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Spatial characterization of the Nile Basin for improved water management

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Key messages

- Hydronomic (water management) zones are instrumental in identifying and prioritizing water management issues and opportunities in different parts of a river basin. Such zoning facilitates the development of management strategies and informed decision-making during planning and operation.
- Hydronomic zones are identified using various maps of the basin, describing topography, climate, water sources and sinks, soil properties, vegetation types, and environmentally sensitive areas.
- Nineteen hydronomic zones are identified in the Nile Basin. Eighteen of these are identified based on six classes of humidity index and three soil classes. In addition, one environmentally sensitive zone is formed by merging wetlands and protected areas. The identified zones have unique climate and soil properties, and point to the need for distinct water management interventions in each zone.
- Nearly 15 per cent of the Nile Basin falls into water sources zone – where run-off is generated. About 10 per cent of the Nile Basin falls into the environmentally sensitive zone, where conservation and protection of the natural ecosystem should be promoted.

Introduction

The rapid population growth and associated environmental degradation have substantially increased the demand for terrestrial freshwater resources. Different economic sectors and riparian communities sharing river basins are competing for water consumption. The river system also requires an adequate amount of water for preserving its quality and for protecting its ecosystem. Moreover, climate variability and change would affect the availability of water required for human development and ecological functions. The current and anticipated challenges of the overwhelming disparity between water demand and supply could be addressed through managing the scarce freshwater resources in an effective and integrated manner within hydrological domains. However, if the water management practice fails to move away from isolated engagements within administrative boundaries, livelihoods, food security and environmental health would be compromised. The water management system should also focus on interventions that use water efficiently and improves productivity. The Nile River Basin covers expansive areas with greater topographic, climatic and hydro-ecological variability. The water management interventions should be very specific and most adaptable to the different parts of the basin. Therefore, it is essential to characterize the spatial variability of water management drivers in the Nile Basin and to classify the basin into similar water management zones.

Water management zones are instrumental in identifying and prioritizing the water management issues and opportunities in different parts of a river basin. Hence, the information and intervention requirements for addressing the water management issues and harnessing the opportunities in each zone could be exhaustively developed in the water development and monitoring strategies. Generally, classifying the river basin into water management zones facilitates development of management strategies and informed decision-making during planning and operation of water management interventions.

The concept of hydronomic (water management) zones was first developed by Molden *et al.* (2001). They proposed hydronomic zones as indispensable tools for defining, characterizing and developing management strategies for river basin areas with similar characteristics. They illustrated the potential of hydronomic zones in improved understanding of complex water interactions within river basins and assisting the development of water management strategies better tailored to different conditions within basins. They classified hydronomic zones based on the fate of water applied to the irrigation field. Later, Onyango *et al.* (2005) applied the hydronomic concept with that of terranomics (land management) to explore the linkages between water and land management in rain-fed agriculture and irrigation areas in the Nyando Basin, Kenya.

The main purpose of this chapter is to improve understanding of the Nile Basin characteristics using a spatial multivariate analysis of biophysical factors that significantly influence the development, management and protection of water resources of the basin. The relevant biophysical factors are used to classify the basin into similar water management zones that require identical interventions for efficient and sustainable development and management of the scarce water resources.

Hydronomic zones and classification methods

Adaptive and integrated water management of river basins is accepted as the best practice of developing, operating and protecting scarce water resources even under competing demands and climate change conditions. Classification of river basins into similar hydronomic zones facilitates efficient and sustainable application of adaptive and integrated water resources management. Molden *et al.* (2001) have developed and defined a set of six hydronomic zones based on similar hydrological, geological and topographical conditions, and the fate of water flowing from the zone. They demonstrated the concept of hydronomic zoning in four agricultural areas with similar characteristics: the Kirindi Oya Basin in Sri Lanka, the Nile Delta in Egypt, the Bhakra command area in Haryana, India, and the Gediz Basin in Turkey. The six hydronomic zones identified are: water source zone, natural recapture zone, regulated recapture zone, stagnation zone, final use zone and environmentally sensitive zone. In addition, two conditions that influence water management are defined in terms of presence or absence of appreciable salinity or pollution loading and availability or inaccessibility of groundwater for utilization. Generic strategies for irrigation in the four water management areas (the natural recapture, regulated recapture, final use, and stagnation zones) are presented in their analysis.

The water source zone and environmentally sensitive zone are also discussed in terms of their overall significance in basin water use and management.

Different classifications of physical systems have been developed to improve utilization of natural resources and protection of the environment. Koppen climate classification is one of the earliest attempts to classify the physical systems into zones of similar climatic patterns. The Koppen climate classification underwent successive improvements using improved precipitation and temperature records (Peel *et al.*, 2007). This climate classification method adopts different threshold values of parameters derived from monthly precipitation and temperature data sets for different climate zones. The other notable classification of the physical system relevant to water management is agro-ecological zones. The agro-ecological classification follows a GIS-based modelling framework that combines land evaluation methods with socio-economic and multi-criteria analyses to evaluate spatial and dynamic aspects of agriculture (Fischer *et al.*, 2002). The agro-ecological methodology provides a standardized objective framework for characterization of climate, soil and terrain conditions relevant to agricultural production.

The availability of spatial GIS and remote sensing information has contributed towards the advancement of classification methods from experience-based subjective decisions to data-intensive objective frameworks. Fraisse *et al.* (2001) applied principal components and unsupervised classification of topographic and soil attributes to develop site-specific management zones for variable application of agricultural inputs according to unique combinations of potential yield-limiting factors. Muthuwatta and Chemin (2003) developed vegetation growth zones for Sri Lanka through analysis and visual interpretation of remote sensing images of biomass production. They claimed that the vegetation growth zones would have better contribution to water resources planning than the agro-ecological zones since the vegetation growth zones are based on the prevailing environment and have strong linkages to hydrological processes.

Biophysical factors relevant to water management

The water management issues in a river basin are largely driven by the biophysical, socio-economic, institutional and ecological factors. Among these drivers of water management, the biophysical factors (such as climate, topography, soil, vegetation and hydro-ecological structures) are the most dominant. Therefore, these biophysical factors could provide the analytical platform required to objectively define the hydronomic zones. Moreover, the water management classification based on these static drivers of the river basin could provide an insight into the relationship among themselves and with water management indicators (Wagener *et al.*, 2007).

Loucks and Beek (2005) assert that a more complete large-scale perspective of the river system management could be achieved when watershed hydrology is combined with landscape ecology and actions in 'problem sheds'. Therefore, different factors that are related, either adversely or beneficially, to the water management issues of the basin should be exhaustively considered during classification of water management zones. The spatial distribution and disparity between water supply and demand within the basin require appropriate management strategies that consider constraints and opportunities of the basin water resources. Classification of the Nile Basin into hydronomic zones that have similar biophysical attributes would enable to devise adaptive and integrated water management strategies. The biophysical factors relevant to water management could be broadly categorized into climatic, hydrological, topographic, soil, vegetation and environmental factors. The following sub-sections provide brief descriptions and spatial patterns of these major categories of the biophysical attributes of the Nile Basin.

Topographic features

The topography of the river basin dictates the movement of water within the basin. The river basin classification into sub-basins and watersheds is primarily based on the altitude of the topography. Crop production and land suitability for agriculture are largely affected by topographic attributes. A high-gradient slope exposes the landscape for soil erosion and land degradation. The undulating topography also influences rainfall generating mechanisms in the mountainous areas. The aspect of sloping land surface could distinguish the rain-shadow part of mountain areas.

The upper parts of the Nile Basin have a ridged topography with steep slopes as depicted in Figure 4.1a, b. The central and downstream parts of the basin are predominantly flat areas. The impact of topography on movement of water within the basin and on the wetness of the underlying land surface could be characterized by a compound topographic index. The compound topographic index at the grid point in the basin is evaluated from its slope and the area that contribute flow to the grid point (USGS, 2000). The compound topographic index map of the Nile Basin in Figure 4.1c shows that flat areas of the basin that receive water from large upstream catchments have greater values of the topographic index. Such areas of the basin would have greater chances of becoming wet if the upstream catchments receive a substantial amount of precipitation.

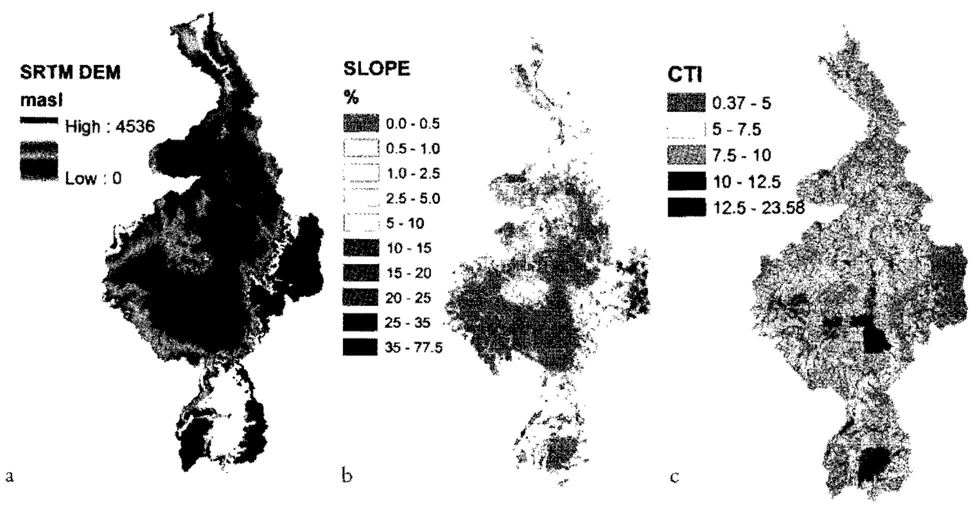


Figure 4.1 Topographic patterns of the Nile Basin: (a) Shuttle Radar Topography Mission Digital Elevation Model (metres above sea level), (b) slope (%) and (c) compound topographic index

Climatic and hydrological factors

The climate system is the major sources and sinks of water for river basins. While the climate system provides precipitation for the river basin, it takes away water in the form of evapotranspiration. The climate of the Nile Basin is largely driven by latitudinal contrasts of about 36°

from the southern (upstream) to the northern (downstream) ends. The Nile Basin climate can be broadly classified as arid, temperate and tropical. The Koppen–Geiger climate classification (Figure 4.2a) shows that the greater part of the basin is either arid desert hot or tropical savannah. The humidity index, the ratio of mean annual precipitation to potential evapotranspiration, characterizes the aridity or humidity of the basin. According to the humidity index derived from IWMI's Climate Atlas (Figure 4.2b), about half of the Nile Basin falls under the arid category. The Ethiopian Highland plateaus and equatorial lakes region below the Sudd wetlands are classified as humid zones.

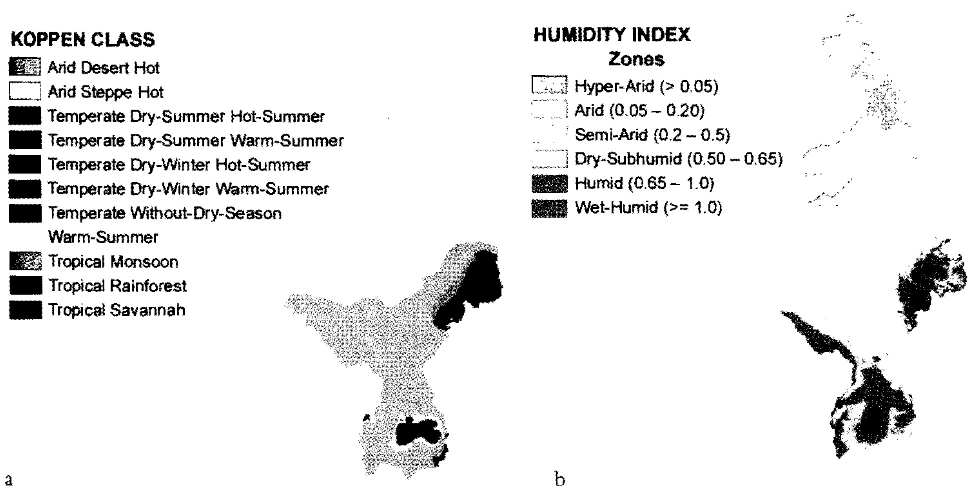


Figure 4.2 Climatic patterns of the Nile Basin from (a) the Koppen–Geiger climate classification and (b) humidity zones derived from the IWMI climate atlas

The hydrological cycle interrelates the physical processes and feedback mechanisms between the hydrological, atmospheric and lithospheric systems. The main sources and sinks of water in the river basin are precipitation and evapotranspiration, respectively. These climate variables exhibit temporal and spatial variability in the Nile Basin as depicted in Figure 4.3a, b, and this has resulted in very low average annual run-off, about 30 mm over the entire basin, as compared with the size of the basin, which is about 3 million km^2 (Sutcliffe and Parks, 1999). Despite their greater spatial variability, precipitation and evapotranspiration are some of the major factors that determine water availability within the river basin. Therefore, water source and deficit zones in the river basin can be identified by analysing differences between these climatic variables. The difference between mean annual precipitation and potential evapotranspiration in the Nile Basin (Figure 4.3c) reveals that most parts of the basin, particularly the central and downstream parts, are predominantly water-deficit zones. The water source zones are located in the Ethiopian Highland plateaus and the equatorial lakes region.

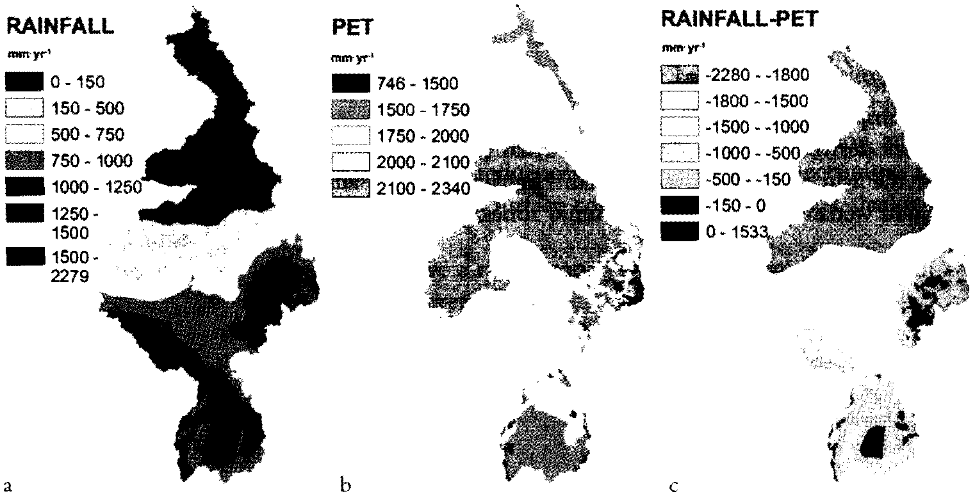


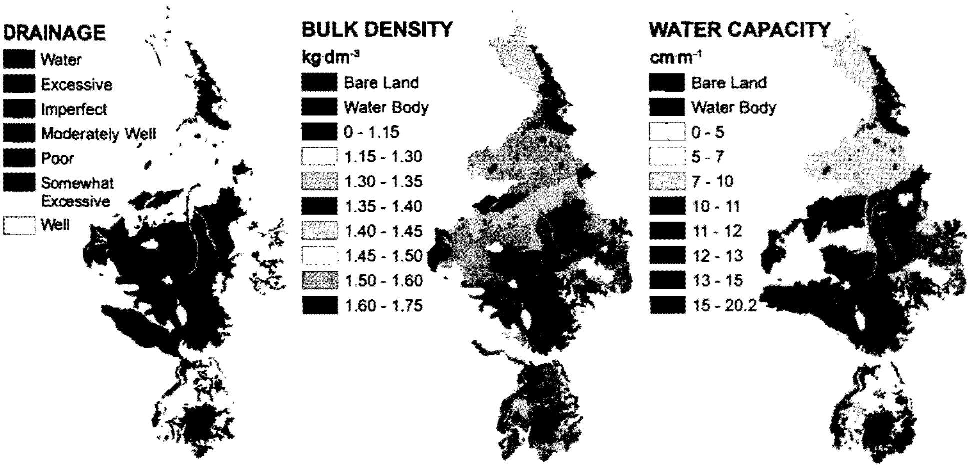
Figure 4.3 Water sources and sinks in the Nile Basin: (a) rainfall distribution, (b) potential evapotranspiration and (c) run-off production potentials derived from the IWMI climate atlas

Soil characteristics

The suitability of landscape for crop production largely depends on the soil properties of the landscape. Like slope, soil is one of the major factors for classifying lands for rain-fed and irrigation farming systems. Among the soil properties, texture, drainage, bulk density, available water content, electrical conductivity and calcium carbonate content could potentially describe the impact of soil on water resources management. These soil factors are obtained from the ISRIC-WISE derived data set (Batjes, 2006). The spatial patterns of the selected soil factors for the Nile Basin are illustrated in Figure 4.4.

Vegetation indices

The vegetation cover of the river basin has significant influence on the proportion of rainfall converted into direct run-off. Similarly, it also influences the infiltration rate of rainwater. Moreover, the degree of soil erosion and land degradation is largely related to vegetation cover. The degraded highland plateaus are producing substantial amounts of sediment that impair water storage facilitations and irrigation infrastructures in downstream parts of the basin. The Normalized Differenced Vegetation Index (NDVI) evaluated from the red and near-infrared reflectance of remotely sensed images characterizes the vegetation cover of the land surface. The United States Geological Survey (USGS) land use land cover map and the average annual SPOT NDVI plots in Figure 4.5 show that the spatial vegetation patterns in the Nile Basin are very similar to the climate patterns shown in Figure 4.2.



a b c

Figure 4.4 Soil properties in the Nile Basin: (a) drainage class, (b) bulk density (kg dm^{-3}) and (c) available water capacity (cm m^{-1}) derived from ISRIC-WISE data

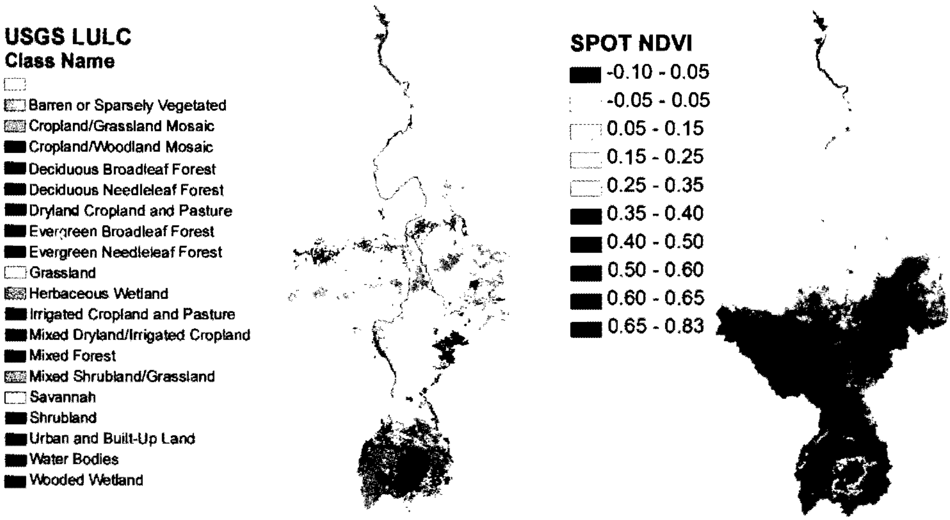


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Figure 4.5 Vegetation profiles in the Nile Basin: (a) USGS land use land cover and (b) average SPOT NDVI (mean annual from 1999 to 2006)

Ecological and environmental considerations

The water management practices should preserve the major ecological and environmental functions of the river systems. The flora and fauna within the river basin should not be seriously affected in the process of harnessing the water resources for improved livelihoods. Therefore, water management interventions applied at a particular area of the basin should consider the ecological conditions of that area. The environmental impact assessment of interventions is often undertaken to identify their potential impacts and devise mitigation measures. However, there are some environmentally sensitive areas where the impacts on the ecology of the area are more important than the benefits of development interventions. As shown in Figure 4.6, some of the environmentally sensitive areas in the Nile Basin include wetlands, flood plains along the river course, the vicinity of water impoundments, and protected areas for natural, game and hunting reserves, sanctuaries and national parks. Water resources development and management interventions should not be allowed in such ecological hot-spot areas of the basin. Therefore, the water management zone should clearly delineate the environmentally sensitive areas in the basin.

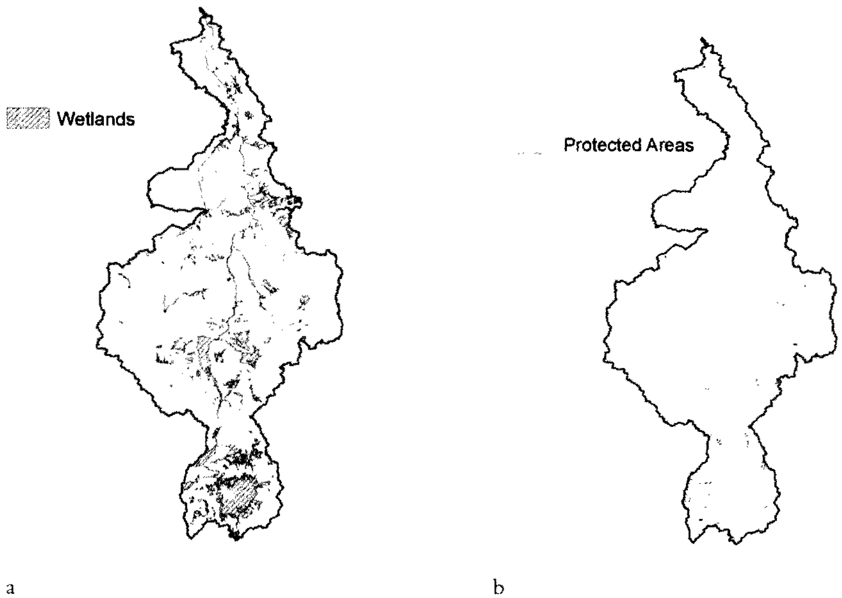

Figure 4.6 Environmentally sensitive areas: (a) wetlands and (b) protected areas compiled from IWMI's Integrated Database Information System Basin Kits

Multivariate analysis of basin characteristics

The biophysical factors of water management discussed in the previous section are obviously related to one another. For example, the climate and vegetation factors have similar spatial patterns in the Nile Basin. In fact, the Koppen climate classification was initially derived from vegetation cover since observed climate variables in the early twentieth century were very limited (Peel *et al.*, 2007). In order to use these biophysical factors for classification of water management zones, the interdependency between the factors should be removed. Moreover, the relative importance of the biophysical factors should be known to minimize the numbers of relevant factors used for classification of water management zones.

Principal components analysis (PCA) is a multivariate statistical technique that transforms interdependent multidimensional variables into significant and independent principal components of the variables with fewer dimensions. The PCA tool is employed for removing interdependency and reducing the dimensions of the biophysical factors of water management. After a preliminary analysis, the following six biophysical factors that represent climatic, topographic, soil and vegetation features of the basin are selected for principal components analysis: humidity index, landscape slope, compound topographic index, soil bulk density, available soil water content and normalized differenced vegetation index.

The selected biophysical factors are standardized by their respective means and standard deviations in order to comply with the Gaussian assumption of PCA and to give equal opportunity to factors with large and small numerical differences. The linear correlation matrix of the selected factors in Table 4.1 shows that the selection process has minimized the interdependency between the factors. The highest correlation was obtained between landscape slope and compound topographic index. The PCA transformation will remove these correlations between the selected factors.

Table 4.1 Linear correlation matrix of the relevant biophysical factors

	HI	*Slope*	*CTI*	*SBD*	*SWC*	*NDVI*
HI	1.00					
Slope	0.17	1.00				
CTI	−0.03	−0.49	1.00			
SBD	−0.19	−0.17	0.14	1.00		
SWC	0.00	0.14	−0.09	−0.22	1.00	
NDVI	0.40	0.09	−0.03	−0.27	−0.11	1.00

Note: HI = humidity index, Slope = landscape slope, CTI = compound topographic index, SBD = soil bulk density, SWC = available soil water content, NDVI = normalized differenced vegetation index

The principal component analysis of the standardized factors is performed using the selected six biophysical factors. The PCA evaluates the eigenvalues and eigenvectors of the covariance matrix of the standardized biophysical factors. The eigenvalue is literally the variance of the normalized factors explained by the corresponding principal component. The transpose of the eigenvectors provides the coefficients (weights) of the normalized factors for each principal component. The amount of the total variances of the normalized factors, which is equal to the number of variables (6), explained by each principal component, and the coefficients (weights) of the factors for each principal component are provided in Table 4.2. While the first principal component has explained half of the total variances of the six biophysical factors, the first three principal components have explained about 99 per cent of the total variance. Therefore, principal components would enable us to reduce the dimensions of the factors from six to two or three without losing significant spatial information.

Table 4.2 The percentage of variance of the biophysical factors explained by each principal component and the weights (coefficients) of the factors for the principal components

Principal components	*% of variance*	*HI*	*Slope*	*CTI*	*SBD*	*SWC*	*NDVI*
PC1	50.21	−0.254	−0.316	0.240	0.321	−0.022	−0.821
PC2	37.52	−0.052	0.545	−0.531	−0.145	0.471	−0.418
PC3	11.72	−0.032	0.311	−0.408	0.348	−0.780	−0.072
PC4	0.36	−0.103	−0.189	−0.094	−0.858	−0.383	−0.248
PC5	0.14	0.305	0.627	0.664	−0.127	−0.149	−0.187
PC6	0.06	0.910	−0.278	−0.211	0.039	0.000	−0.221

Note: HI = humidity index, Slope = landscape slope, CTI = compound topographic index, SBD = soil bulk density, SWC = available soil water content, NDVI = normalized differenced vegetation index

The weights of the biophysical factors, which linearly transform the relevant factors to the principal components, reveal that vegetation (NDVI), topographic (Slope and CTI) and soil (SWC) attributes are the most dominant factors for the first, the second and the third principal components, respectively. The graphical patterns of the principal components (Figure 4.7) are very similar to the corresponding biophysical factors.

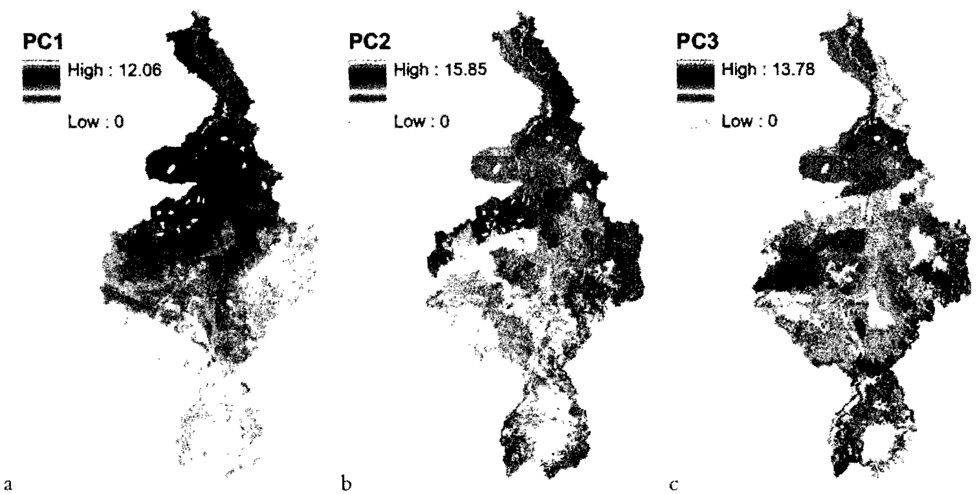

Figure 4.7 The dominant principal components of the biophysical factors: (a) PC1, (b) PC2 and (c) PC3

Classification of hydronomic zones

The similarity patterns of the biophysical factors discussed and the results of the principal components analysis are used to develop a classification framework for hydronomic zoning of the Nile Basin. Both subjective and objective approaches are employed in setting out the classification framework. The assessment of the biophysical factors indicated that climatic and vegetation attributes have similar spatial patterns in the Nile Basin. However, the principal components analysis of the relevant biophysical factors revealed that vegetation (NDVI) is the most dominant factor for water management classification, followed by topographic (Slope and CTI) and soil (SWC) attributes. The unsupervised classification of the first three principal components provided indicative patterns of the water management zones. But these zones are very patchy and often mixed up, since the analysis was performed at 1 km resolution. Therefore, the climatic factor (humidity index) that has distinctive zones is used as the primary (first-level) classification factor instead of NDVI since both factors have similar patterns. The humidity index in Figure 4.8a has six unique zones: hyper-arid (Ha), arid (Aa), semi-arid (Sa), dry subhumid (Ds), humid (Hh) and wet humid (Wh).

The topographic factors have greater spatial variability and could not provide distinct classes for the entire basin. These factors could provide better classification for sub-basins and catchments as suggested by the principal components analysis. Consequently, the soil attribute (SBD) is used for secondary (second-level) classification. The soil bulk density was divided into three classes: light soil (Ls), medium soil (Ms) and dense soil (Ds), as shown in Figure 4.8b. Hence, for each of the primary six classes defined by humidity index, there are three classes of soil attributes, which classify the basin into eighteen water management zones.

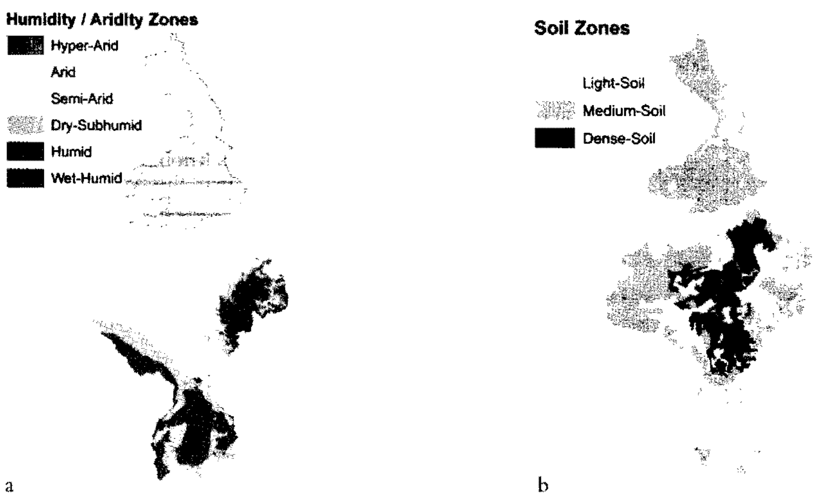

Figure 4.8 Water management classification framework for the Nile Basin: (a) humidity/aridity zones and (b) soil zones

Following the works of Molden *et al.* (2001), the environmentally sensitive (EnSe) zone was formed by merging the wetland and protected areas in Figure 4.6. The final hydronomic zones of the Nile Basin are developed by superimposing the EnSe zone over the eighteen identified zones (Figure 4.9).

The developed hydronomic zones of the Nile Basin have 19 distinct zones in which similar water management interventions could be applied. The hydronomic zoning includes

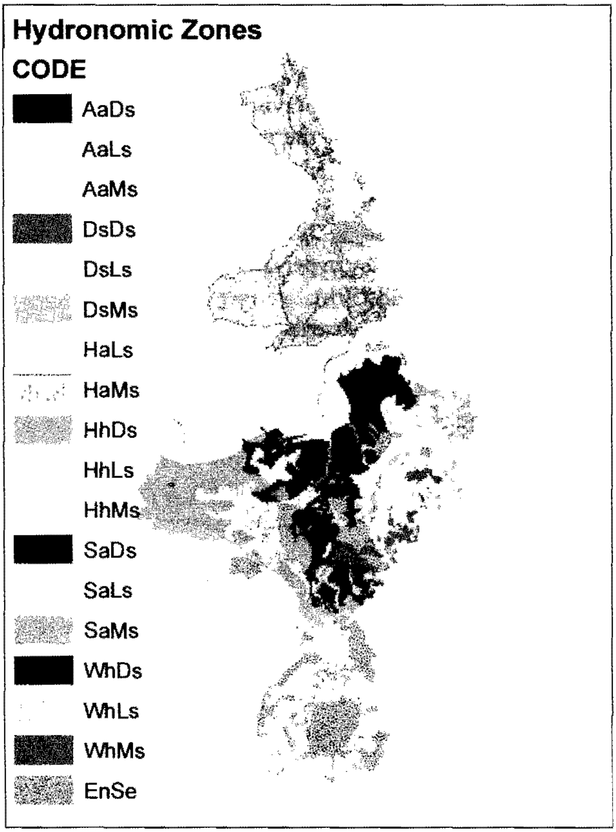

Figure 4.9 The hydronomic zones of the Nile Basin

Note: The first part of each label defines the zone, as follows: Aa = arid, Ds = dry subhumid, Hh = humid, Ha = hyper-arid, Sa = semi-arid, Wh = wet humid. The second part defines the soil bulk density, as follows: Ds = dense soil, Ls = light soil, Ms = medium soil

different aspects of water management. For example, the water source areas of the basin can be easily identified as humid and wet humid zones (HhLs, HhMs, HhDs, WhLs, WhMs and WhDs) where the humidity index is greater than 0.65.

The classes of the developed hydronomic zones could be increased to 37 by including two classes of topographic attribute as a third classification factor for applications at sub-basin or watershed levels.

Discussions and concussions

The spatial patterns of the biophysical factors relevant to the water management of the Nile Basin are examined for the purpose of identifying potential attributes for classification of water management zones. The principal component analysis of the selected biophysical factors indicated that the vegetation (NDVI) attribute has the greatest spatial variability followed by the topographic indices (Slope and CTI) and the soil variable (SWC). These identified biophysical factors have greater spatial variability in the Nile Basin. Hence, the water management zones obtained through unsupervised classification of the dominant principal components have shown greater variation across the basin. Attaching physical names for such a detailed classification requires extensive ground observation; and this may not be applicable to large basins like the Nile. However, the observed patterns of the biophysical factors indicated that the vegetation indices have a similar spatial pattern with the humidity index, and the variability of the soil bulk density is much smoother than, but has similar patterns with, the topographic indices. Therefore, the humidity index and the soil bulk density are used for setting a classification framework for water management zones.

Eighteen water management zones are identified from six classes of humidity index and three classes of the soil factor. In addition, one environmentally sensitive zone is formed by merging wetland and protected areas. The proportional areas of the 19 water management zones are listed in Table 4.3. About 10 per cent of the Nile Basin falls under the environmentally sensitive zone. In this zone, water development interventions should not be permitted. Rather, conservation and protection of the natural ecosystem should be promoted.

The humid and wet humid zones are the water source zones of the Nile Basin. The water source zones account for less than 15 per cent of the basin area. This fact complies with the low specific run-off of the Nile Basin. Since the identified zones have unique climate and soil properties, the water management interventions required to address issues in each zone should also be unique. Therefore, developing a water management strategy for the Nile Basin should commence by mapping potential water management interventions at basin and regional scales within such similar hydronomic zones.

Table 4.3 The proportional areas of the hydronomic zones in the Nile Basin

Name of zone	*Zone code*	*Zone area (million km^2)*	*Percentage of basin area*
Hyper arid – light soil	HaLs	537.45	17.22
Hyper arid – medium soil	HaMs	0.00	0.00
Hyper arid – dense soil	HaDs	179.45	5.75
Arid – light soil	AaLs	196.29	6.29
Arid – medium soil	AaMs	188.26	6.03
Arid – dense soil	AaDs	78.24	2.51
Semi-arid – light soil	SaLs	276.41	8.86
Semi-arid – medium soil	SaMs	265.43	8.51
Semi-arid – dense soil	SaDs	280.94	9.00
Dry subhumid – light soil	DsLs	189.30	6.07
Dry subhumid – medium soil	DsMs	85.21	2.73
Dry subhumid – dense soil	DsDs	23.52	0.75
Humid – light soil	HhLs	296.99	9.52
Humid – medium soil	HhMs	80.76	2.59
Humid – dense soil	HhDs	4.11	0.13
Wet humid – light soil	WhLs	23.56	0.75
Wet humid – medium soil	WhMs	27.87	0.89
Wet humid – dense soil	WhDs	0.09	0.003
Environmentally sensitive	EnSe	351.49	11.26
Unclassified		35.24	1.13
Total		3120.59	100.00

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