes in landuse took place in the same period, 1989 and 2007, in Luelo watershed. In 1989 the allocation of land in Luelo watershed was 40% non-cleared land, 52% cleared land and 8% dambo grasslands. In 2007 forest area had reduced to 29% while cleared land had expanded to 63% and dambo area remained almost constant at 9%.

Table 4.3. Comparison in Landuse in Luelo between 1989 and 2007

Year	1989				
2007	landuse	not cleared	cleared	dambo	total
	cleared	21.32	41.34	0.00	62.67
	not cleared	18.17	10.63	0.03	28.83
	dambo	0.20	0.39	7.92	8.51
	total	39.69	52.37	7.95	100.00

4.1.3.3. Landuse change in Mphiri between 1989 and 2007

Table 4.4 depicts the landuses in Mphiri in 1989 and 2007. Forest, cleared land and dambo occupied 52%, 34% and 14% respectively of the total land area in 1989. Land that was not cleared in 1989 had decreased to 44% in 2007 while cleared land had increased by the same percentage. Dambo land has decreased a little and is at 11%.

Table 4.4. Landuses in 1989 and 2007 in Mphiri

Year	1989				
2007	landuse	not cleared	cleared	dambo	total
	cleared	21.24	21.92	1.21	44.36
	not cleared	30.36	11.73	2.17	44.26
	dambo	0.40	0.22	10.75	11.37
	total	52.00	33.87	14.13	100.00

5.1.3.4. Landuse change in Kanyanga between 1989 and 2007

Table 4.5 compares landuses in 1989 and 2007 in Kanyanga watershed. Land that was not cleared accounted for 57% in 1989 while cleared and dambo areas accounted for 35% and 9%, respectively. In 2007 non-cleared, cleared and dambo areas accounted for 34%, 54% and 11, respectively.

Table 4.5. Landuse changes in Kanyanga from 1989 to 2007

Year	1989				
2007		not cleared	cleared	dambo	total
	cleared	30.08	24.15	0.12	54.35
	not cleared	23.11	10.51	0.70	34.32
	dambo	3.34	0.00	7.98	11.32
		56.53	34.66	8.80	100.00

4.1.3.5 Changes in landuses in Kamwamphula from 1994 to 2007

Table 4.6 summarizes the changes in landuses that took place between 1994 and 2007 in Kamwamphula. By 1994 the total amount of forest in Kamwamphula had reduced slightly from the initial 95% to 92%. Cleared land accounted for 5%, while dambo areas accounted for 3% of the total watershed area.

Table 4.6. Changes in Landuses in Kamwamphula between 1994 and 2007

Year	1994				
2007	landuse	not cleared	cleared	dambo	total
	cleared	21.80	4.02	0.00	25.83
	not cleared	70.37	0.53	0.00	70.90
	dambo	0.04	0.02	3.21	3.27
	total	92.22	4.57	3.21	100.00

5.1.3.6 Changes in landuses in Luelo from 1994 to 2007

Changes in landuses for Luelo for the period 1994 and 2007 are summarized in table 4.7. The allocations to land in 1994 were such that 42% was not cleared, 49% was cleared 9% was dambo areas. By 2007 the redistribution of landuses were such that 63% was cleared, 29% was not cleared and 9% was dambo.

Table 4.7. Changes in Landuses in Luelo between 1994 and 2007

Year	1994				
2007	landuse	not cleared	cleared	dambo	total
	cleared	22.51	40.15		62.67
	Not cleared	19.83	8.82	0.18	28.83
	dambo			8.51	8.51
	total	42.34	48.97	8.69	100.00

4.1.3.7 Landuse changes in Kamwamphula between 2002 and 2007

Table 4.8 is shows a comparison in the land patterns between 2002 and 2007 for Kamwamphula. In 2002 land allocated to forest was 86%. A significant (16%) drop was seen from 2002 land cover to 2007 land cover as it dropped to 71% in 2007. The amount of cleared land went up from 10% to 26%, rising almost at the same rate as the decrease in land cover. Dambo did not change within this period.

Table 4.8. Landuse changes in Kamwamphula between 2002 and 2007

Year	2002				
2007	landuse	not cleared	cleared	dambo	total
	cleared	15.53	10.30		25.83
	not cleared	70.79	0.11		70.90
	dambo	0.00		3.27	3.27
	total	86.32	10.41	3.27	100.00

5.1.3.8 Landuse changes in Luelo between 2002 and 2007

Table 4.9 depicts the landuse changes in 2002 and 2007 in Luelo watershed. The 2002 landuses showed that non-cleared land, cleared land and dambo occupied 39%, 52% and 9%, respectively, of the total area. Cleared land increased to 63% while non-cleared land decreased from 39% to 29%.

Table 4.9. Landuse changes in Luelo between 2002 and 2007

Year	2002				
2007	landuse	not cleared	cleared	dambo	total
	cleared	16.66	46.01		62.67
	not cleared	21.83	6.38	0.62	28.83
	dambo	0.12	0.05	8.34	8.51
	total	38.60	52.43	8.96	100.00

4.1.3.9 Summary of trends in landuse change in Kamwamphula, Luelo, Kanyanga, and Mphiri watersheds between 1989 and 2007

Figure 4.1 summarizes the changes in percentage non-cleared, cleared and dambo areas in the four watersheds from the three Landsat imageries and IKONOS imagery between the years 1989 and 2007. There was general decline in forest in all the watersheds between 1989 and 2007. On the contrary, there seemed to be an increasing trend in cleared land in the same period with Kamwamphula attaining the highest land cleared. Dambo land had remained fairly constant.

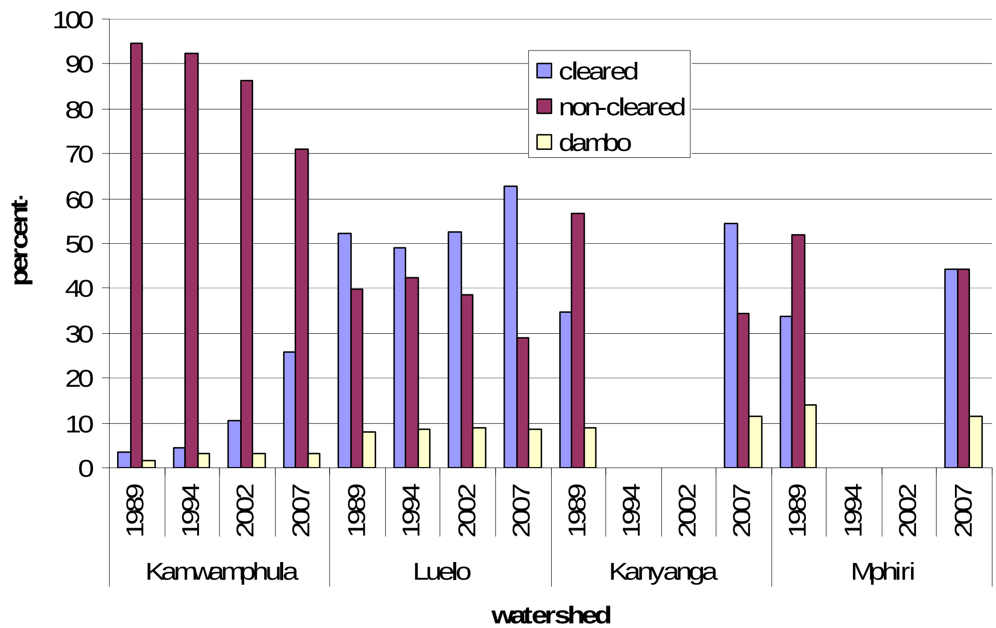

Figure 4.1. Trends in non-cleared, cleared and dambo land percentages between 1989 and 2007 in Kamwamphula, Luelo, Kanyanga and Mphiri

4.2 GWLF SIMULATION RESULTS

4.2.1 Introduction

This section analyzes the GWLF model simulation results. The objective of the simulation was to find out the effect on runoff, streamflow and erosion of the current landuses in the four watersheds. Nutrients were not simulated in this research.

4.2.2. Streamflow in Kamwamphula, Luelo, Kanyanga and Mphiri watershed.

Table 4.10 shows average predicted monthly streamflow values in the four watersheds. Zambia has a unimodal rainfall pattern with one rainfall season, starting in October and ending in May. Both runoff and streamflow started in October, soon after the onset of the rainy season in with the maximum occurring in January. The amount of runoff and streamflow are directly related to the amount of rainfall, which is expected. Between June and September streamflow ceases due to absence of rainfall. Despite differences in the size of watersheds, there appears to no significant differences in runoff and streamflows.

Table 4.10. Average streamflow (cm) for Kamwamphula, Luelo, Kanyanga, and Mphiri watersheds

	Kamwamphula		Luelo		Kanyanga		Mphiri	
month	runoff	streamflow	runoff	streamflow	runoff	streamflow	runoff	streamflow
Apr	0.34	2.00	0.49	2.65	0.49	3.49	0.46	4.17
May	0.01	0.02	0.03	0.11	0.03	0.48	0.03	1.00
Jun	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.23
Jul	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.06
Aug	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Sep	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oct	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Nov	1.28	1.70	2.03	2.24	2.01	2.14	1.87	1.96
Dec	1.67	3.90	2.50	4.23	2.51	3.92	2.36	3.59
Jan	4.90	14.21	7.17	13.44	7.13	12.28	6.70	11.28
Feb	1.87	12.08	3.07	11.81	3.08	11.24	2.86	10.62
Mar	2.06	8.69	2.99	9.41	2.98	10.01	2.81	10.24

4.2.3. Erosion and sediment loss

Table 4.11 shows the extent of erosion and sediment loss in tonnes/ha in the four watersheds. Highest soil erosion and sediment losses occurred in January in all the watersheds. This is expected since this is the time when there is highest rainfall and therefore erosive forces are at their maximum during this time. The highest amount of erosion and sediment loss in the month of January was predicted to come from Luelo watershed at 25 and 3 tonnes/ha respectively. This result is expected since Luelo has the highest amount of cropland area (Table 4.1) and has higher slopes as it is in the hilly region. The lowest erosion and sediment loss, 10 tonnes/ha and 2 tonnes/ha, respectively, was predicted to come from Mphiri watershed. Mphiri watershed has gentle slopes and also soils that are generally more permeable. The annual average erosion rates for Kamwamphula, Luelo, Kanyanga and Mphiri are 33, 68, 34, and 29 tonnes/ha/yr, respectively. Corresponding sediment yields were 5, 10, 6 and 5 tonnes/ha/yr, respectively, for Kamwamphula, Luelo, Kanyanga and Mphiri.

Table 4.11. Erosion and sediment loss (tonnes/ha) in Kamwamphula, Luelo, Kanyanga and Mphiri watersheds

Month	Kamwamphula		Luelo		Kanyanga		Mphiri	
	Erosion	sediment	erosion	sediment	erosion	sediment	erosion	sediment
Apr	0.32	0.00	0.65	0.01	0.33	0.01	0.28	0.00
May	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00
Jun	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jul	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aug	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sep	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oct	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nov	1.20	0.03	2.46	0.06	1.24	0.04	0.96	0.03
Dec	5.81	0.36	11.98	0.64	6.02	0.39	5.05	0.31
Jan	12.07	1.68	24.80	3.22	12.49	1.95	10.44	1.56
Feb	7.54	1.31	15.51	2.70	7.80	1.63	6.53	1.30
Mar	6.22	1.90	12.76	3.74	6.42	2.27	5.40	1.82
Annual average values	33.16	5.28	68.18	10.36	34.30	6.28	28.67	5.02

4.2.4. Erosion and sediment yield by landuse

Table 4.12 shows runoff and erosion by landuse in tonnes/ha/yr in the four watersheds. The highest rates of erosion were predicted to occur from roads with rates as high as 595 tonnes/ha/yr occurring in Kamwamphula watershed. The corresponding sediment yield from roads in Kamwamphula watershed was 95 tonnes/ha/yr. The ranges for erosion and sediment yields from roads in the four watersheds were, respectively, 343 to 595 and 60 to 95 tonnes/ha/yr. Settlement and cropland, in that order, came next to roads with Kamwamphula giving highest values of erosion and sediment in both these values. The ranges in erosion and sediment yield for settlement were 261 to 471 and 45 to 75 tonnes/ha/yr, respectively. Cropland had erosion rates ranging from 61 to 123 tonnes/ha/yr and sediment yields between 11 and 20 tonnes/ha/yr. The high values in roads, settlements, and cropland are not unexpected since they have poor vegetative cover and, therefore, poor protection from raindrop impact.

Table 4.12. Erosion and sediment yield by landuse (tonnes/ha/yr) in Kamwamphula, Luelo, Kanyanga and Mphiri watersheds

Landuse	Kamwamphula		Luelo		Kanyanga		Mphiri	
	erosion	sediment	erosion	sediment	erosion	sediment	erosion	sediment
settlement	470.92	75.02	389.32	59.18	275.52	50.42	261.36	45.74
playground	9.96	1.59	10.11	1.54	18.87	3.45	5.14	0.90
Roads	594.89	94.77			375.29	68.68	342.80	59.99
forest dense	1.32	0.21	0.62	0.09	0.64	0.12	0.62	0.11
forest sparse	1.83	0.29	1.69	0.26	0.92	0.17	0.84	0.15
fallow 1	2.26	0.36	1.78	0.27	0.03	0.00	1.04	0.18
fallow 2	0.72	0.11	0.81	0.12	0.29	0.05	2.38	0.42
regrowing forest	1.65	0.26	1.65	0.25	1.24	0.23	1.26	0.22
Cropland	123.27	19.64	107.50	16.34	63.07	11.54	61.19	10.71
Dambo	0.00	0.00	1.08	0.16	0.71	0.13	0.72	0.13
transitional forest	-	-	1.07	0.16	0.74	0.14	0.75	0.13

4.2.5 Validation of the GWLF model

Figure 4.2 compares the streamflow results from obtained by GWLF simulation and observed values between the months of December and March in the 2008/2009 rainfall season for Kamwamphula watershed. Although the model seemed to pick the trends in the streamflow, it under-predicted the streamflow for Kamwamphula.

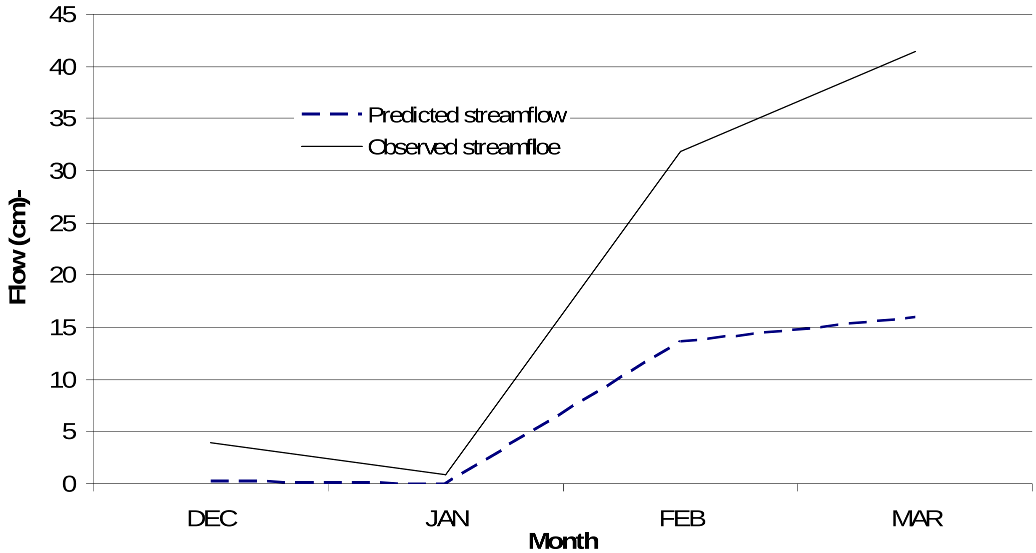

Figure 4.3. Predicted and observed streamflow results for Kamwamphula watershed

Figure 4.3 shows the predicted and observed results for Luelo watershed. The GWLF over-predicted streamflow for December, under-predicted the streamflow for January and February, and over-predicted the streamflow for the month of March.

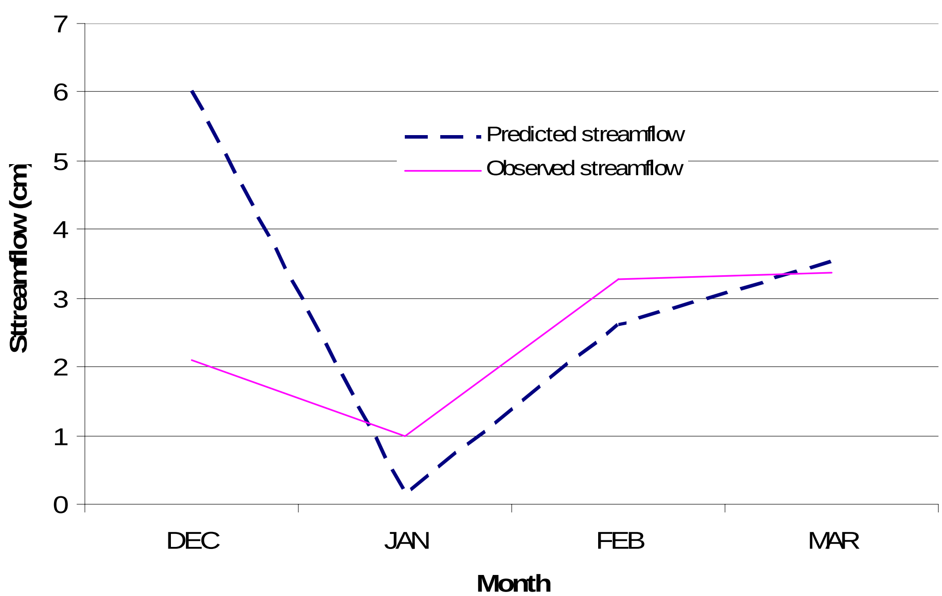

Figure 4.3. Predicted and observed streamflow results for Luelo watershed

Figure 4.4 shows the predicted and observed streamflow results for Kanyanga watershed. The GWLF model over-predicted streamflow for December, February and Marrch and under-predicted the flow for January.

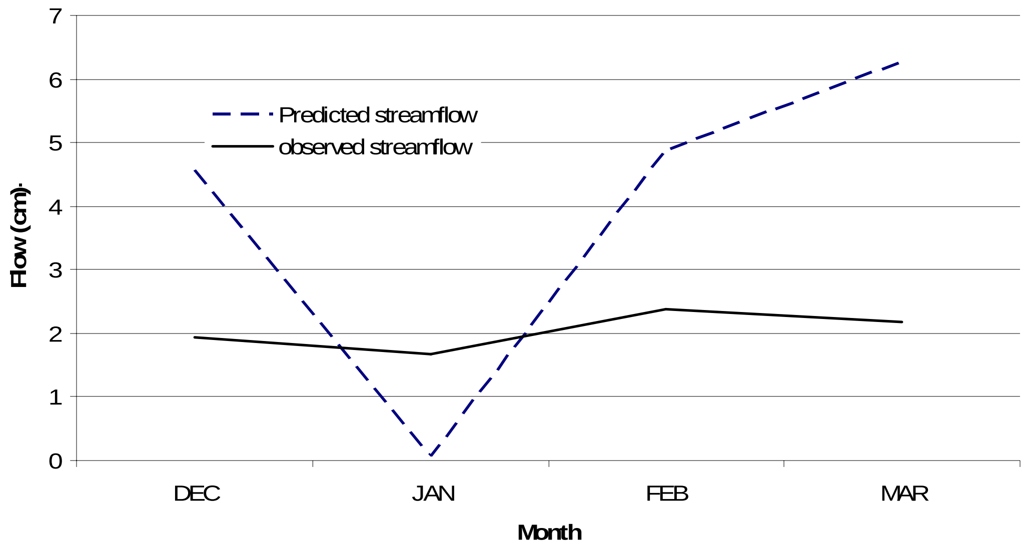

Figure 4.4. Predicted and observed streamflow results for Kanyanga watershed

Figure 4.5 shows the results of GWLF simulation and observed results for Mphiri watershed. The GWLF model over-predicts the streamflow, except for January.

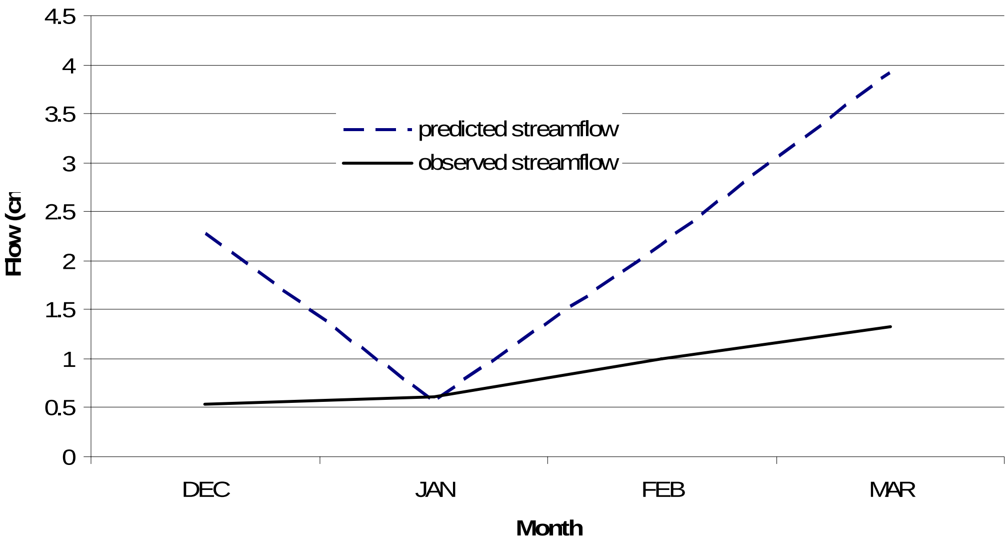

Figure 4.5. Predicted and observed streamflow results for Mphiri watershed

4.2.6. Sensitivity analysis of the GWLF model

A sensitivity analysis of the GWLF was carried out to find the sensitivity of the model to recession coefficient and unsaturated storage. The sensitivity analysis was carried out on Kanyanga watershed to see how changes in recession coefficient affects groundwater levels. The GWLF model was run by varying the recession coefficients and unsaturated soil moisture capacity while holding other parameters constant.

4.2.6.1 Sensitivity of GWLF to changes in recession coefficient

The 1985-1995 precipitation data was used as the weather input. Every parameter in the transport file for Kanyanga watershed was held constant except for the recession coefficients. Five recession coefficients were used: 0.02, 0.04, 0.06, 0.08, and 0.10. Figure 4.6 shows how groundwater flow changes with changes in recession coefficients. The model is sensitive to changes in recession coefficients. The recession coefficient affects the distribution of groundwater levels in time but does not affect the total volume of groundwater. In general, higher recession coefficients result in quicker attainment of peak levels and higher peak volumes. The GWLF model, however, is insensitive to very high recession coefficients. On the other hand, lower recession coefficients result in delayed attainment of peak levels and lower volumes at peak.

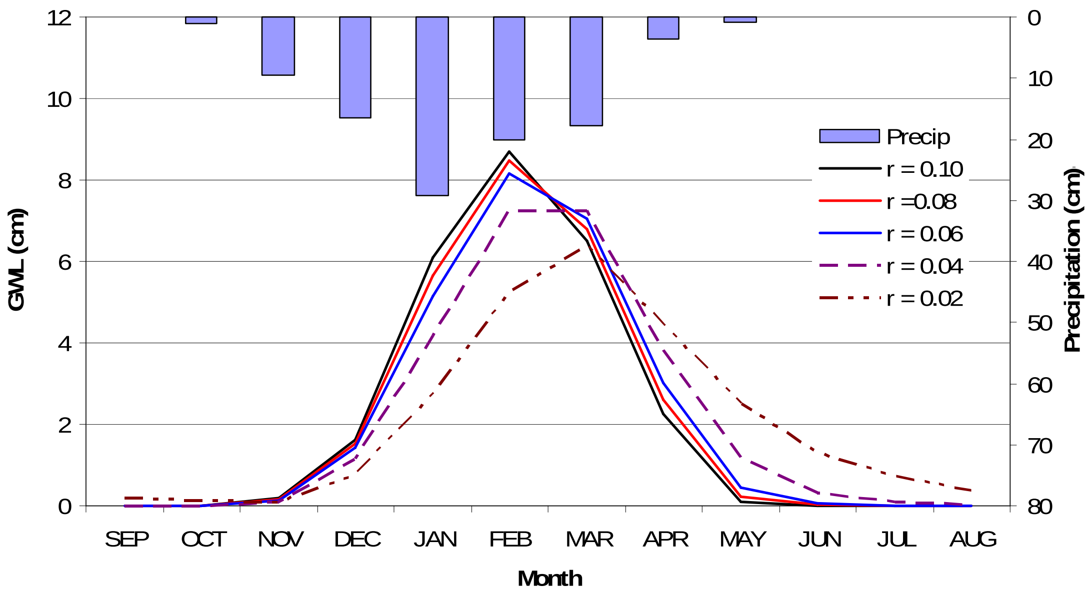

Figure 4.6. Groundwater response to changes in recession coefficient

Table 4.7 shows the predicted annual water balance for each recession coefficient value. It can be seen that the recession does not change either the volume of groundwater or the annual water balance but only the distribution of water in time.

Table 4.13 Annual water balance resulting from changes in the recession coefficient

r = 0.02	r = 0.04	r = 0.06	r = 0.08	r = 0.10
98.90	98.90	98.90	98.90	98.90
55.29	55.29	55.29	55.29	55.29
24.91	25.26	25.41	25.46	25.49
18.24	18.24	18.24	18.24	18.24
197.34	197.69	197.84	197.89	197.92

4.2.6.1 Sensitivity of GWLF to changes in unsaturated moisture capacity (U^*)

Figure 4.8 shows how groundwater varied with changes in unsaturated soil moisture capacity (SMC) storage for Kamwamphula . GWLF simulation was done by changing the unsaturated soil moisture capacity at each run, setting the initial unsaturated storage at (U^*-3).

The results show that GWLF is sensitive to unsaturated moisture but within a certain range of this parameter. Generally, higher unsaturated soil moisture capacity ranges give rise to lower groundwater levels and vice versa. However, very low unsaturated soil moisture storage (< 8 cm, in the case of Kanyanga) does not produce any change in GWL. In addition, there is no sensitivity of groundwater to unsaturated storage under conditions of low precipitation.

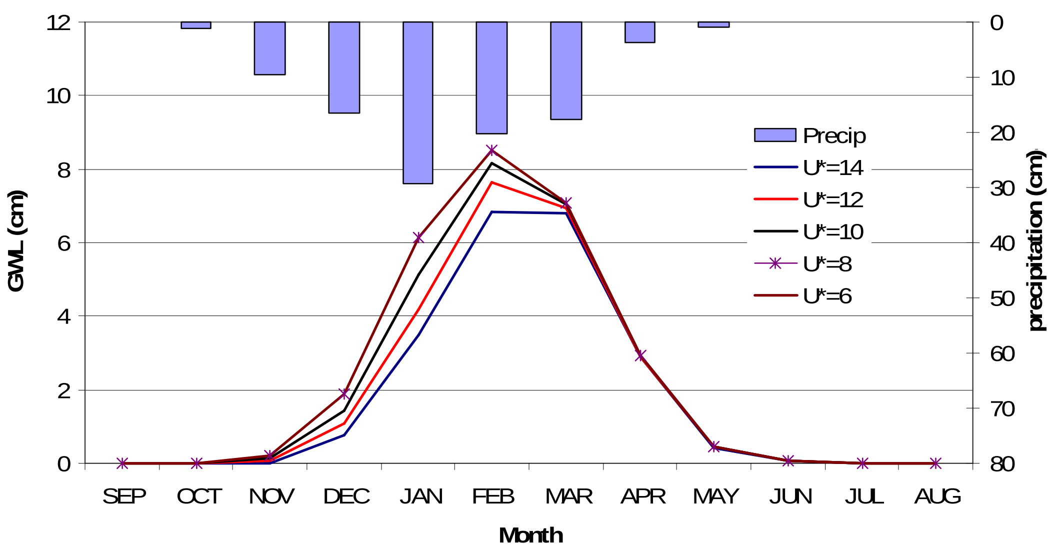

Figure 4.8 Groundwater flow response to changes in unsaturated storage (U*)

Table 4.14 shows the predicted annual water balances produced by varying unsaturated soil moisture storage SMC water balances. Higher unsaturated soil moisture decease lower groundwater levels but increases ET and vise versa.

Table 4.14. Annual water balance for different unsaturated storage capacity.

Component	U* = 14 cm	U* = 12 cm	U* = 10 cm	U* = 8 cm	U* = 6 cm
Precipitation	98.90	98.90	98.90	98.90	98.90
ET	59.06	57.06	55.06	53.05	50.82
GWL	21.32	23.31	25.31	27.33	29.55
Runoff	18.24	18.24	18.24	18.24	18.24

4.2.6 Summary of GWLF simulation results

GWLF simulation results show that Luelo watershed had the highest amount of runoff, erosion, and sediment yield while the lowest values came from Mphiri. High values in Luelo could be explained in terms of less vegetative cover presenting this watershed. Low values in Mphiri could be because of the moderate slopes in this area.
The GWLF model generally under-predicted streamflow for Kamwamphula watershed and over-predicted the streamflow of Luelo, Kanyanga and Mphiri watershed. This could be because poor parameters were selected.

GWLF is sensitive to both recession coefficient and unsaturated storage within certain ranges of these values. The model is not very sensitive to very high recession coefficients and very low recession coefficients. These results could explain the mismatch between the predicted and observed streamflows. For example the recession coefficients assigned to Luelo and Kamwamphula are very high such that the model may not be sensitive to such these values and underestimate or overestimate the monthly and annual water balances. Likewise the values of unsaturated SMC might be too high for the model to make accurate hydrological erosion predictions.

5.0 Conclusions and recommendations

5.1 Conclusions

GIS has been used to delineate landuses and track landuse changes between 1989 and 2007. From the data given above it is evident that forest land area was on the decrease in all the watersheds. However, Kanyanga and Kamwamphula had lost more forest land than the other two watersheds. Cropland was expanding in the four watersheds with Kamwamphula showing the highest cropland expansion. Based on the imagery, forests are being converted into croplands. At the same time, some of the croplands are being abandoned and they revert to forest landuse. Dambo land seemed to remain constant over this period.

According to the results of GWLF simulation, cropland contributes more runoff than any other landuse. This is obviously because of cropland in general has less vegetative cover, exposing more soil to erosive forces, even when good management is used. The contribution to runoff by roads and settlement is remarkable. Despite being smaller in area, these areas contribute a lot of runoff. The reason for high runoff is due to their being bare.

The highest soil erosion and soil loss was obtained from Luelo watershed while the lowest loss was obtained from Mphiri watershed, according to GWLF simulation results. High soil erosion in Luelo is probably due to expansive cropland area that exists in this watershed. The lower soil loss in Mphiri could be attributed to lower slopes that exist in this area.

The GWLF simulation results also showed that areas having a dense dambo network, such as in Kanyanga and Mphiri watersheds, will give rise to higher runoff than non-dambo areas. This finding is consistent with findings of other authors in dambo research such as Balek (1973) and Bullock (1992b).

Generally, modeling results show that GWLF has some limitations in predicting streamflow. This result could emanate from lack of proper understanding of the dambo hydrology. There is need for more thorough study of the area in order to come up with parameters that could closely resemble the hydrological characteristics of the area. Other factors affecting the accuracy of modeling result from the weaknesses of the model. For example, dambo soils have high infiltration capacities during the onset of the dry season and lower infiltration capacity later in the rainy as the soils become more saturated. This change is not well represented in the model as a single curve number value must apply for both of these conditions.

5.2 Recommendations

The progressive changes in land use that are apparent from this study, and the resulting increase in runoff and erosion highlight the importance of changing current practices to halt the impacts. Since croplands, dambos, settlements and roads seem to be the major sources of runoff in the area, there is need for proper management of these landuses. Proper soil conservation practices need to be implemented such as farming on the contour and agroforestry. Dambos need to have good land cover at all times if dambo erosion is to be prevented. Proper road designs need to be in place so that water is safely led away from areas where it is likely to be an erosion hazard.

To support these management recommendations, there is also the need for research to better understand the behavior of dambos as well as models to better represent their hydrologic function in the landscape. Of primary importance is the need for better data on soils and land characteristics in order to come up with parameters that define the characteristics of the landscape. Also needed are runoff and streamflow data in order to validate the application of hydrologic models that can accurately reflect the impact of different land use and management scenarios.

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APPENDIX A: Nutrient file for Magodi used in GWLF simulation

0,0,0,0
4,11,12,7,8
0,0
0,0
0,0
0,0
0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0,0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
1
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0
0,0,0,0

APPENDIX B-1: Transport file for Kamwamphula used in GWLF simulation

```
10,0,0.0
0.208,0,10,0,0,0.1593,10.0,10,1985,1995,0,0.0,5000,0.5
0
0
0
0
0
"APR",1.000,11.90,1,0.13
"MAY",1.000,11.50,0,0.06
"JUN",0.816,11.30,0,0.06
"JUL",0.816,11.40,0,0.06
"AUG",0.816,11.70,0,0.06
"SEP",0.816,12.10,0,0.06
"OCT",0.816,12.50,0,0.06
"NOV",0.816,12.90,0,0.14
"DEC",1.000,13.10,1,0.42
"JAN",1.000,13.00,1,0.42
"FEB",1.000,12.70,1,0.42
"MAR",1.000,12.30,1,0.42
"settlement",6.06,89,0.629,"settlement"
"playground",0.75,89,0.0133,"playground"
"roads",6.81,93,0.791,"roads"
"Forest_dense",1527.03,66,0.00205,"dense"
"forest_sparse",440.41,66,0.00285,"sparse"
"fallow_1",34.19,86,0.00304,"fallow1"
"fallow_2",1.87,79,0.00102,"fallow2"
"regrowth",0.82,66,0.00257,"regrowth"
"cropland",667.27,81,0.172,"cropland"
"dambo",90.77,92,0.0.000800,"dambo"
```

APPENDIX B-2: Transport file for Luelo used in GWLF simulation

```
10,0,0.0
0.108,0,10,0,0,0.152,10.0,10,1985,1995,0,0.0,5000,0.5
0
0
0
0
0
"APR",1.000,11.90,1,0.13
"MAY",1.000,11.50,0,0.06
"JUN",0.546,11.30,0,0.06
"JUL",0.546,11.40,0,0.06
"AUG",0.546,11.70,0,0.06
"SEP",0.546,12.10,0,0.06
"OCT",0.546,12.50,0,0.06
"NOV",0.546,12.90,0,0.14
"DEC",1.000,13.10,1,0.42
"JAN",1.000,13.00,1,0.42
"FEB",1.000,12.70,1,0.42
"MAR",1.000,12.30,1,0.42
"settlement",44.55,89,0.520,"settlement"
"playground",1.106,89,0.0135,"playground"
"Forest_dense",423.628,66,0.000961,"dense"
"forest_sparse",417.062,66,0.00263,"sparse"
"fallow_1",69.356,86,0.00240,"fallow1"
"fallow_2",36.212,79,0.00115,fallow2"
"regrowth",116.906,66,0.00257,"Regrowth"
"Cropland",1930.561,81,0.150,"cropland"
"dambo",280.129,92,0.00144,"dambo"
"transitional",2.523,92,0.00143,"transitional"
```

APPENDIX B-3: Transport file for Kanyanga used in GWLF simulation

```
11,0,0.0
0.063,0,10,0,0,0.183,10.0,10,1985,1995,0,0.0,5000,0.5
0
0
0
0
0
"APR",1.000,11.90,1,0.13
"MAY",1.000,11.50,0,0.06
"JUN",0.595,11.30,0,0.06
"JUL",0.595,11.40,0,0.06
"AUG",0.595,11.70,0,0.06
"SEP",0.595,12.10,0,0.06
"OCT",0.595,12.50,0,0.06
"NOV",0.595,12.90,0,0.14
"DEC",1.000,13.10,1,0.42
"JAN",1.000,13.00,1,0.42
"FEB",1.000,12.70,1,0.42
"MAR",1.000,12.30,1,0.42
"settlement",7.28,89,0.368,"settlement"
"playgrounds",3.90,89,0.0252,"playgrounds"
"road",0.52,93,0.499,"road"
"forest_dense",224.71,66,0.00100,"dense"
"forest_sparse",82.87,66,0.00143,"sparse"
"fallow_1",28.17,86,0.000036,"fallow1"
"fallow_2",2.37,79,0.000408,fallow2"
"Regrowth",83.20,66,0.001933,"Regrowth"
"Cropland",576.60,81,0.0880,"cropland"
"dambo",93.84,92,0.000941,"dambo"
"transitional",35.10,92,0.000988,"transitional"
```

APPENDIX B-4: Transport for Mphiri used in GWLF simulation

```
11,0,0.0
0.045,0,10,0,0,0.175,10.0,10,1985,1994,0,0.00,5000,0.5
0
0
0
0
0
"APR",1.000,11.90,1,0.13
"MAY",1.000,11.50,0,0.06
"JUN",0.674,11.30,0,0.06
"JUL",0.674,11.40,0,0.06
"AUG",0.674,11.70,0,0.06
"SEP",0.674,12.10,0,0.06
"OCT",0.674,12.50,0,0.06
"NOV",0.674,12.90,0,0.13
"DEC",1.000,13.10,1,0.42
"JAN",1.000,13.00,1,0.42
"FEB",1.000,12.70,1,0.42
"MAR",1.000,12.30,1,0.42
"settlement",14.311,89,0.350,"settlement"
"playgrounds",0.325,89,0.00688,"playground"
"roads",5.407,93,0.457, "roads"
"Forest_dense",424.635,66,0.000973,"dense"
"Forest_sparse",110.623,66,0.001305,"sparse"
"fallow_1",38.005,86,0.00140,"fallow1"
"fallow_2",3.184,79,0.00339,"fallow2"
"regrowth",255.256,66,0.00197,"Regrowth"
"cropland",731.191,81,0.0856,"cropland"
"dambo",179.576,92,0.000965,"dambo"
"transitional",23.552,92,0.00100,"transitional"
```

APPENDIX B-5: Transport file used for GWLF model validation for Kamwamphula watershed

```
10,0,0.0
0.208,0,10,0,0,0.1593,10.0,2,2008,2009,0,0.0,5000,0.5
0
0
0
0
0
"APR",1.000,11.90,1,0.13
"MAY",1.000,11.50,0,0.06
"JUN",0.816,11.30,0,0.06
"JUL",0.816,11.40,0,0.06
"AUG",0.816,11.70,0,0.06
"SEP",0.816,12.10,0,0.06
"OCT",0.816,12.50,0,0.06
"NOV",0.816,12.90,0,0.14
"DEC",1.000,13.10,1,0.42
"JAN",1.000,13.00,1,0.42
"FEB",1.000,12.70,1,0.42
"MAR",1.000,12.30,1,0.42
"settlement",6.06,89,0.629,"settlement"
"playground",0.75,89,0.0133,"playground"
"roads",6.81,93,0.791,"roads"
"Forest_dense",1527.03,66,0.00205,"dense"
"forest_sparse",440.41,66,0.00285,"sparse"
"fallow_1",34.19,86,0.00304,"fallow1"
"fallow_2",1.87,79,0.00102,"fallow2"
"regrowth",0.82,66,0.00257,"regrowth"
"cropland",667.27,81,0.172,"cropland"
"dambo",90.77,92,0.0.000800,"dambo
```

APPENDIX B-6: Transport file used for GWLF model validation for Luelo watershed

10,0,0.0
0.108,0,10,0,0,0.152,10.0,2,2008,2009,0,0.0,5000,0.5
0
0
0
0
0
"APR",1.000,11.90,1,0.13
"MAY",1.000,11.50,0,0.06
"JUN",0.546,11.30,0,0.06
"JUL",0.546,11.40,0,0.06
"AUG",0.546,11.70,0,0.06
"SEP",0.546,12.10,0,0.06
"OCT",0.546,12.50,0,0.06
"NOV",0.546,12.90,0,0.14
"DEC",1.000,13.10,1,0.42
"JAN",1.000,13.00,1,0.42
"FEB",1.000,12.70,1,0.42
"MAR",1.000,12.30,1,0.42
"settlement",44.55,89,0.520,"settlement"
"playground",1.106,89,0.0135,"playground"
"Forest_dense",423.628,66,0.000961,"dense"
"forest_sparse",417.062,66,0.00263,"sparse"
"fallow_1",69.356,86,0.00240,"fallow1"
"fallow_2",36.212,79,0.00115,fallow2"
"regrowth",116.906,66,0.00257,"Regrowth"
"Cropland",1930.561,81,0.150,"cropland"
"dambo",280.129,92,0.00144,"dambo"
“transitional”,2.523,92,0.000143,“transitional”

APPENDIX B-7: Transport file used for GWLF model validation for Kanyanga watershed

```
11,0,0.0
0.063,0,10,0,0,0.183,10.0,2,2008,2009,0,0.0,5000,0.5
0
0
0
0
0
"APR",1.000,11.90,1,0.13
"MAY",1.000,11.50,0,0.06
"JUN",0.595,11.30,0,0.06
"JUL",0.595,11.40,0,0.06
"AUG",0.595,11.70,0,0.06
"SEP",0.595,12.10,0,0.06
"OCT",0.595,12.50,0,0.06
"NOV",0.595,12.90,0,0.14
"DEC",1.000,13.10,1,0.42
"JAN",1.000,13.00,1,0.42
"FEB",1.000,12.70,1,0.42
"MAR",1.000,12.30,1,0.42
"settlement",7.28,89,0.368,"settlement"
"playgrounds",3.90,89,0.0252,"playgrounds"
"road",0.52,93,0.499,"road"
"forest_dense",224.71,66,0.00100,"dense"
"forest_sparse",82.87,66,0.00143,"sparse"
"fallow_1",28.17,86,0.000036,"fallow1"
"fallow_2",2.37,79,0.000408,fallow2"
"Regrowth",83.20,66,0.001933,"Regrowth"
"Cropland",576.60,81,0.0880,"cropland"
"dambo",93.84,92,0.000941,"dambo"
"transitional",35.10,92,0.000988,"transitional"
```

APPENDIX B-8: Transport file used for GWLF validation for Mphiri

```
11,0,0.0
0.045,0,10,0,0,0.175,10.0,2,2008,2009,0,0.00,5000,0.5
0
0
0
0
0
"APR",1.000,11.90,1,0.13
"MAY",1.000,11.50,0,0.06
"JUN",0.674,11.30,0,0.06
"JUL",0.674,11.40,0,0.06
"AUG",0.674,11.70,0,0.06
"SEP",0.674,12.10,0,0.06
"OCT",0.674,12.50,0,0.06
"NOV",0.674,12.90,0,0.13
"DEC",1.000,13.10,1,0.42
"JAN",1.000,13.00,1,0.42
"FEB",1.000,12.70,1,0.42
"MAR",1.000,12.30,1,0.42
"settlement",14.311,89,0.350,"settlement"
"playgrounds",0.325,89,0.00688,"playground"
"roads",5.407,93,0.457, "roads"
"Forest_dense",424.635,66,0.000973,"dense"
"Forest_sparse",110.623,66,0.001305,"sparse"
"fallow_1",38.005,86,0.00140,"fallow1"
"fallow_2",3.184,79,0.00339,"fallow2"
"regrowth",255.256,66,0.00197,"Regrowth"
"cropland",731.191,81,0.0856,"cropland"
"dambo",179.576,92,0.000965,"dambo"
"transitional",23.552,92,0.00100,"transitional"
```

APPENDIX C: Weather file

30,4-85	22.30,0.00	17.65,0.00	18.10,0.00
19.50,0.09	20.80,0.00	18.95,0.00	17.95,0.00
21.75,1.13	20.75,0.00	17.25,0.00	17.40,0.00
22.35,0.00	18.30,0.00	16.45,0.00	16.45,0.00
21.90,0.00	17.45,0.00	16.20,0.00	17.95,0.00
21.65,0.00	17.50,0.00	15.50,0.00	16.70,0.00
22.80,0.00	17.35,0.00	31,7-85	17.80,0.00
22.65,1.45	17.65,0.00	15.50,0.00	18.35,0.00
22.10,0.35	18.60,0.00	16.30,0.00	16.10,0.00
22.65,0.01	18.10,0.00	16.30,0.00	16.65,0.00
21.05,0.00	18.60,0.00	16.95,0.00	17.60,0.00
19.55,0.00	18.80,0.00	17.20,0.00	18.70,0.00
18.90,0.00	18.05,0.00	19.20,0.00	18.10,0.00
19.20,0.00	16.75,0.00	19.65,0.00	17.85,0.00
19.65,0.00	17.05,0.00	18.15,0.00	17.95,0.00
20.20,0.00	19.50,0.00	18.25,0.00	17.55,0.00
20.75,0.00	17.00,0.00	16.05,0.00	16.40,0.00
21.20,0.00	16.40,0.00	16.90,0.00	16.95,0.00
21.30,0.00	16.80,0.00	16.65,0.00	18.00,0.00
20.90,0.00	30,6-85	15.70,0.00	17.75,0.00
21.30,0.00	17.20,0.00	14.60,0.00	18.25,0.00
20.84,0.00	17.40,0.00	14.15,0.00	16.95,0.00
19.35,0.00	17.45,0.00	13.90,0.00	15.00,0.00
20.70,0.00	14.90,0.00	13.95,0.00	16.45,0.00
22.30,0.00	14.85,0.00	13.70,0.00	17.40,0.00
20.30,0.00	15.15,0.00	15.20,0.00	18.95,0.00
18.75,0.00	14.40,0.00	16.80,0.00	30,9-85
21.10,0.00	16.90,0.00	17.90,0.00	21.10,0.00
19.85,0.00	17.30,0.00	18.65,0.00	20.70,0.00
19.80,0.00	16.85,0.00	17.95,0.00	22.45,0.00
21.05,0.00	17.45,0.00	17.15,0.00	21.80,0.00
31,5-85	17.00,0.00	17.10,0.00	21.45,0.00
20.40,0.00	17.50,0.00	15.60,0.00	21.45,0.00
20.75,0.00	17.50,0.00	14.65,0.00	19.85,0.00
20.50,0.00	15.90,0.00	15.60,0.00	19.90,0.00
20.20,0.00	16.90,0.00	16.45,0.00	20.25,0.00
20.95,0.00	15.95,0.00	17.40,0.00	21.25,0.00
19.45,0.00	16.30,0.00	17.75,0.00	20.75,0.00
20.30,0.00	15.15,0.00	31,8-85	22.35,0.00
21.10,0.00	15.20,0.00	14.65,0.00	24.35,0.00
21.95,0.00	15.05,0.00	15.60,0.00	21.20,0.00
19.45,0.00	14.70,0.00	15.95,0.00	23.45,0.00
20.55,0.00	17.70,0.00	16.70,0.00	24.70,0.00
20.75,0.36	16.60,0.00	18.50,0.00	22.05,0.00
21.45,0.00	21.10,0.00	22.10,0.00	30,11-85
20.95,0.00	21.85,0.00	21.05,0.00	25.45,0.00
21.70,0.00	23.55,0.00	22.45,0.00	25.45,0.00
21.35,0.00	22.70,0.00	23.65,0.00	26.65,0.00
20.85,0.00	23.25,0.00	23.20,0.00	27.30,0.00
21.95,0.00	20.05,0.00	23.10,0.00	26.05,0.00
21.35,0.00	21.70,0.00	23.65,0.00	25.05,0.01
22.95,0.00	22.10,0.00	22.80,0.00	24.50,0.00
21.05,0.00	23.00,0.00	23.45,0.00	24.15,2.10
22.15,0.00	21.20,0.00	23.80,1.20	23.05,0.00
20.20,0.00	22.40,0.00	23.45,0.01	24.05,2.20
19.80,0.00	22.05,0.00	24.05,0.00	21.80,3.40
20.65,0.00	24.60,0.00	25.75,0.00	21.35,0.03
31,10-85	24.05,0.00	25.70,0.80	21.05,0.00
20.15,0.00	24.00,0.00	25.55,0.01	21.80,0.00

APPENDIX C: Weather file

22.95,0.00	21.50,0.01	23.35,3.44	22.90,3.98
22.80,0.00	22.15,0.00	20.65,1.25	23.05,0.33
22.60,0.00	22.20,0.00	21.15,2.28	21.40,0.00
21.10,0.37	23.60,0.00	20.05,1.92	22.40,2.00
20.75,0.89	23.40,0.00	23.10,0.16	22.85,0.00
21.00,0.74	23.45,0.02	21.75,0.20	23.15,2.75
20.55,6.30	21.65,0.54	23.60,0.00	21.20,0.15
20.80,0.17	21.05,1.27	22.10,0.21	22.80,0.00
19.15,1.45	23.35,0.96	20.75,0.02	22.10,0.00
19.45,3.86	22.70,0.00	22.20,2.04	22.35,6.50
21.90,1.65	23.65,0.77	21.75,0.15	19.10,1.27
24.05,0.47	23.75,0.00	22.80,2.46	22.70,0.00
23.15,0.55	24.35,0.00	20.60,4.44	22.65,5.31
21.85,1.93	22.80,0.00	22.45,0.13	22.15,1.60
22.40,2.50	23.35,3.45	22.10,0.15	22.75,0.10
22.50,0.00	23.45,1.25	22.90,0.60	23.60,0.00
31,12-85	23.15,0.00	21.50,3.29	24.25,0.00
21.65,0.00	23.00,0.00	21.75,0.08	23.80,0.00
23.30,7.59	22.65,0.48	23.00,1.09	24.10,0.36
22.05,1.73	31,1-86	23.05,3.55	22.30,0.00
22.65,0.15	21.85,1.01	20.85,0.05	22.25,0.00
22.55,0.86	22.40,0.99	20.95,0.07	23.05,0.00
22.55,0.20	20.95,1.55	28,2-86	31,3-86
21.65,0.23	22.05,0.20	23.20,1.61	22.55,0.00
22.05,2.04	21.30,0.27	23.95,0.30	22.55,0.65
23.00,0.45	22.75,4.18	21.85,0.50	23.25,0.09
23.60,0.35	21.05,0.00	21.15,0.02	22.40,0.22
22.70,0.40	22.50,2.98	22.90,2.71	21.90,0.25
20.95,1.35	20.45,0.01	21.00,1.16	21.25,0.65
21.95,0.02	21.60,0.00	19.95,0.00	19.55,0.00
20.80,0.27	20.35,0.00	18.75,0.00	19.45,0.00
22.20,0.00	21.50,0.00	19.30,0.00	18.80,0.00
21.90,0.00	20.85,0.03	18.55,0.00	17.10,0.00
21.95,0.00	22.25,0.00	18.85,0.00	16.80,0.00
22.75,1.02	21.35,0.00	19.00,0.00	16.15,0.00
21.60,0.33	21.80,0.00	19.10,0.00	16.70,0.00
22.95,0.82	20.80,0.00	18.90,0.00	16.70,0.00
23.95,0.00	22.60,0.42	20.05,0.00	16.45,0.00
23.75,0.00	21.35,0.20	20.65,0.00	15.90,0.00
23.70,0.00	22.30,0.00	20.30,2.72	13.60,0.00
24.20,0.00	22.00,0.00	19.18,0.00	15.05,0.00
23.35,1.44	22.80,0.21	19.55,0.00	14.05,0.00
22.60,1.95	23.75,0.00	19.20,0.00	14.75,0.00
22.90,0.16	23.05,0.00	18.05,0.00	16.35,0.00
20.60,2.00	22.25,0.93	19.55,0.00	17.35,0.00
21.85,0.02	21.50,0.00	19.00,0.00	17.45,0.00
22.20,0.30	21.60,0.00	19.55,0.00	15.35,0.00
21.35,0.00	21.75,0.27	19.45,0.00	15.25,0.00
20.80,0.03	20.60,0.01	18.15,0.00	16.30,0.00
20.30,0.00	21.35,0.00	17.70,0.00	17.45,0.00
21.35,0.00	21.25,1.45	19.25,0.00	15.70,0.00
21.65,0.01	20.25,0.01	17.70,0.00	14.40,0.00
22.90,0.33	21.45,0.00	17.75,0.00	14.35,0.00
22.80,0.01	20.45,0.00	19.10,0.00	14.55,0.00
30,4-86	31,5-86	19.30,0.00	15.75,0.00
21.30,0.35	20.75,0.00	30,6-86	31,7-86
22.30,0.00	19.55,0.00	20.60,0.00	16.70,0.00
21.85,0.00	19.35,0.00	19.70,0.00	16.25,0.00
20.60,0.13	19.35,0.00	20.30,0.00	19.95,0.00
20.90,0.04	19.60,0.00	20.60,0.00	17.30,0.00

APPENDIX C: Weather file

16.75,0.00
16.35,0.00
13.55,0.00
14.10,0.00
15.60,0.00
16.45,0.00
17.25,0.00
16.95,0.00
16.10,0.00
16.80,0.00
17.25,0.00
16.85,0.00
16.50,0.00
20.85,0.00
22.25,0.00
20.35,0.00
23.35,0.00
22.85,0.00
21.10,0.00
21.65,0.00
30,9-86
18.60,0.00
21.60,0.00
21.35,0.00
19.95,0.00
19.00,0.00
18.65,0.00
20.50,0.00
21.35,0.00
21.60,0.00
18.90,0.00
20.35,0.00
20.20,0.00
20.10,0.00
19.65,0.00
20.75,0.00
21.80,0.00
21.25,0.00
20.60,0.00
20.45,0.00
20.90,0.00
21.55,0.00
22.50,0.00
23.80,0.00
21.20,0.00
24.75,0.00
24.00,0.00
24.30,0.00
22.20,0.00
21.90,0.00
21.75,0.00
31,10-86
22.65,0.00
23.55,0.00
22.35,0.00
22.25,0.00
23.10,0.00
23.10,0.00
23.25,0.06
16.35,0.00
16.25,0.00
16.35,0.00
15.40,0.00
15.90,0.00
15.50,0.00
15.90,0.00
17.05,0.00
16.10,0.00
15.35,0.00
14.10,0.00
16.40,0.00
15.90,0.00
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25.10,0.00
25.10,0.00
24.65,0.00
25.00,0.00
25.50,0.55
23.55,0.00
24.15,0.00
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23.90,0.00
24.80,0.00
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24.35,0.00
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24.65,1.35
22.80,0.00
24.25,0.00
24.80,0.00
24.75,0.00
23.85,0.00
30,11-86
23.95,0.10
23.35,0.36
22.50,0.00
23.40,0.00
23.85,0.00
23.35,0.64
23.60,0.00
23.25,0.00
25.40,0.00
23.85,4.70
22.45,0.00
21.90,0.10
22.05,0.00
22.20,0.00
22.25,0.10
23.05,0.00
22.40,0.00
23.00,0.00
22.40,0.00
22.50,0.00
15.70,0.00
31,8-86
17.50,0.00
16.30,0.00
16.70,0.00
16.35,0.00
16.70,0.00
17.90,0.00
18.45,0.00
17.35,0.00
17.70,0.00
18.05,0.00
17.50,0.00
22.85,0.00
23.20,0.00
22.95,0.00
23.60,0.00
23.75,0.00
23.60,0.00
23.90,0.00
23.75,0.00
25.00,0.00
24.45,1.21
22.70,0.00
31,12-86
23.75,0.00
23.70,0.00
23.25,1.65
23.85,3.26
22.65,0.44
22.45,0.01
22.80,0.00
21.45,2.68
21.40,1.85
21.45,5.51
21.85,1.22
21.55,2.07
19.55,1.27
21.05,5.15
21.70,0.00
22.35,0.00
21.10,0.30
22.25,0.17
20.80,2.05
21.70,0.00
21.75,0.00
22.35,0.01
23.00,0.00
24.30,0.00
22.25,0.54
23.75,0.00
23.30,0.00
23.90,0.42
24.10,0.54
22.05,1.74
22.45,0.62
31,1-87
22.80,0.25
23.60,5.75
15.55,0.00
15.70,0.00
17.05,0.00
16.90,0.00
17.60,0.00
17.20,0.00
17.90,0.00
19.15,0.00
17.95,0.00
17.35,0.00
18.15,0.00
19.10,0.00
18.05,0.00
22.75,0.16
22.55,1.60
21.70,1.40
22.60,0.01
22.85,0.00
22.40,0.00
22.35,0.00
22.95,0.00
23.20,0.00
23.05,0.00
23.25,0.02
22.95,0.07
23.35,0.00
22.65,1.61
23.45,0.70
23.35,0.24
23.00,1.05
24.25,1.55
23.00,0.13
24.00,3.80
23.50,3.57
23.75,0.70
22.75,0.08
20.80,0.00
24.05,0.60
22.50,3.05
25.70,0.92
23.50,0.00
24.25,2.57
22.90,0.00
28,2-87
23.30,0.00
24.15,2.70
23.70,1.70
22.40,0.00
23.40,0.22
23.75,0.00
23.75,0.00
22.55,0.26
23.10,1.22
23.05,0.98
23.20,0.10
23.75,1.65
23.50,0.12
22.95,0.00
22.80,0.00

APPENDIX C: Weather file

23.80,0.00
22.85,0.00
24.10,0.00
22.55,1.86
19.70,0.70
23.60,3.73
23.90,0.27
22.20,0.00
22.95,0.00
20.75,0.00
31,3-87
23.65,0.00
24.80,0.80
23.50,0.17
23.75,0.40
23.10,0.00
23.00,0.45
23.10,0.45
24.25,0.00
23.75,7.70
24.00,0.35
25.30,1.05
23.20,0.05
23.30,0.01
23.25,0.00
23.95,0.00
23.50,0.00
22.50,0.00
23.47,0.00
22.00,0.00
23.50,0.42
22.50,0.00
22.10,0.05
22.75,0.05
25.25,0.13
23.50,0.00
22.00,1.60
21.75,0.00
23.30,0.03
25.55,0.05
24.60,3.01
23.45,0.65
30,4-87
24.35,0.27
17.45,0.00
17.25,0.00
18.45,0.00
18.60,0.00
20.65,0.00
19.45,0.00
18.35,0.00
19.50,0.00
19.40,0.00
20.85,0.00
20.80,0.00
18.85,0.00
17.90,0.00
18.25,0.00
18.05,0.00
18.95,0.00
24.10,0.33
24.45,6.20
22.85,0.00
22.35,0.00
21.45,0.00
20.55,0.00
22.40,0.00
23.10,0.02
23.10,0.00
21.65,0.00
21.65,0.00
21.90,0.00
21.95,0.00
22.95,0.00
22.45,0.00
21.74,0.00
21.35,0.00
20.35,0.00
19.50,0.00
19.60,0.00
20.80,0.00
21.85,0.00
21.70,0.00
21.40,0.00
19.70,0.00
20.60,0.00
20.65,0.00
21.15,0.30
20.50,0.00
31,5-87
19.00,0.00
22.00,0.00
21.30,0.00
21.60,0.00
21.75,0.00
21.45,0.00
21.25,0.00
20.45,0.00
21.45,0.00
22.15,0.00
20.95,0.00
21.55,0.00
20.60,0.00
21.25,0.00
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21.10,0.00
21.20,0.00
20.10,0.00
19.40,0.00
19.85,0.00
20.85,0.00
21.15,0.00
30,9-87
21.00,0.00
20.55,0.00
22.35,0.00
22.15,0.00
22.35,0.00
20.90,0.00
18.90,0.00
21.50,0.00
19.50,0.00
19.80,0.00
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21.70,0.00
21.80,0.00
20.20,0.00
19.70,0.00
18.90,0.00
18.80,0.00
17.45,0.00
19.35,0.00
19.95,0.00
19.65,0.00
18.60,0.00
17.75,0.00
17.60,0.00
30,6-87
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18.25,0.00
19.05,0.00
18.70,0.00
17.45,0.00
17.80,0.00
16.30,0.00
18.75,0.00
16.60,0.00
17.10,0.00
15.50,0.00
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15.50,0.00
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15.95,0.00
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17.45,0.00
16.85,0.00
15.20,0.03
13.75,0.00
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13.80,0.00
15.45,0.00
16.80,0.00
17.60,0.00
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21.75,0.00
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21.30,0.00
22.45,0.00
21.10,0.00
22.35,0.00
21.25,0.00
20.55,0.00
21.00,0.00
21.25,0.00
22.75,0.00
22.95,0.00
22.55,0.00
17.35,0.00
16.75,0.00
15.15,0.00
14.75,0.00
31,7-87
15.20,0.00
14.70,0.00
15.90,0.00
17.60,0.00
17.85,0.00
18.00,0.00
16.10,0.00
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18.05,0.00
17.40,0.00
17.90,0.00
18.05,0.00
17.35,0.00
15.45,0.00
16.45,0.00
17.90,0.00
18.95,0.00
17.80,0.00
17.15,0.00
17.55,0.00
17.15,0.00
17.75,0.00
19.20,0.00
19.60,0.00
20.50,0.00
18.65,0.00
18.25,0.00
31,8-87
18.80,0.00
19.25,0.00
18.75,0.00
20.20,0.00
20.25,0.00
18.35,0.00
17.10,0.00
22.95,0.00
24.55,0.00
25.55,0.00
25.50,0.00
24.85,0.00
21.50,0.00
23.50,0.00
31,10-87
24.25,0.12
23.55,0.00
22.80,0.00
19.25,0.00
20.70,0.00
22.00,0.00
22.75,0.00
23.90,0.00

APPENDIX C: Weather file

24.45,0.00
24.20,0.00
23.40,0.00
23.50,0.00
24.55,0.00
26.00,0.00
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24.05,0.00
23.00,0.00
23.25,0.00
22.80,0.00
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23.25,0.00
22.60,0.00
24.10,0.00
26.05,0.00
26.65,1.95
25.55,0.00
25.10,0.00
24.60,0.00
24.90,0.00
24.75,0.00
24.55,0.00
30,11-87
24.25,0.00
24.80,0.00
24.55,0.00
26.40,0.00
22.30,1.17
19.60,0.20
22.25,1.17
22.70,0.35
22.10,0.07
23.75,0.05
29,2-88
24.05,0.15
21.95,2.00
22.35,0.00
22.70,0.67
23.95,1.50
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23.20,0.80
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23.95,0.00
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24.50,0.00
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APPENDIX C: Weather file

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31,7-88
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26.95,0.00
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24.05,0.00
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16.85,0.00
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31,12-88
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24.25,2.20
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21.15,0.00
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23.10,0.00
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20.85,0.52
21.55,0.05
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22.40,0.00
21.85,3.94
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21.60,0.01

APPENDIX C: Weather file

22.30,4.84	23.20,0.28	21.80,0.14	19.50,0.00
21.30,7.61	23.35,0.05	20.90,0.38	19.50,0.00
18.70,0.52	23.15,0.03	20.90,0.18	18.85,0.05
22.30,0.02	24.35,0.43	21.05,0.11	20.40,0.00
23.15,0.88	23.85,0.26	21.95,1.23	18.55,0.00
22.95,0.15	31,3-89	20.90,0.35	17.55,0.00
21.90,0.00	23.40,0.00	21.55,0.00	18.20,0.00
19.80,0.44	22.00,1.32	20.95,0.00	19.70,0.00
21.20,1.54	23.30,0.60	21.15,0.00	19.50,0.00
20.65,0.35	23.35,3.35	20.25,0.00	20.50,0.00
20.70,0.07	22.60,1.74	20.45,0.00	19.95,0.00
22.55,3.12	20.20,0.65	21.55,0.00	17.65,0.00
22.55,3.00	18.70,2.46	20.45,0.00	18.80,0.00
22.90,0.27	18.85,1.22	21.55,0.13	18.15,0.00
23.25,0.70	22.25,0.39	20.45,0.00	17.10,0.00
22.85,0.70	24.05,0.47	20.60,0.00	18.25,0.00
28,2-89	22.65,0.00	21.50,0.00	20.40,0.00
22.90,0.25	23.05,0.00	20.60,0.00	19.50,0.00
23.15,0.36	22.30,1.11	20.30,0.00	18.80,0.04
22.65,1.15	22.55,0.00	20.50,0.00	18.25,0.00
22.70,0.02	22.75,0.00	21.55,0.00	30,6-89
23.45,0.21	22.35,0.00	20.60,0.00	17.75,0.00
21.95,1.40	22.50,0.00	20.70,0.00	18.65,0.00
22.30,0.14	23.00,0.74	20.05,0.00	18.90,0.00
22.85,0.00	22.45,0.27	20.75,0.00	18.40,0.00
21.65,0.34	21.40,0.00	21.55,0.00	19.85,0.00
21.00,0.45	22.05,2.01	21.65,0.00	17.80,0.00
22.95,2.11	21.70,1.80	22.25,0.05	20.45,0.00
22.85,1.15	20.20,6.44	31,5-89	17.45,0.00
23.15,0.00	21.05,0.00	22.00,0.00	16.75,0.00
22.85,0.00	22.25,0.00	21.25,0.52	17.95,0.00
22.95,0.26	20.60,1.55	20.85,0.10	15.45,0.00
23.25,0.03	22.05,0.00	20.55,0.73	15.90,0.00
22.90,0.75	20.90,0.18	20.40,0.00	15.40,0.00
21.80,0.02	21.95,4.51	20.45,0.00	15.65,0.00
21.95,1.39	21.25,0.05	19.60,0.00	14.00,0.00
23.85,2.55	22.30,0.00	19.55,0.00	15.25,0.00
19.80,0.16	30,4-89	19.65,0.00	15.70,0.00
22.75,0.01	21.30,4.19	20.00,0.00	15.30,0.00
23.90,0.90	21.00,0.11	19.35,0.00	16.60,0.00
17.10,0.00	15.65,0.00	14.75,0.00	21.05,0.00
19.15,0.00	16.05,0.00	17.20,0.00	16.35,0.00
17.90,0.00	16.50,0.00	17.80,0.00	16.35,0.00
18.05,0.00	15.90,0.00	31,8-89	17.05,0.00
18.15,0.00	15.35,0.00	16.45,0.00	17.75,0.00
16.55,0.00	15.50,0.00	15.80,0.00	18.65,0.00
18.45,0.00	16.65,0.00	18.25,0.00	15.95,0.00
17.45,0.00	19.05,0.00	17.25,0.00	15.45,0.00
16.95,0.00	17.30,0.00	16.75,0.00	16.65,0.00
16.45,0.00	19.15,0.00	16.15,0.00	18.95,0.00
15.95,0.00	17.95,0.00	16.85,0.00	19.85,0.00
31,7-89	17.70,0.00	17.70,0.00	19.15,0.00
16.75,0.00	15.05,0.00	18.65,0.00	19.55,0.00
17.40,0.00	16.05,0.00	19.30,0.00	20.50,0.00
17.20,0.00	16.10,0.00	20.20,0.00	19.95,0.00
16.55,0.00	15.40,0.00	18.60,0.00	30,9-89
16.85,0.00	14.50,0.00	19.05,0.00	20.10,0.00
16.30,0.00	16.00,0.00	19.15,0.00	19.45,0.00
15.65,0.00	15.80,0.00	18.05,0.00	20.40,0.00
17.10,0.00	15.50,0.00	19.05,0.00	20.90,0.00

APPENDIX C: Weather file

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31,10-89
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22.60,0.00
30,11-89
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23.27,0.57
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23.29,0.04
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APPENDIX C: Weather file

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24.15,0.00
31,5-90
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23.40,1.42
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APPENDIX C: Weather file

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APPENDIX C: Weather file

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APPENDIX C: Weather file

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23.70,0.00
22.75,0.00
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23.45,0.00
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25.60,0.00
24.25,0.00
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24.50,0.00
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26.55,0.00
26.20,0.00
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26.20,0.00
30,11-92
25.70,0.00

APPENDIX C: Weather file

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26.55,0.03
26.35,0.48
24.25,0.00
25.95,1.80
22.00,0.03
21.85,0.17
21.75,2.83
23.65,0.05
23.60,0.05
23.65,2.10
24.95,0.00
25.10,0.00
25.05,0.74
20.30,0.00
20.45,0.00
21.30,0.00
21.55,0.00
31,12-92
23.10,0.00
25.45,0.00
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23.55,0.00
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21.35,2.40
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22.10,0.47
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22.05,0.51
21.70,0.02
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22.50,0.02
23.90,0.88
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24.05,0.25
24.05,0.00
24.80,0.00
31,1-93
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23.75,0.00
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22.30,0.00
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21.85,0.19
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22.50,0.48
23.30,0.64
23.65,6.50
28,2-93
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22.95,0.00
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23.50,0.00
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22.85,0.45
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31,3-93
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22.97,0.27
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31,5-93
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30,6-93
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APPENDIX C: Weather file

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31,10-93
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23.70,0.10
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24.50,0.00
25.35,0.00
23.90,0.06
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23.95,0.82
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25.60,0.00
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31,12-93
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23.42,0.00
23.01,0.00
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22.83,0.07
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23.68,0.00
23.41,0.00
23.68,0.00
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23.43,0.25
23.46,0.00
23.71,0.00
24.03,0.07
24.43,1.29
24.06,1.77
24.16,0.30
23.82,0.00
23.66,0.79
24.09,0.06
23.29,0.00
31,1-94
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22.54,4.70
22.58,0.00
22.70,0.00
22.81,0.00
22.77,0.00
22.42,0.63
22.86,0.59
22.38,0.00
22.54,0.00
22.29,0.61
22.78,0.02
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22.98,0.60
23.23,0.00
22.80,0.59
22.64,0.06
22.32,0.00
22.57,0.16
22.04,0.45
21.92,0.11
21.96,0.40
23.04,0.01
22.95,0.15
23.06,0.60
22.84,0.00
28,2-94
23.18,8.23
23.17,0.05
22.89,0.99
23.30,0.27
23.08,0.20
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22.41,0.07
22.78,0.00
22.68,1.82

APPENDIX C: Weather file

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23.02,0.05
23.23,0.03
23.19,0.00
23.32,0.00
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22.83,1.45
22.73,1.55
22.96,0.21
31,3-94
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23.38,2.94
23.58,1.43
23.31,0.37
23.04,0.00
22.72,0.00
22.40,0.55
22.16,0.00
22.93,0.00
23.09,0.00
23.19,0.00
22.94,0.27
22.97,0.24
23.48,0.00
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23.28,0.05
22.90,0.00
23.27,0.00
23.08,0.00
22.71,0.00
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22.83,0.00
22.21,0.00
22.20,0.74
21.90,0.24
21.81,1.27
22.31,3.73
22.84,0.00
22.50,0.10
30,4-94
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22.43,0.27
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21.93,0.00
21.62,0.00
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21.75,0.01
21.59,0.00
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21.46,0.00
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21.66,0.00
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20.94,0.00
20.97,0.00
31,5-94
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19.05,0.00
18.35,0.00
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30,6-94
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31,7-94
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31,8-94
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19.35,0.00
30,9-94
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19.20,0.00
20.70,0.00
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23.70,0.00

APPENDIX C: Weather file

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31,10-94
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24.55,0.00
24.65,0.00
25.00,0.00
25.45,0.00
30,11-94
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25.55,0.00
24.75,0.00
23.55,0.00
23.25,0.00
24.70,0.00
25.65,0.00
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24.35,0.00
25.65,0.00
25.25,0.00
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26.55,0.59
24.05,6.54
21.80,0.17
24.30,0.00
24.80,1.13
21.80,0.15
31,12-94
22.70,0.16
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28,2-95
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23.20,1.54
22.70,0.41
23.10,0.00
22.90,0.00
22.55,0.00
23.55,0.00
22.20,2.65
20.00,0.64
23.55,0.00
22.55,0.00
22.30,0.00
22.50,0.25
23.55,0.06
24.15,0.00
21.75,0.00
22.15,0.05
23.05,0.03
23.50,0.21
23.25,0.06
23.20,0.00
22.95,0.00
23.15,0.00
22.40,0.00
22.35,0.48
22.40,0.00
22.25,0.00
22.40,0.87
22.15,0.10
23.05,0.00
23.20,0.00
23.70,0.0

APPENDIX D-1: RSP files used for modeling 1985 and 1995 hydrology for Magodi watersheds

KAMWAMPHULA:
transport\transportKAMWAMPHULA.dat, nutrient\nutrientMAGODI.dat, weather\weatherMAGODI.dat, bethKAMWAMPHULA

LUELO:
transport\transportLUELO.dat, nutrient\nutrientMAGODI.dat, weather\weatherMAGODI.dat, bethLUELO

Kanyanga:
transport\transportKANYANGA.dat, nutrient\nutrientMAGODI.dat, weather\weatherMAGODI.dat, bethKANYANGA

MPHIRI:
transport\transportMPHIRI.dat, nutrient\nutrientMAGODI.dat, weather\weatherMAGODI.dat, bethMPHIRI

APPENDIX D-2: RSP files used for validating the GWLF model for the 2008/2009 rainy season

KAMWAMPHULA:
transport\transportKAMWAMPHULAVAL.dat, nutrient\nutrientMAGODI.dat, weather\weatherKamwamphula.dat, bethKAMWAMPHULAVAL

LUELO:
transport\transportLUELOVAL.dat, nutrient\nutrientMAGODI.dat, weather\weatherLuelo.dat, bethLUELOVAL

KANYANGA:
transport\transportKANYANGAVAL.dat, nutrient\nutrientMAGODI.dat, weather\weatherKanyanga.dat, bethKANYANGAVAL

MPHIRI:
transport\transportMPHIRIVAL.dat, nutrient\nutrientMAGODI.dat, weather\weatherMphiri.dat, bethMPHIRIVAL

APPENDIX E-1: Summary output file for Kamwamphula watershed

bethKAMWAMPHULA summary file	Wednesday, Aug 26 2009, 04:22:30 AM						
Average Monthly Values							
Metric Units	(cm)	(cm)	(cm)	(cm)	(cm)	(Mg)	(Mg)
Month	Precip	Evapo Trans	Gr Wat Flow	Runoff	Strm Flow	Erosion	Sediment
APR	3.607778	7.806167	1.6548	0.34	2.00	878.12	11.25
MAY	0.877778	4.447967	2.27E-03	0.01	0.02	18.09	0.15
JUN	3.33E-03	0.1284	0	0.00	0.00	0	0
JUL	1.89E-02	1.89E-02	0	0.00	0.00	0	0
AUG	3.56E-02	3.56E-02	0	0.00	0.00	0	0
SEP	1.11E-02	1.11E-02	0	0.00	0.00	0	0
OCT	1.155556	1.1167	0	0.00	0.00	4.74	0
NOV	9.512222	4.603267	0.417956	1.28	1.70	3330.42	74.28
DEC	16.44667	9.817178	2.229889	1.67	3.90	16132.2	996.29
JAN	29.29778	10.16529	9.314378	4.90	14.21	33509.72	4675.6
FEB	20.17889	9.112456	10.20343	1.87	12.08	20918.2	3625.95
MAR	17.75778	9.153456	6.635156	2.06	8.69	17272.02	5282.2
Average Annual Values:							
(Mg)	(Mg)	(Mg)	(cm)				
Sediment Yield	Stream Bank Erosion	Erosion	Runoff				
14665.72	0	92063.51	12.1403				
Average Land Use Values							
Metric Units	(ha)	(cm)	(Mg)	(Mg)	(cm)		
Source	Area	Runoff	Erosion	Sediment	Area-weighted RO		
settlement	6.06	32.53	2853.804	454.611	7.10E-02		
playground	0.75	32.53	7.468	1.19	8.79E-03		
roads	6.81	43.73	4051.234	645.362	0.1072779		
Forest_dense	1527.03	7.87	2012.911	320.657	4.3291832		
forest_sparse	440.41	7.87	807.096	128.57	1.2485777		
fallow_1	34.19	26.68	77.122	12.285	0.3286008		
fallow_2	1.87	17.38	1.344	0.214	1.17E-02		
regrowth	0.82	7.87	1.355	0.216	2.32E-03		
cropland	667.27	19.59	82251.17	13102.61	4.7089025		
dambo	90.77	40.42	0	0	1.3216678		

APPENDIX E-2: Summary output file for Luelo watershed

bethLUELO summary file	Wednesday, Aug 26 2009, 04:23:11 AM						
Average Monthly Values							
Metric Units	(cm)	(cm)	(cm)	(cm)	(cm)	(Mg)	(Mg)
Month	Precip	Evapo Trans	Gr Wat Flow	Runoff	Strm Flow	Erosion	Sediment
APR	3.60778	7.806167	2.151722	0.49	2.65	2163.96	28.17
MAY	0.87778	4.244867	7.99E-02	0.03	0.11	43.26	0.65
JUN	3.33E-03	0.106944	2.06E-03	0.00	0.00	0	0
JUL	1.89E-02	1.89E-02	0	0.00	0.00	0	0
AUG	3.56E-02	3.56E-02	0	0.00	0.00	0	0
SEP	1.11E-02	1.11E-02	0	0.00	0.00	0	0
OCT	1.15556	0.931578	0	0.00	0.00	8.85	0
NOV	9.51222	3.4675	0.217311	2.03	2.24	8178.47	205.14
DEC	16.4467	10.09157	1.726511	2.50	4.23	39791	2110
JAN	29.2978	10.14328	6.268467	7.17	13.44	82387.6	10703
FEB	20.1789	9.112456	8.7453	3.07	11.81	51533.2	8953
MAR	17.7578	9.153456	6.421444	2.99	9.41	42400.9	12429
Average Annual Values:							
(Mg)	(Mg)	(Mg)	(cm)				
Sediment Yield	Stream Bank Erosion	Erosion	Runoff				
34429.1	0	226507.3	18.28612				
Average Land Use Values							
Metric Units	(ha)	(cm)	(Mg)	(Mg)	(cm)		
Source	Area	Runoff	Erosion	Sediment	Area-weighted RO		
settlement	44.55	32.53	17344.11	2636.3	0.436242		
playground	1.106	32.53	11.179	1.699	1.08E-02		
Forest_dense	423.628	7.87	261.777	39.79	1.003588		
forest_sparse	417.062	7.87	705.309	107.21	0.988033		
fallow_1	69.356	26.68	123.509	18.773	0.557014		
fallow_2	36.212	17.38	29.353	4.462	0.189452		
regrowth	116.906	7.87	193.194	29.365	0.276954		
Cropland	1930.56	19.59	207532.8	31545	11.3845		
dambo	280.129	40.42	303.261	46.096	3.408399		
transitional	2.523	40.42	2.712	0.412	3.07E-02		

APPENDIX E-3: GWLF summary output file for Kanyanga watershed

bethKANYANGA summary file	Wednesday, Aug 26 2009, 04:23:34 AM						
Average Monthly Values							
Metric Units	(cm)	(cm)	(cm)	(cm)	(cm)	(Mg)	(Mg)
Month	Precip	Evapo Trans	Gr Wat Flow	Runoff	Strm Flow	Erosion	Sediment
APR	3.607777778	7.806166667	3.003188889	0.49	3.49	372.89	5.83
MAY	0.877777778	4.249644444	0.453033333	0.03	0.48	7.18	0.14
JUN	3.33E-03	0.103733333	5.96E-02	0.00	0.06	0	0
JUL	1.89E-02	1.89E-02	8.38E-03	0.00	0.01	0	0
AUG	3.56E-02	3.56E-02	8.33E-04	0.00	0.00	0	0
SEP	1.11E-02	1.11E-02	0	0.00	0.00	0	0
OCT	1.155555556	0.970744444	0	0.00	0.00	1.26	0
NOV	9.512222222	3.685344444	0.129722222	2.01	2.14	1410.45	42.54
DEC	16.44666667	10.00654444	1.4147	2.51	3.92	6856.96	438.47
JAN	29.29777778	10.14003333	5.140888889	7.13	12.28	14215.7	2218.57
FEB	20.17888889	9.112455556	8.166044444	3.08	11.24	8886.37	1861.42
MAR	17.75777778	9.153455556	7.034411111	2.98	10.01	7305.5	2580.33
Average Annual Values:							
(Mg)	(Mg)	(Mg)	(cm)				
Sediment Yield	Stream Bank Erosion	Erosion	Runoff				
7147.3	0	39056.3	18.23601014				
Average Land Use Values							
Metric Units	(ha)	(cm)	(Mg)	(Mg)	(cm)		
Source	Area	Runoff	Erosion	Sediment	Area-weighted RO		
settlement	7.28	32.53	2005.765	367.055	0.207998173		
playgrounds	3.9	32.53	73.581	13.465	0.111427593		
road	0.52	43.73	195.15	35.712	0.019972246		
forest_dense	224.71	7.87	144.493	26.442	1.553249455		
forest_sparse	82.87	7.87	76.2	13.945	0.572817331		
fallow_1	28.17	26.68	0.752	0.138	0.660110666		
fallow_2	2.37	17.38	0.682	0.125	3.62E-02		
Regrowth	83.2	7.87	103.414	18.925	0.57509837		
Cropland	576.6	19.59	36363.809	6654.577	9.920947513		
dambo	93.84	40.42	66.385	12.149	3.33141231		
transitional	35.1	40.42	26.071	4.771	1.246084528		

APPENDIX E-4: GWLF summary output file for Mphiri watershed

bethMPHIRI summary file	Wednesday, Aug 26 2009, 04:23:50 AM						
Average Monthly Values							
Metric Units	(cm)	(cm)	(cm)	(cm)	(cm)	(Mg)	(Mg)
Month	Precip	Evapo Trans	Gr Wat Flow	Runoff	Strm Flow	Erosion	Sediment
APR	3.6077778	7.806166667	3.706544444	0.46	4.17	491.3	7.25
MAY	0.8777778	4.288577778	0.972977778	0.03	1.00	10.91	0.16
JUN	3.33E-03	0.106155556	0.229922222	0.00	0.23	0	0
JUL	1.89E-02	1.89E-02	5.86E-02	0.00	0.06	0	0
AUG	3.56E-02	3.56E-02	1.40E-02	0.00	0.01	0	0
SEP	1.11E-02	1.11E-02	3.11E-03	0.00	0.00	0	0
OCT	1.1555556	1.034233333	3.78E-04	0.00	0.01	3.5	0
NOV	9.5122222	4.032366667	9.54E-02	1.87	1.96	1722.99	48.87
DEC	16.446667	9.887966667	1.229111111	2.36	3.59	9016.52	554.05
JAN	29.297778	10.14947778	4.579644444	6.70	11.28	18654.91	2786.18
FEB	20.178889	9.112455556	7.762033333	2.86	10.62	11669.96	2319.3
MAR	17.757778	9.153444444	7.438322222	2.81	10.24	9640.03	3245.96
Average Annual Values:							
(Mg)	(Mg)	(Mg)	(cm)				
Sediment Yield	Stream Bank Erosion	Erosion	Runoff				
8961.77	0	51210.11	17.09890138				
Average Land Use Values							
Metric Units	(ha)	(cm)	(Mg)	(Mg)	(cm)		
Source	Area	Runoff	Erosion	Sediment	Area-weighted RO		
settlement	14.311	32.53	3740.368	654.564	0.26064943		
playgrounds	0.325	32.53	1.67	0.292	5.92E-03		
roads	5.407	43.73	1853.54	324.37	0.13238494		
Forest_dense	424.635	7.87	264.95	46.366	1.87108389		
Forest_sparse	110.623	7.87	92.574	16.201	0.48744195		
fallow_1	38.005	26.68	39.378	6.891	0.56771361		
fallow_2	3.184	17.38	7.588	1.328	3.10E-02		
regrowth	255.256	7.87	322.461	56.431	1.12474334		
cropland	731.191	19.59	44739.979	7829.496	8.01988264		
dambo	179.576	40.42	129.94	22.739	4.06394052		
transitional	23.552	40.42	17.66	3.091	0.53299955		

APPENDIX E-5: GWLF validation output summary for Kamwamphula watershed

bethKAMWAMPHULAVAL summary file	Wednesday, Aug 26 2009, 07:02:31 AM						
Average Monthly Values							
Metric Units	(cm)	(cm)	(cm)	(cm)	(cm)	(Mg)	(Mg)
Month	Precip	Evapo Trans	Gr Wat Flow	Runoff	Strm Flow	Erosion	Sediment
APR	0.57	7.8432	0	0	0	0	0
MAY	0	2.7267	0	0	0	0	0
JUN	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	0
NOV	0	0	0	0	0	0	0
DEC	17.22	9.8547	0	0.217836	0.2178	8997.69	17.45
JAN	10.43	10.4818	0	5.88E-02	0.0588	6314.9	3.49
FEB	26.19	8.5287	10.5339	3.088818	13.6227	27341.25	5171.36
MAR	23.4	8.8817	14.5078	1.45372	15.9614	16641.68	4253.48
Average Annual Values:							
(Mg)	(Mg)	(Mg)	(cm)				
Sediment Yield	Stream Bank Erosion	Erosion	Runoff				
9445.78	0	59295.52	4.819156				
Average Land Use Values							
Metric Units	(ha)	(cm)	(Mg)	(Mg)	(cm)		
Source	Area	Runoff	Erosion	Sediment	Area-weighted RO		
settlement	6.06	17.14	1900.438	302.74	3.74E-02		
playground	0.75	17.14	4.973	0.792	4.63E-03		
roads	6.81	26.44	2685.678	427.829	6.49E-02		
Forest_dense	1527.03	2.54	828.367	131.959	1.397221		
forest_sparse	440.41	2.54	332.142	52.91	0.402972		
fallow_1	34.19	12.82	50.611	8.062	0.157896		
fallow_2	1.87	6.96	0.848	0.135	4.69E-03		
regrowth	0.82	2.54	0.558	0.089	7.50E-04		
cropland	667.27	8.21	53491.91	8521.261	1.97346		
dambo	90.77	23.59	0	0	0.771354		

APPENDIX E-6: GWLF validation output summary file for Luelo watershed

bethLUELOVAL summary file	Wednesday, Aug 26 2009, 07:02:45 AM						
Average Monthly Values							
Metric Units	(cm)	(cm)	(cm)	(cm)	(cm)	(Mg)	(Mg)
Month	Precip	Evapo Trans	Gr Wat Flow	Runoff	Strm Flow	Erosion	Sediment
APR	0.57	7.8432	0	0	0	0	0
MAY	0	2.7267	0	0	0	0	0
JUN	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	0
NOV	0	0	0	0	0	0	0
DEC	19.06	7.8214	0	6.01365	6.0136	45890.1	6155.17
JAN	11.14	11.53	0	0.131776	0.1317	5936.03	16.81
FEB	19.2	10.2345	0.2847	2.340393	2.6251	37409.03	6728.57
MAR	14.13	10.658	3.0488	0.486855	3.5357	19189.1	3579.95
Average Annual Values:							
(Mg)	(Mg)	(Mg)	(cm)				
Sediment Yield	Stream Bank Erosion	Erosion	Runoff				
16480.49	0	108424.3	8.972673				
Average Land Use Values							
Metric Units	(ha)	(cm)	(Mg)	(Mg)	(cm)		
Source	Area	Runoff	Erosion	Sediment	Area-weighted RO		
settlement	44.55	24.72	8938.739	1358.688	0.331507		
playground	1.106	3.9	4.63	0.704	1.30E-03		
Forest_dense	423.628	3.43	81.819	12.436	0.437396		
forest_sparse	417.062	6.33	346.159	52.616	0.794695		
fallow_1	69.356	12.36	63.207	9.607	0.258047		
fallow_2	36.212	7.36	14.197	2.158	8.02E-02		
regrowth	116.906	5.88	94.818	14.412	0.206924		
Cropland	1930.561	8.64	98723.66	15006	5.021036		
dambo	280.129	21.63	155.649	23.659	1.82394		
transitional	2.523	21.63	1.392	0.212	0.016427		

APPENDIX E-7: GWLF validation summary output for Kanyanga watershed

bethKANYANGAVAL summary file	Wednesday, Aug 26 2009, 07:03:30 AM						
Average Monthly Values							
Metric Units	(cm)	(cm)	(cm)	(cm)	(cm)	(Mg)	(Mg)
Month	Precip	Evapo Trans	Gr Wat Flow	Runoff	Strm Flow	Erosion	Sediment
APR	0.57	7.8432	0	0	0	0	0
MAY	0	2.7267	0	0	0	0	0
JUN	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	0
NOV	0	0	0	0	0	0	0
DEC	19.06	7.8214	0	4.567299	4.5674	7464.7	1259.36
JAN	11.14	10.4818	0	6.57E-02	0.0657	134.89	1.07
FEB	19.2	8.5287	3.4738	1.407563	4.8813	6436.44	1215.41
MAR	14.13	8.8817	6.0201	0.254834	6.275	3281.3	693.23
Average Annual Values:							
(Mg)	(Mg)	(Mg)	(cm)				
Sediment Yield	Stream Bank Erosion	Erosion	Runoff				
3169.07	0	17317.33	6.295353				
Average Land Use Values							
Metric Units	(ha)	(cm)	(Mg)	(Mg)	(cm)		
Source	Area	Runoff	Erosion	Sediment	Area-weighted RO		
settlement	7.28	12.36	1017.304	186.167	7.90E-02		
playgrounds	3.9	12.36	37.32	6.829	4.23E-02		
road	0.52	19.09	100.122	18.322	8.72E-03		
forest_dense	224.71	2.32	45.161	8.265	0.457883		
forest_sparse	82.87	2.32	23.816	4.358	0.168861		
fallow_1	28.17	9.41	0.377	0.069	0.23282		
fallow_2	2.37	5.48	0.305	0.056	1.14E-02		
Regrowth	83.2	2.32	32.322	5.915	0.169533		
Cropland	576.6	6.33	16013.15	2930.406	3.205697		
dambo	93.84	16.97	34.072	6.235	1.398666		
transitional	35.1	16.97	13.381	2.449	0.523158		

APPENDIX E-8: AGWLF validation output summary for Mphiri

bethMPHIRIVAL summary file	Wednesday, Aug 26 2009, 07:03:57 AM						
Average Monthly Values							
Metric Units	(cm)	(cm)	(cm)	(cm)	(cm)	(Mg)	(Mg)
Month	Precip	Evapo Trans	Gr Wat Flow	Runoff	Strm Flow	Erosion	Sediment
APR	0.57	7.8432	0	0	0	0	0
MAY	0	2.7267	0	0	0	0	0
JUN	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	0
NOV	0	0	0	0	0	0	0
DEC	16.86	7.9314	0	2.281427	2.2814	6794.85	1044.99
JAN	12.76	10.4818	0.0963	0.464605	0.5608	5870.85	827.18
FEB	13.97	8.5287	1.8448	0.316937	2.1617	3510.64	872.23
MAR	13.09	8.8817	3.8353	7.96E-02	3.9149	3017.62	614.55
Average Annual Values:							
(Mg)	(Mg)	(Mg)	(cm)				
Sediment Yield	Stream Bank Erosion	Erosion	Runoff				
3358.94	0	19193.96	3.142618				
Average Land Use Values							
Metric Units	(ha)	(cm)	(Mg)	(Mg)	(cm)		
Source	Area	Runoff	Erosion	Sediment	Area-weighted RO		
settlement	14.311	7.89	1440.41	252.072	6.32E-02		
playgrounds	0.325	7.89	0.643	0.113	1.44E-03		
roads	5.407	13.26	715.233	125.166	4.01E-02		
Forest_dense	424.635	0.59	60.985	10.672	0.140272		
Forest_sparse	110.623	0.59	21.308	3.729	3.65E-02		
fallow_1	38.005	5.61	14.288	2.5	0.119373		
fallow_2	3.184	2.65	2.3	0.403	4.72E-03		
regrowth	255.256	0.59	74.223	12.989	8.43E-02		
cropland	731.191	3.27	16807.96	2941.393	1.338694		
dambo	179.576	11.55	49.834	8.721	1.161269		
transitional	23.552	11.55	6.773	1.185	0.152304		