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Water availability and demand analysis in the Kabul River Basin, Afghanistan

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FOR
MY PARENTS AND FAMILY!
whose utmost support and prayers are always with me

"And your Lord has commanded that you shall not serve (any) but Him, and goodness to your parents. If either or both of them reach old age with you, say not to them (so much as) "Uff" nor chide them, and speak to them a generous word."
[Quran 17:23-24]

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ABSTRACT

Kabul River Basin (KRB), the most populated and highly heterogenic river basin of Afghanistan is the lifeline of millions of people in terms of supplying them with water for agricultural, municipal, and industrial as well as hydropower production purposes. Unfortunately, KRB is facing a multiplicity of governance, management and development relevant challenges for the last couple of decades. Detailed and reliable assessments of land use and land cover, water demand (for different sectors) as well as the available water resources are prerequisites for Integrated Water Resources Management across the basin. To achieve increased accuracy for water availability and demand analysis across the KRB, the study area was segregated into different hydrological and administrative units (provincial level, subbasin level etc.) in order to capture the heterogeneity driven by complex physiographic conditions (mainly due to huge elevation differences) and resulting in diverse cropping pattern at different reaches of the river basin. The innovative part of this study has been the concept of introducing spatial segregation of the large heterogenic river basin and using crop phenological information for evapotranspiration and land cover analysis respectively; it gave a distinct value to the output of this study. Phenologically tuned normalized difference vegetation indices (NDVI) of Aqua and Terra platforms with moderate resolution (250 m) proved to be very effective in the estimation of the land cover across the KRB with high accuracy. The phenology based segregated spatial analyses of the LULC of KRB with reference to 2003 (the base year of the study) highlighted the change in the ground coverage of main crops across the KRB e.g. wheat, barley, maize and rice. Based on the evaluation of the above results referring to the period 2003 to 2013, the rise in wheat ground coverage has been compensated by the decline in barley cultivation; maize and rice share has been almost consistent among the dominant cereals production in KRB. Upon spatial segregation, across the sub-basins (Alingar, Chak aw Logar, Ghorband aw Panjshir, Gomal, Kabul, Kunar and Shamal) Shamal, Kunar and Kabul showed highest actual evapotranspiration (ET_a) throughout the study period of 2003 to 2013. The later three sub-basin host relatively large irrigated areas and production of two crops per year due to relatively favorable climatic and geographic conditions. Besides the agricultural water demand (ET_a), water availability estimation through rainfall-runoff modelling by the use of the Soil and Water Assessment Tool (SWAT) has been very useful in data scarce regions like KRB. The application of the hydrological model using remote sensing products as input is the only effective choice in data scarce regions and exhibited results which are required by policy makers and investors for the strategic and sustainable planning and management of land and water resources.

KURZFASSUNG

Das Einzugsgebiet des Kabul Flusses (KRB) ist das bevölkerungsreichste Einzugsgebiet in Afghanistan und weist eine ausgeprägte Heterogenität auf. Durch die Entstehung und Bereitstellung von Wasserressourcen für landwirtschaftliche, kommunale und industrielle Nutzungen sowie die Wasserkraft bildet das KRB die Lebensgrundlage für Millionen von Menschen. Unglücklicherweise ist das KRB (bzw. seine Einwohner) seit Jahrzehnten mit einer Vielzahl von Herausforderungen in Form von Governance-, Management- und Entwicklungs-relevanten Problemen konfrontiert. Die detaillierte und zuverlässige Einschätzung der Landnutzung/-bedeckung, des Wasserbedarfs (für die relevanten Sektoren) sowie der verfügbaren Wasserressourcen sind Voraussetzungen für die Integrierte Bewirtschaftung der Wasserressourcen im Einzugsgebiet. Um eine erhöhte Genauigkeit der Analysen in Bezug auf Wasserverfügbarkeit und –bedarf für das KRB zu erreichen, wurde das Untersuchungsgebiet in hydrologische und administrative Unter-Einheiten (Provinzialebene, Teil-Einzugsgebiete) differenziert, damit auf diesem Weg die Heterogenität erfasst werden konnte, die durch komplexe physiographische Verhältnisse (im Wesentlichen als Folge ausgesprochen großer Höhenunterschiede) entsteht und in unterschiedlichen landwirtschaftliche Anbauplänen in den Teilbereichen des KRB resultiert. Innovative Elemente der Arbeit liegen in der detaillierten räumlichen Diskretisierung des großen und heterogenen Flussgebietes und der expliziten Nutzung phänologischer Informationen bei der Fernerkundungs-gestützten Bestimmung der Evapotranspiration und der Landnutzung/-bedeckung; dadurch konnten Ergebnisse erzielt werden, die in dieser detaillierten Form für das KRB bisher noch nicht vorliegen. Die Verwendung des an die phänologischen Daten angepassten, Vegetationsindizes ‚Normalized Difference Vegetation Index‘ (NDVI) - ermittelt aus Aqua- und Terra-Plattformen mit moderater Auflösung (250 m) - erwiesen sich als sehr effektiv bei der Einschätzung der Landnutzung/-bedeckung im KRB mit hoher Genauigkeit. Die Phänologie-basierten und räumlich segregierten Analysen der Landnutzung/-bedeckung im KRB mit Bezug auf 2003 (Basisjahr der Untersuchungen) machten Veränderung in den Flächenanteilen der Hauptanbaukulturen im KRB (Weizen, Gerste, Mais und Reis) deutlich. Aus der Analyse dieser Ergebnisse für den Zeitraum 2003-2013 lässt sich schließen, dass der flächenmäßige Anstieg des Weizenanbaus durch einen Rückgang der Anbaufläche für Gerste kompensiert wurde; die Anteile für Mais und Reis blieben nahezu unverändert im KRB. Die Bestimmung der aktuellen Evapotranspiration mit räumlicher Unterscheidung in Teil-Einzugsgebiete (Alingar, Chak aw Logar, Ghorband aw Panjshir, Gomal, Kabul, Kunar and Shamal) lieferte über den gesamten Untersuchungszeitraum 2003 – 2013 die höchsten Werte für die Teil-Einzugsgebiete Shamal, Kunar und Kabul. In diesen letztgenannten drei Teil-Einzugsgebieten liegen vergleichsweise große

Bewässerungsgebiete, in denen aufgrund der günstigen klimatischen und geografischen Voraussetzungen zwei Kulturen pro Jahr angebaut werden. Zusätzlich zur Bestimmung der aktuellen Evapotranspiration (Wasserbedarf der landwirtschaftlichen Kulturen) ist die Abschätzung der Wasserverfügbarkeit insbesondere in Gebieten mit ungünstiger Datenlage (wie im KRB) wichtig und äußerst nützlich. Dazu wurde das hydrologische Einzugsgebietsmodell SWAT (Soil and Water Assessment Tool) zur Erfassung von Niederschlag-Abflussvorgängen eingesetzt. Die Anwendung von hydrologischen Modellen in Verbindung mit Techniken und Produkten der Fernerkundung (zur Bereitstellung von Modell-Input) ist in Fällen mit eingeschränkter Datenverfügbarkeit die einzig wirksame Option, um Ergebnisse in einer Qualität zu erreichen, die von Entscheidungsträgern und Investoren für die strategische und nachhaltige Planung der Bewirtschaftung von Land- und Wasserressourcen benötigt werden.

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ACRONYMS

ANDS	AFGHANISTAN NATIONAL DEVELOPMENT STRATEGY
CDC	COMMUNITY DEVELOPMENT COUNCIL
CSO	CENTRAL STATISTICS ORGANIZATION
DEM	DIGITAL ELEVATION MODEL
ERDAS	EARTH RESOURCE DATA ANALYSIS SYSTEM
ET	EVAPOTRANSPIRATION
FAO	FOOD AND AGRICULTURE ORGANIZATION
GDP	GROSS DOMESTIC PRODUCT
GIS	GEOGRAPHIC INFORMATION SYSTEM
GTP	GROUND TRUTH POINTS
HRU	HYDROLOGICAL RESPONSE UNIT
IROA	ISLAMIC REPUBLIC OF AFGHANISTAN
IWRM	INTEGRATED WATER RESOURCES MANAGEMENT
KRB	KABUL RIVER BASIN
LULC	LAND USE AND LAND COVER
L/S	LITER PER SECOND
MAIL	MINISTRY OF AGRICULTURE, IRRIGATION AND LIVESTOCK
METRIC	MAPPING EVAPOTRANSPIRATION AT HIGH RESOLUTION WITH INTERNALIZED CALIBRATION
MEW	MINISTRY OF ENERGY AND WATER
MOCN	MINISTRY OF COUNTER NARCOTICS
MODIS	MODERATE RESOLUTION IMAGING SPECTRORADIOMETER
MOM	MINISTRY OF MINES
MPBH	MINISTRY OF PUBLIC HEALTH
MRRD	MINISTRY OF RURAL REHABILITATION AND DEVELOPMENT
MUD	MINISTRY OF URBAN DEVELOPMENT
NASA	NATIONAL AERONAUTICAL SPACE ADMINISTRATION
NDVI	NORMALIZED DIFFERENCE VEGETATION INDEX

NEPA	NATIONAL ENVIRONMENTAL PROTECTION AGENCY
PDC	PROVINCIAL DEVELOPMENT COMMITTEE
RBA	RIVER BASIN AGENCY
SCWAM	SUPREME COUNCIL FOR WATER AFFAIRS MANAGEMENT
SEBAL	SURFACE ENERGY BALANCE ALGORITHM
SEBI	SURFACE ENERGY BALANCE INDEX
SEBS	SURFACE ENERGY BALANCE SYSTEM
SPOT	SATELLITE POUR L'OBSERVATION DE LA TERRE/ SATELLITE FOR OBSERVATION OF EARTH
SRTM	SHUTTLE RADAR TOPOGRAPHY MISSION
S-SEBI	SIMPLIFIED SURFACE ENERGY BALANCE INDEX
SWAT	SOIL AND WATER ASSESSMENT TOOL
UN	UNITED NATIONS
UNEP	UNITED NATIONS ENVIRONMENT PROGRAM
UNODC	UNITED NATIONS OFFICE FOR DRUGS AND CRIME
WFP	WORLD FOOD PROGRAM
WUA	WATER USER ASSOCIATION
GLDAS	GLOBAL LAND DATA ASSIMILATION SYSTEM
UTC	COORDINATED UNIVERSAL TIME
GMT	GREENWICH MEAN TIME

1 INTRODUCTION

1.1 Background

Afghanistan is an agricultural country with a land area of around 652,864 km^2 where water is the lifeblood for its inhabitants both in terms of enabling life and providing the base for economy. The essential importance of water among Afghans can be very well understood with a famous Afghan proverb “may Kabul be without gold but not without snow”. For integrated water resources management, the country is divided into five major river basins (Figure 1.1):

i. Kabul River Basin
ii. Northern River Basin
iii. Helmand River Basin
iv. Hari-Rod Murghab River Basin and
v. Panj-Amu River Basin.

These river basins are of transboundary nature and therefore Kabul River Basin drains into Pakistan, Helmand River Basin drains into Iran, Panj-Amu River Basin flows to the North-west and joins the Amu Darya in Central Asia. The Harirod-Murghab River Basin as a major tributary of the Amu Darya; it consists of the Hari Rod river, which flows west from its source west of Kabul into Iran and the Murghab river which dries up in Turkmenistan. Among the five major river basins, the Northern basin has the smallest annual flow contribution (~ 2% of the total annual flow in Afghanistan), but, unlike other transboundary river basins of the country, the entire amount of water generated in the basin is used within the country’s boundaries. The basin consists of small watersheds that have their sources in the high mountains of the central highlands of the country. The rivers of this river basin dry up in irrigation canals or desert sands long before reaching the Amu Darya River.

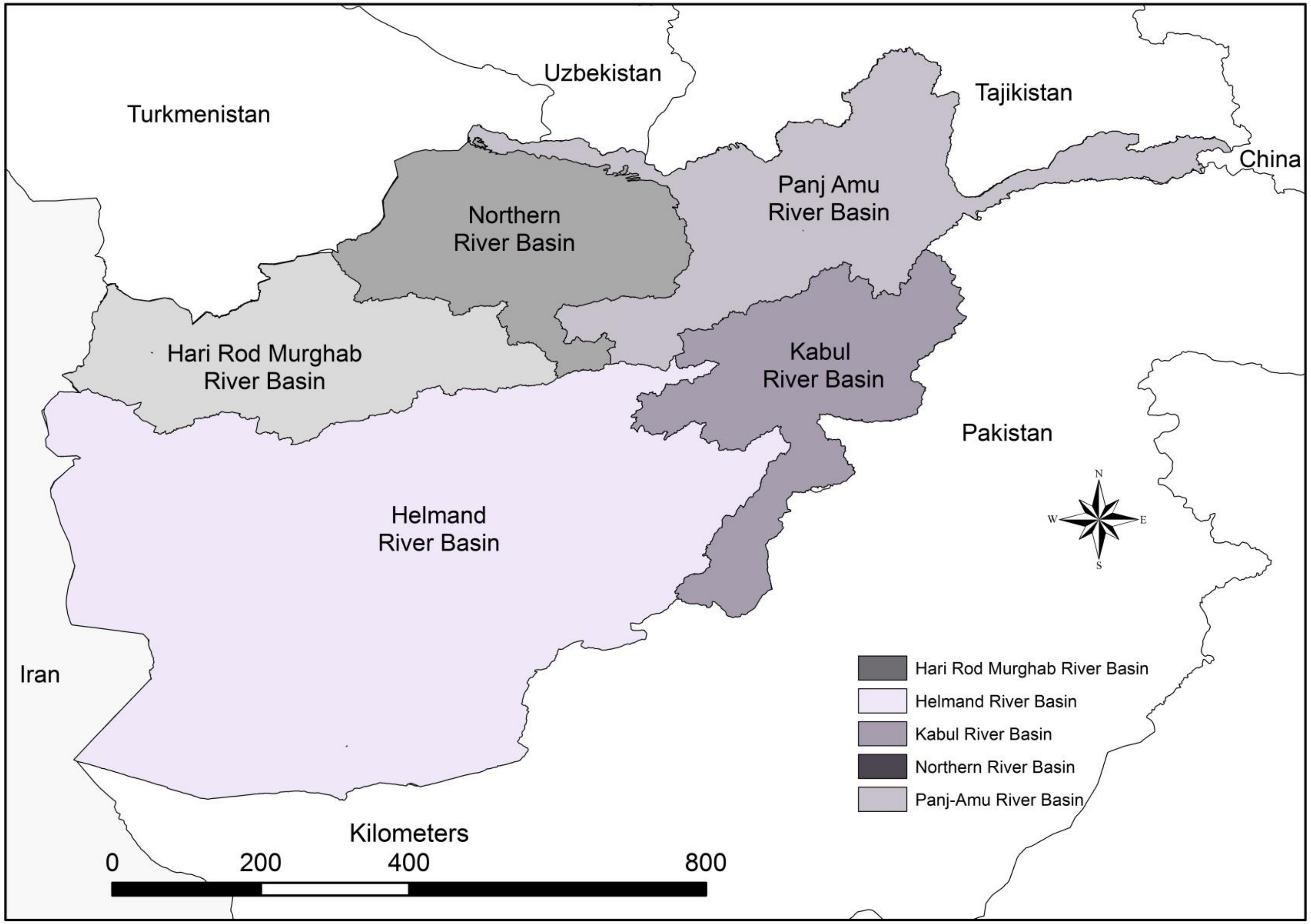


Figure 1.1: River Basin map of Afghanistan

Afghanistan's economy is dominated by agriculture which accounts for more than 50% of the national gross domestic product (GDP) and employs around 66% of the country's workforce (FAO, 2015c). More than 95% of the current water use in Afghanistan is accounted for agriculture (Qureshi, 2002).

So far, around 12% (~77,850 km^2) of the total land area of Afghanistan is arable and about 46% (~36,027 km^2) of the total arable area (around 5.5% of the total land area) is irrigated, while the other half is rainfed (Figure 1.2) (World Bank, 2016). Irrigation is therefore essential for ensuring reliable agricultural production.

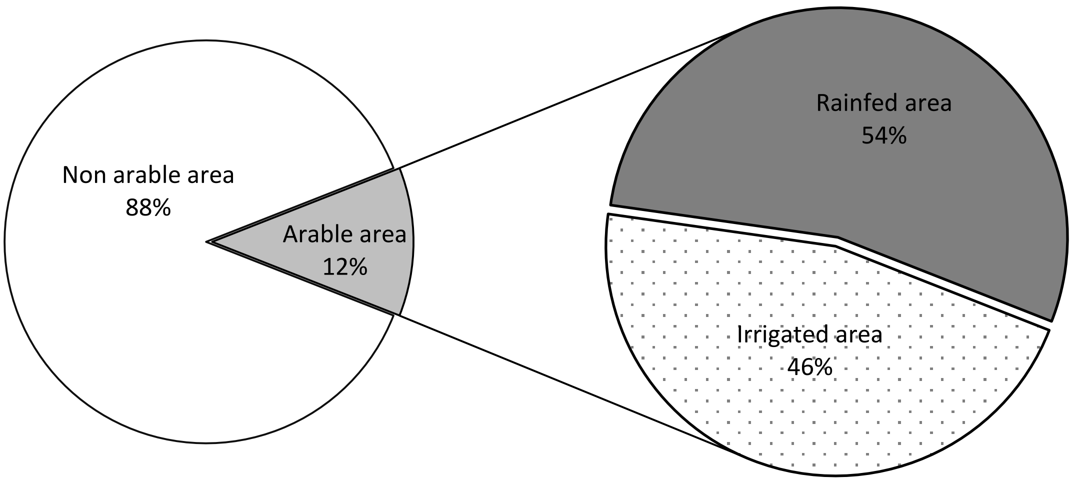


Figure 1.2: Shares of non-arable and arable land in Afghanistan; based on World Bank data (World Bank, 2016)

The main arable lands for permanent corps are located in the river basins in the north (east), south and east of the country. The cultivated land is irrigated to a varying degree depending upon its geographic location, extent of the rainfall during the crop season and access to surface (e.g. rivers and canals) and groundwater flow (e.g. groundwater wells and Karezes (Qanat) etc.). Within the irrigated area, around 85% of all agricultural productions are achieved (CSO-IRoA, 2015a). Yet Afghanistan imports major staple food (e.g. wheat) from the neighboring countries. It is therefore evident that rather low water productivity in agriculture is one of the basic limitations to agricultural production in Afghanistan whereby the major hydraulic infrastructures have been destroyed by war in the past decades (FAO, 2013).

Afghanistan is a country which is prone to drought where a severe drought generally means to low winter rainfall in two successive years. The weather records from the region show that low winter precipitation in two successive years occurs at least once every 10-15 years. The last under-average successive years across the country were 1963-1964, 1966-1967, 1970-1972, 1999-2001 and parts of 2002 (Favre and Kamal, 2004). Several droughts were also observed during the period of 2002 to 2011 (WFP 2004; Rafferty, 2011) that drastically affected the agriculture and livestock sector. As the long-term drought management should be seen as part of wider water management strategies, updated information on water resources will help facilitate better planning for drought management in the future. Droughts such as that of 2004 caused an aggregate decline of 43%, around 3.06 million tons, compared to that of the record harvest in the cereal production in 2003. Such a situation typically highlights the importance of a strategic integrated water resources management aiming at sustainability and allowing adaption to variability in precipitation at river basin scales. Moreover, around 50 to 75% of the cropped area across the country experienced failure due to the aforesaid drought conditions (FAO/WFP, 2004). Currently more than 7 million people (about 30% of the population) are food insecure (consuming less than 2,100 kcal/day) out of which 2.1 million suffer severely from food insecurity (UCDAVIS, 2011). Development of water resources and improvement in water productivity for irrigated agriculture are thus paramount to sustainable economic growth and addressing rural poverty.

1.1.1 Climate regions of Afghanistan

Due to the geographic heterogenic nature of Afghanistan, NEPA and UN Environment (2016) divided the country into five major regions (Figure 1.3) based mainly on elevation, annual precipitation and land cover. Major features of these regions are pointed out below:

1. The Hindukush region: It is the most elevated and mountainous region of Afghanistan which receives maximum precipitation and is consequently a major

source of water which feed rivers of regional (Central Asian) importance like the Amu Darya.

2. The Northern Plains (North): this region has a mean elevation of around 600 m and is dominated by grasslands. Although the region is comparatively dry, it is still essential for agriculture, especially due to the cultivation of almond trees and providing grazing opportunities for sheep and goat.
3. The Central Highlands: These highlands are located almost in the center of Afghanistan and are famous for its deep valleys and mountain ranges up to 6,400 m.
4. The Eastern Slopes: this region is influenced by the moist air masses of the sub-continental (Indian) monsoon received on the high mountain slopes and cause rain in most parts of the eastern Afghanistan. The area is covered by forests and allows agriculture. Yet, the rains (when reaching high amounts and intensities) also can cause flooding and land/mud slides.
5. The Southern Plateau: it is the largest region which is mainly dominated the by desert. Agriculture is possible solely along the river-sides as well as in the marshlands. The Helmand River in this region divides the region and nourishes the Helmand Lake. This region is naturally prone to dust and sand storms which is mainly linked with northerly winds.

Out of these regions, the KRB includes mainly the Eastern Slopes, the Hindukush region and partly the Central Highlands.

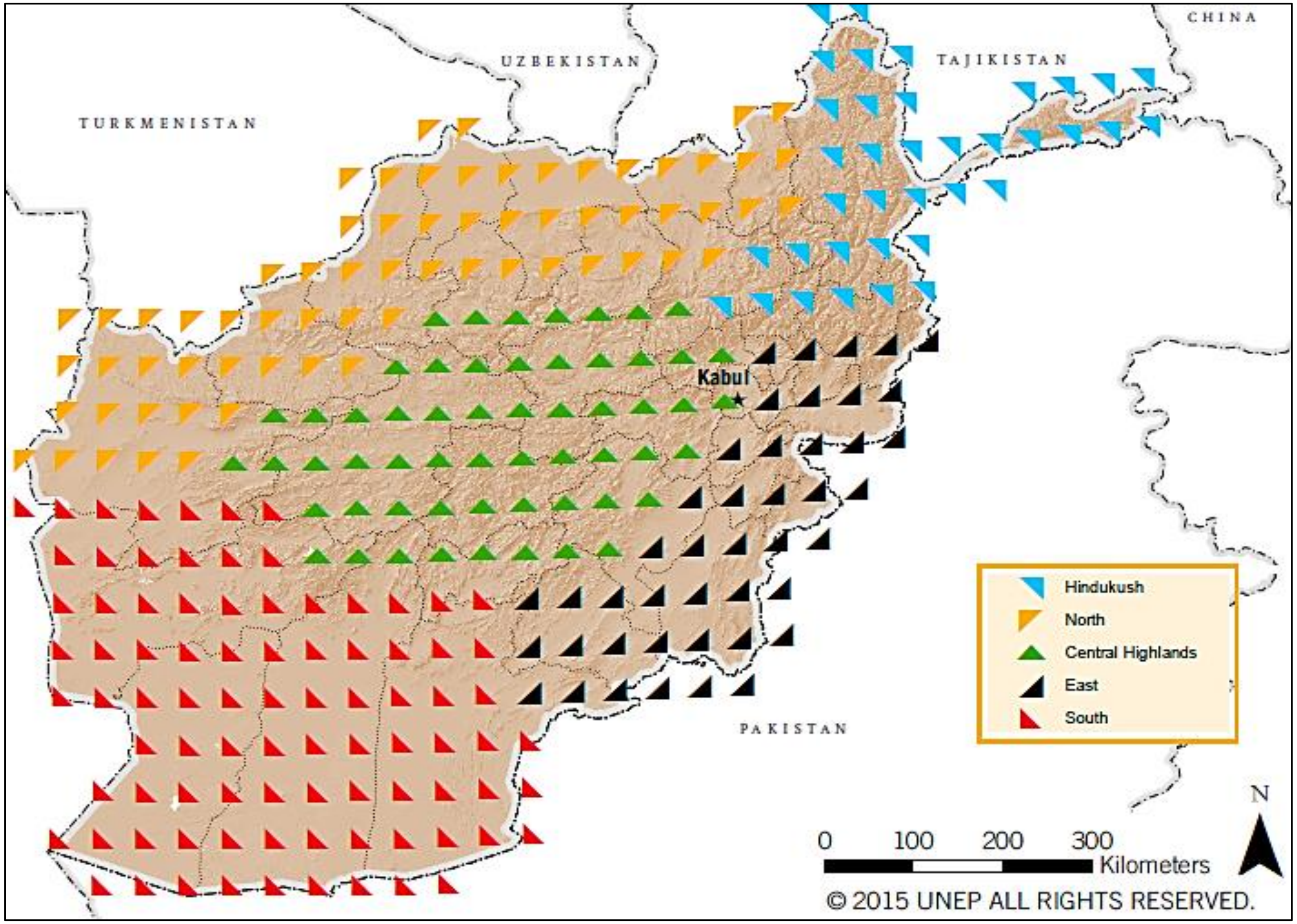


Figure 1.3: Climate Regions of Afghanistan; Source: NEPA & UN Environment (2016)

1.1.2 Water resources availability and water security

The climate conditions of Afghanistan vary between arid and semi-arid country receiving inconsistent rainfall over the years. The rainfall varies from as low as 75 mm in Farah to 1,170 mm in south Salang pass in the Hindu Kush Mountains; rainfall occurs mostly in the winter months (February-April). This wet season coincides with periods of low vegetative cover. At higher elevations, precipitation falls as snow which melts when temperature rise, and is very critical for streamflow as well as irrigation in summer. From June to October, Afghanistan receives relatively little precipitation. The rainfall patterns cause high dependency of irrigated agriculture on snow and glacier melts.

Available data shows that natural storage of water in the form of winter precipitation or snow at elevations beyond 2,000 m constitute around 80% of Afghanistan's water resources (excluding the fossil groundwater) (Aini, 2007; Klemm, 1996). The amount of water received in the country through precipitation (327 mm/year) is estimated to be around 213.5 km^3 per year (FAO 2016). According to current estimates, Afghanistan has 65.3 km^3 of potential water resources produced annually out of which 55.7 km^3 is surface water and 10.65 km^3 is groundwater. Out of the total surface water produced, about 18.18 km^3 is externally produced while 37.5 km^3 is produced internally. The contribution to internally produced water from Kabul river basin is around 11.5 km^3, Helmand river basin 9.3 km^3, Hari Rod-Murghab river basin 3.1 km^3, Northern river basin 1.9 km^3 and Amu Darya (Panj) river basin 11.7 km^3. Similarly, out of the total groundwater produced internally (i.e. 10.65 km^3) the Kabul river basin contributes around 1.92 km^3; Helmand and Western river basins 2.98 $km^{3,}$ Northern and Murghab river basins 2.14 km^3, Hari-Rod river basin 0.64 km^3 and Amu Darya (Panj) river basin is 2.97 km^3. The overlap between surface and groundwater amounts to around 1 km^3 (FAO, 2016).

In 1987, the total annual water withdrawal was estimated to be around 26.11 km^3 out of which 25.8 km^3 (99%) was meant only for agricultural purposes. But the most updated figure for the water withdrawal is that of 1998 whereby the total annual volume of water withdrawn for irrigation purpose was estimated to be around 20 km^3

(Rout, 1998). It is evident that there is a high uncertainty in available information on water withdrawals across the country without providing a clear explanation for the differences having been observed in a relatively short period of around 10 years. It therefore underlines the needs for an importance of studies on water availability and demand to be carried out for facilitating the overall water management across the country. Out of the total water withdrawn, 3 km^3 (15%) is the groundwater extraction (Rout, 1998) while the remaining 17 km^3 (85%) is contributed by the surface water (Figure 1.4) (FAO, 2015$_b$). Around 98% of the total water withdrawn is used for agriculture and 1% each for domestic and industrial purpose across the country (Figure 1.5).

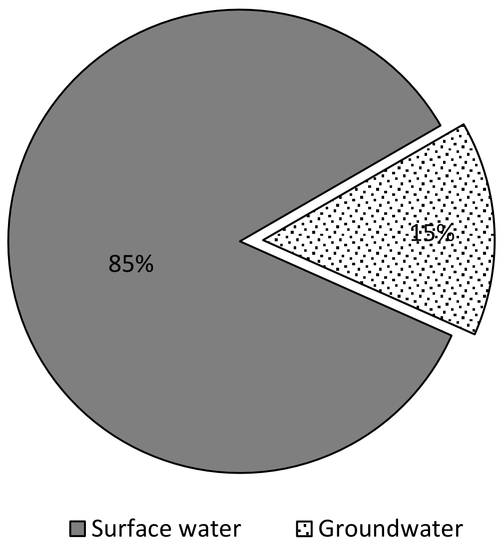


Figure 1.4: Source based water withdrawal in Afghanistan

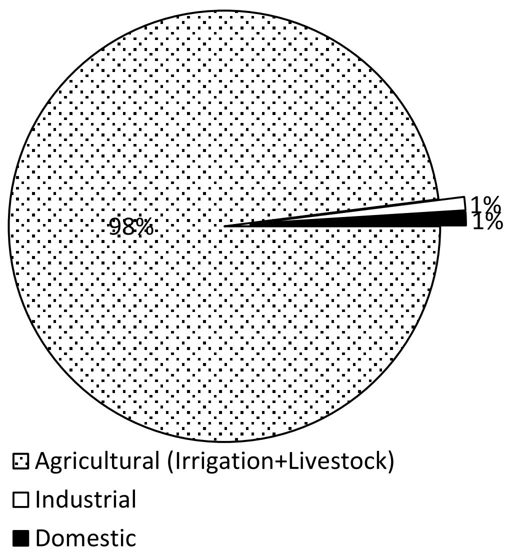


Figure 1.5: Sector-based water use in Afghanistan

The total groundwater recharge in the country is estimated to be in the range of 10.65 km^3 (VUA, 2003, reported in (Uhl and Tahiri, 2003)) to 16.5 km^3 (FAO, 1996). The study carried out on the KRB upstream (Mack et al., 2010b) shows that in areas where water withdrawal from groundwater is high and recharge is low, e.g. in Kabul city, aquifers are increasingly depleted as indicated by the fact that groundwater-level decline may reach tens of meters. A 10% reduction in the total annual precipitation has been predicted in the next 50 years caused by the climate change (Vining and Vecchia, 2007). Currently, most of the total annual recharge of the groundwater aquifers occurs in late winter and spring during peak snowmelt periods. The projected climate change scenarios of increased temperatures may cause aquifer recharge to peak earlier in the year, and will shift it away from the summer period when water is needed most for irrigation purposes (Mack et al., 2010b). The shift in hydrograph is even more serious to irrigated agriculture.

About 61% of the drainage area of the Amu Darya Basin lies within Uzbekistan, Tajikistan and Turkmenistan while only 39% is part of Afghanistan (Rakhmatullaev et al., 2010). During the distribution of the Amu Darya water quota, the riparian countries received their share e.g. Uzbekistan 48.2%, Turkmenistan 35.7%, Kyrgyzstan 0.6%, Tajikistan 15.5% while Afghanistan being the upstream country was excluded in the water quota arrangement of the Aral Sea basin (Water Unites, 2017). There were an estimated 5 km^3 diversions of surface flows to the Amu-Darya in 1980 (Ahmad and Wasiq, 2004). Amu Darya basin also offers the best return to additional investment in water resources development in Afghanistan but there is the need to strengthen transboundary water allocation in the basin by including Afghanistan because the potential future use of flow generated at its territory may impact the downstream water users in the Amu Darya basin.

The KRB, part of the wider Indus River system, surrounds around 12% of Afghanistan's territory and accounts for about 26% of Afghanistan's total annual river flow (World Bank, 2010). Pakistan partly relies on the discharge generated from Afghan territory; the transboundary dimension even increases the need to manage water resources very carefully and thus enhances the necessity for developing a centralized database for record keeping and also for providing calibrated and validated modelling tools (such as SWAT under this study) in order to react on changing situations (climate and land use changes) which is essential for any transboundary river basin and associated deals and understanding.

According to UN-Water (2013), the definition of water security is "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability". The population growth and consumption patterns are at the root of near-term water challenges between Afghanistan and its neighbors especially those with whom Afghanistan shares its water resources, and predicted climate change scenarios are expected to exacerbate the situation (Dehgan et al., 2014). The lack of international treaties governing the shared water resources of Afghanistan is another consideration in the future water security initiatives. Therefore, the increase in water use demand of Afghanistan and its downstream neighbors as well as the impacts of climate changes over the precipitation patterns will likely lead to increased and significant strain on water resources and will largely challenge the water security for the millions of people living within the lap of these river basins. The (mis)management of this strained and shared natural resource may have direct and severe impacts on the human development of the multitude of communities that rely on these waters for their routine livelihoods (Hanasz, 2011).

The United States' Intelligence Community (2012) highlighted some of the key issues and problems with river basins that are strategically important to the United States because of their transboundary status. Among these river basins (Nile, Indus, Tigris-Euphrates, Mekong, Jordan, Brahmaputra and Amu Darya) are two river basins i.e. Amu Darya (which includes Panj-Amu and Northern River basins of Afghanistan) and Indus (including the Kabul River Basin on Afghanistan territory) which are shared by Afghanistan with its neighbors due to their hydrological boundaries. The type of issues, their associated future impacts and relevant management capacity are elaborated below in a tabular format. According to the United States' Intelligence Community (2012) the river basin management capacity is described as an assessment of the strength and resilience of institutional factors, such as treaties and river basin organizations that can provide stability, increase cooperation, and mitigate political grievances over water. The United States' Intelligence Community (2012) further says that even well-prepared river basins are likely to be challenged in the future by increased water demand and impacts from climate change, which is expected to lead to greater variability in rainfall which in consequence is favoring the occurrence of extreme events in terms of floods and low flow situations/droughts (Intelligence Community, 2012).

Table 1-1: Overview of the expected issues and challenges to the Indus and Amu Darya basin: Source (Intelligence Community, 2012)

River Basin	Type of water issue	Impact/Expected Time	River Basin Management Capacity
Indus	• Poor water management • Inefficient agricultural practices • Soil salinization • Inadequate infrastructure • Greater variability in water availability • Water pollution	• Degraded regional food security—present to 2040 • Reduced resiliency to floods and droughts—present to 2040	Moderate
Amu Darya	• Inadequate water agreements • Degradation of water quality and • disruption of flows some states • Poor water management	• Degraded regional food security—present to 2040 • Increased regional tensions over water—present to 2040 • Decreased health of populations around dried Aral Sea	Inadequate

Beside the aforesaid major issues, the future security is further threatened by the predicted climate change scenarios that will largely limit the precipitation and water availability across the river basins of Afghanistan. In addition to this, the climate change is expected to raise water demand due to enhanced evapotranspiration as a consequence of higher temperatures; in addition, the land use dynamics are reasons leading to an increasing demand which is mainly driven by population growth. As a consequence, gaps between supply and demand may occur or may exacerbate, these trends create the need for improving water management which needs to be based on updated and spatially explicit information and on appropriate modelling tools. Therefore it is assumed that during the next 10 years, many countries of strategic importance to the United States with transboundary basins will experience water problems (shortages, poor water quality, or floods) which may lead to instability and state failure and may increase regional tensions (Intelligence Community, 2012). This will therefore hamper the capability of key countries to produce more food and energy and will be a big threat to the global food markets as well as economic growth. The numerous problems stated above highlight the importance of water resource estimation, handling and mitigating the issues mentioned to avoid future conflicts as well as to fulfil food security standards and contribute to ecosystem management.

The Helsinki rules (International Law Association, 1967), applicable to all drainage basins that cross national boundaries, except where other agreements between bordering nations exist, affirm the rights of all bordering nations to an equitable share in the water resources, with reasonable consideration of such factors as past customary uses of the resource and balancing variant needs and demands of the bordering nations. It also sets forth recommendations for resolving disputes and conflicts over the usage of such watercourses. In order to determine the reasonability and equitability in share, all associated factors need to be considered together in order to reach a conclusion upon the share of each contributing nation. The most important among these factors is the geography of the basin or the extent of the drainage area in the territory of each basin state, hydrology of the basin (contribution of water by each basin state), and the population dependency on the water of the basin being shared. Based on these terms, Afghanistan legally qualifies to siphon away water being contributed to the Amu Darya basin generated over its territory. Beside this, improving the management strategies highlighted through this research will also reduce the aforesaid problems.

1.1.3 Situation of the irrigation and drainage infrastructure

The irrigation network in Afghanistan has a share of 88% unlined irrigation canals which causes around 40% of the total water losses across the country (Qureshi, 2002).

The hydraulic infrastructure is under further strong threats; since 1980s, around 46% of the hydraulic structures have been damaged as a result of war and power struggle Therefore, most of the canals are silted with declined hydraulic capacity in terms of water conveyance compared to that in the actual design. In recent years, FAO and the Ministry of Energy and Water carried joint efforts towards rehabilitation of the irrigation canal network under which around 495,299 ha of agricultural lands were rehabilitated across Kabul, Nangarhar, Kandahar, Herat, Kunduz, Mazar-e-Sharif and Bamyan provinces. Due to these efforts, the average crop yield increased by 24% in irrigated areas (FAO, 2015c).

The existing irrigation system in the KRB consists of conventional schemes usually developed, constructed, maintained and operated by farmers according to the traditional customs and practices with some exceptions of recent interventions by the Afghan government. Most of the farmers are unaware of the actual (site-specific and time-depending) water requirements of the crop that they cultivate and of appropriate irrigation schedules. As a consequence, the delivery of water in the fields is based on the rule of maximizing the amount captured, leading to imbalance of water supply availability between up- versus downstream canal reaches and water losses at the different reaches along the canals with potential yield and biomass loss (in tendency: combined impact of yield loss due to over-irrigation in upper reaches and due to under-supply in the lower parts)..

The irrigation systems in Afghanistan can be classified into two main types: informal irrigation systems (surface water systems, Karez, springs and wells) and formal irrigation systems. The formal irrigation system has centuries' long history and has been managed and developed locally using the available local resources. It is further subdivided into four main categories (FAO, 2015_b; Qureshi, 2002; FAO, 1997):

I. ***Informal Surface water systems***

a. ***Small-scale informal surface water systems:***

These are the conventional irrigation systems established centuries back whereby water is supplied from the streamflow diverted using the brush weirs made of local materials. Usually these systems are located in remote valleys along the streams and rivers. They are constructed and maintained in a conventional way through communal village based Shuras and councils. The water rights are also set up in a similar manner. These types of systems cover around 100 ha area per system.

b. Large-scale informal surface water systems:

The ground coverage limit per system of these irrigation systems is up to 200,000 ha and it exists along the plains and main river valleys. Although they are known as informal, yet their operation and maintenance is very much structured and involves local communities of different backgrounds. Different stakeholders (village) share water from these systems. At least there is one water master (locally called Mirab) per village who delegates his authority to sub-water masters which are responsible for the allocation of water to different fields within the scheme. The repair and maintenance (canal cleaning etc.) works are carried out through mobilization of a large workforce. The farmers in the irrigation command area are supposed to assist in terms of labor and cash. Due to the impacts of war, conflicts, water logging and salinization, large parts of these schemes have been abandoned especially in the Harirod, Farah, Helmand and Murghab valleys.

II. Shallow wells or arhad system:

In this system, groundwater is lifted from shallow wells with the help of the Persian wheel (arhad) supplying irrigation water to the agricultural land. The area of irrigated land is usually below 3 ha. Shallow and deep wells account for 0.4 % of the total irrigated area in the country (Favre and Kamal, 2004). There are around 8600 shallow wells in Afghanistan, irrigating around 12000 ha of agricultural land. Recently, modern well-drilling and pumping technology has also become common which has considerably increased the number of wells and their capacity (ICARDA, 2002; Routh, 2008). These trends and reasons standing behind create the urgent need to estimate water balance components (including groundwater recharge) in order to avoid over-exploitation of the groundwater aquifers.

III. Springs:

Springs are made when the groundwater table reaches the ground surface, it starts flowing down through gravity. There are around 5,558 springs across the country irrigating about 188,000 ha of agricultural land. As springs directly dependent on the groundwater level a fluctuations of the groundwater level determine the discharge from springs; this dependency becomes especially relevant in periods with declining in the groundwater levels and as a consequence a decreasing discharge from springs . That is why most of the worst drought-hit areas are located in the eastern and southern regions of the country, which are heavily dependent on irrigation from spring water. Springs cover around 6.9 % of the irrigated area of the country (Favre and Kamal, 2004).

IV. Karez (qanat) systems:

Karezes (qanats) are the underground tunnels with mild slopes which transmit water from the underground aquifer for domestic or irrigation purposes. Karezes are usually smaller in size but its length could extend in kilometers. The average discharge from these Karezes varies between 10 l/s to 200 l/s but may reach up to 500 l/s. The technique underground tunneling for water deliver has been utilized for thousands of years in different parts of the country and its neighborhood. It is one of the most cost-effective methods of using groundwater for irrigation purposes, and is environmentally safe; water is drawn by gravity. There are 6,741 Karezes in the south and southwest of the country with a few examples in the northern areas. One of the drawbacks of the Karez system is that there is no proper mechanism to stop water during its flow in winter or in case of no need for irrigation, in order to overcome this problem, storage facilities are an option to reserve water for use during peak demand period and thereby contributing to sustainable water management of these systems. The Karez irrigation system cover around 6.2 % of the total irrigated area of the country (Favre and Kamal, 2004).

(B) Formal irrigation systems

I. Formal surface water systems without storage:

This kind of system has a permanent intake structure; which is used to direct water from the source of supply, such as a reservoir or a river, into the irrigation scheme or system. The intake structure is typically built at the entry to the irrigation system. This kind of irrigation scheme management trails the rules of the large-scale conventional surface water schemes as elaborated above. However, the difference between the two systems is the difference in regulations of water flow to the system which depends on the understanding between relevant government officials and the village/rural communities.

II. Formal surface water systems with storage:

The large-scale irrigation system development is rather a recent innovation in Afghanistan which dates back to 1960-1978. Around five large-scale modern irrigation systems had been built by the 1970s. Due to differences in land tenure rules at that time, some parts of these schemes were operated under private land ownership agreements, while others were operated as the state owned farms which belonged to the government. The governmental authorities heavily subsidized these schemes but the local farmers were given partial choice in terms of farming practices and crop selection.

III. Formal groundwater systems:

There is little information regarding the irrigation schemes which are supplied with groundwater from deep wells. Till the late 1980s, in Khost and Paktia provinces, the surface water irrigation schemes existed which were irrigated by water withdrawal from 100 deep wells. About 100,000 ha are said to have been under sprinkler irrigation (both private and government owned) in the 1970s. Sometimes in the lower reaches of large traditional schemes where water shortage is common, individual farmers used to irrigate their fields from water drawn from the shallow wells.

1.1.4 Challenges to information availability on water resources

As the discharge represents the response of a catchment on precipitation, evapotranspiration (considering storage changes), river flow measurements form the basis for hydrological analyses and therefore started in Afghanistan in the mid1940s across a few known sites. The number of these measurement sites increased progressively over the years until the late 1970s. Measurements were discontinued soon after the Soviet invasion and civil strife in the country. Almost no records have been stored since 1980, and the river gauging stations have either been destroyed or are otherwise not operable. Afghanistan had a network of around 160 river gauging stations until 1978. (Mack et al., 2010; Favre and Kamal, 2004). Information on Afghanistan's land and water resources are thus old, outdated and limited (Mack et al., 2013) especially under climate and land use change conditions. As a consequence, this situation highlights the need of extensive research studies at all five basin levels.

The first comprehensive analysis on these river basins was prepared by the FAO decades ago (FAO, 1965). In collaboration with UNDP, the FAO also prepared the Watershed Atlas of Afghanistan in 2004 to provide updated information of land and water resources in the country (Favre and Kamal, 2004). This information was further updated in 2012 with additional ground data (FAO, 2012). Currently, the problem is not only the scarcity of data, but also the fact that available hydrological and meteorological data parameters often do not allow the analyses required for future water management and development. Due to the lack of reliable historic meteorological data, significant refinement is frequently required for the projection of climate change scenarios. Afghanistan's complex topography also reveal that local variations in response to global warming, especially precipitation, are likely to be huge, in magnitude and may become highly diverse depending on the specific location. In addition, sporadic and poor quality socio-economic data make cost-benefit analyses of adaptation and mitigation policies extremely difficult. Another factor which restricts the capacity to carry out structured fieldwork for the assessment of the potential mitigation and adaptation options is the prevailing countrywide insecurity (Savage et al., 2009). These conditions favour the need to apply global data-sets as well as the remote sensing products as the only option for carrying out long term analyses.

Due to degrading catchment conditions and general environmental decline, the sustainability of the water resources, however, has been severely affected in recent years. The river basins and their sub-watersheds have suffered significantly from uncontrolled exploitation, overgrazing, deforestation and other forms of environmental degradation. Deforestation, together with dry land farming on steep slopes has led to substantial erosion. Sedimentation is another serious problem in many of the reservoirs and the irrigation systems. In addition, for various reasons rangelands are overgrazed resulting into declining pasture land coverage.

Another reason for the missing hydrological and meteorological data is the lack of appropriate water control structures along the rivers, canals and watercourses. The damaged canal embankments and changing river morphology thereby threatens the stability of existing water intakes and are some of the key problems faced by the irrigation sector. There are around 174 hydro-meteorological stations planned to be installed around the country over various rivers for measuring rainfall, relative humidity, water level, water quality, temperature and sunshine (FAO, 2015c). Yet, the issues associated with some of these installations are misplacement (installation along the river embankment with non-uniform and changing cross sections), inappropriate calibration and delays in repair in case of technical faults due to the lack of local technical personnel and facilities. Beside the aforesaid reasons, there are further issues hindering reliable monitoring at many gauges installed over the river network for example:

- the gauge is installed over the elevated bed along the cross section while the river flow, e.g. in late summer season, takes place in the opposite extreme of the river cross section and therefore the gauge is untouched for flow measurement;
- while construction takes place, the flow is intentionally diverted without having intermediate solutions for flow measurements (Figure 1.6);
- the river stream is split to two parts by excavating sands from one half of the river bed for construction purposes, and therefore the water depth which

touches the gauge at one side is considered to be representing the water depth along the entire river-bed (Figure 1.7). Generalizing the gauge reading at one half for the entire river is technically incorrect and leads to unrealistic data records and is creating severe problems for analyses for the water resources management;

- Another issue is the installation of discontinued vertical staff gauges at the river edge that mislead the reader and consequently undermine the quality of the data due to gaps between any two consecutive staff gauge pieces.

Figure 1.6: Staff gauge installed at the downstream Kabul river (Behsud Bridge, Jalalabad Afghanistan) with (a) obstacle in the flow direction as well as standing water and disturbing influences by sharp change in cross-section (pillar) and meanwhile (c) the non-aligned staff gauge at the river bank used for discharge measurement.

Figure 1.7: Streamflow divisions through temporary bifurcation and sand excavation along the river-bed while the staff gauge is installed at the far right along the cross section at Behsud Bridge on Kabul River; (a) and (b) are the two arms of the river as a result of the temporary bifurcation with the (c) sand piles in the middle of the river bed and causing the split of stream into two parts.

1.2 Research needs

Future water security needs to be addressed through innovative practices and targeted investments. On the irrigation front, these include improved water management practices at farm, irrigation system and watershed levels, through innovative strategies, technology and reforms in management and institutions. Irrigation system rehabilitation needs to adopt a holistic river-basin approach strengthening service-oriented water control being output-oriented and designed to meet the provision of irrigation and drainage service (Malano and van Hofwegen, 1999). It also needs to take into account issues related to water allocation among schemes, linkages between surface and groundwater resources, and inter-relationships between the irrigation systems in the form of return flows and recirculation of water within and among the systems as well as inter-sector use of water. This approach to irrigation rehabilitation will not only help secure water supply in the systems that have suffered considerable loss and destruction in the past but will also reduce producers' vulnerability to the annual variations in precipitation. It will also allow them to adopt new types of on-farm water management practices. The approach further needs to be complemented by including an impact assessment of hydrographs modified by changing water use/rehabilitated irrigation systems, altered sedimentation and erosion patterns as well as changes of material flow in rivers and stream discharges. This refers to water users in Afghanistan as well as to the riparian neighboring countries on the larger scale. Detailed analysis of the land use and land cover is of paramount importance for two main reasons: land use influences runoff generation and in turn hydrographs and available water resources. In addition, water demand especially in the agricultural sector is clearly affected by the land use and land cover. The Kabul river basin is a typical example for such interrelationships, which strongly influence people and the environment due to the high dependency of the population on irrigated agriculture in this basin. Selection of the KRB for the detailed research has been further motivated by the fact that it hosts the highest population density compared to other river basins in Afghanistan, and therefore it is important to explore these inter-relations between the population and environment.

Given these challenges, improving water management in Afghanistan entails addressing various environmental, technical and institutional issues. This demands a shift from a conventional sectoral approach towards an integrated water resources management and development. As an entry point, such an approach requires improved understanding and reliable information on the status of water availability and uses in the country. It also requires researching the impact of climate and land use changes which will further change both water availability and demand to be estimated by scenarios especially for agriculture; as these processes are highly dynamic developing of model-based tools is a further must in order to update information and to enable adaptive water management.

Available literature sources show that Afghanistan's water sector will face growing challenges through climate change, as its water availability is largely dependent on accumulation, storage and melting of the snow cover. The available information on land and water resources need to be analyzed and reviewed in a new context, as Afghanistan has embarked upon large scale water resources development programs in recent years. In addition, future land and water uses will be also highly molded by the economic advancement, population growth and the impacts of climate change, as it will affect both supply and demand of water resources. A comprehensive analysis on water resources has thus become imperative for sound planning and development of the future water management in the country. It needs to include (1) provision and analysis of information on water balance components and (2) providing a calibrated/validated model (needed to run scenarios of climate and land use change), alternative options for water management strategies as well as impact assessment.

1.3 Innovation of this study

Due to instability of political regimes in Afghanistan, data availability on land and water resources has always been scarce and unreliable for the last four decades. During this time, a tug-of- war on power gaining in this country was always the priority of the warlords, and therefore no attention has been paid so far to the necessity of system establishment on safeguarding and accumulation of data which would have been urgently needed for the management of land and water resources. Therefore, current situation features a wide gap between the data required for the future planning and management of the vital water and land resources versus a limited availability of data.

There are various physiographic differences between the upstream and downstream of the KRB which largely drives the cropping pattern and length of crop growth period in the different spatial and administrative units. The novel approach used in this study is the spatial segregation of the entire KRB into 7 major subbasins (watersheds) and 13 administrative units or provinces.

For the cropping pattern analysis over the study period (2003-2013), spatial segregation of the KRB into 13 provincial administrative units with their relevant crop calendar provides more reliable results than by generalizing the entire basin in terms of geography and climatic conditions. The administrative units are Kabul, Kunar, Kapisa, Panjshir, Paktya, Paktika, Parwan, Logar, Khost, Laghman, Nangarhar, Nuristan and Maidan Wardak provinces.

The use of phenologically tuned MODIS (Moderate Resolution Imaging Spectroradiometer)-NDVI (Normalized Difference Vegetation Index) was extremely helpful in achieving the objectives to a higher accuracy. Since the river basin planning and management mainly considers the natural watershed boundaries, therefore studying the water demand at the spatially segregated subbasins contributes the detailed information required for sound master planning and management.

Future climate variability is expected to severely affect snow cover, thereby changing the hydrograph in tendency in terms of a shift towards a more quick discharge response to precipitation. Counterbalancing negative impacts of this trend on the water users (especially irrigation) creates the need for raising the storage capacity of the basins by technical measures (i.e. reservoirs) and by management interventions for improving the storage capacity of landscapes and use of underground storage or aquifers.

An up-to-date analysis of this issue is undertaken in this research. This can effectively support decision-makers e.g. Ministry of Energy and Water (MEW) when considering additional capacities of reservoirs in order to compensate the loss of snow cover. In addition, the findings of this research present the required crop-water demand based on an updated land-use and land-cover map for the KRB. Due to data scarcity in Afghanistan, the Surface Energy Balance System (SEBS) was used for different spatial and temporal units of the KRB. The data required in the SEBS was downloaded from different satellite platforms (for details see Chapter 4). It is therefore the task of the Ministry of Agriculture, Irrigation and Livestock (MAIL) to ensure on-farm water availability for meeting the crop water demand. This will provide options for the aforesaid ministries to rethink the irrigation water quota for the irrigated agriculture alongside the highest population demand for drinking water supply, industrial demand and other domestic uses. Another innovative feature of this study is the use of remote sensing products for the land use and land cover analysis, later utilized as high-resolution input to SWAT model that was used for estimating water availability in the KRB (Bouraoui and Grizzetti, 2014; Ndomba et al., 2008; Stehr et al., 2008), and to help the planners to prepare their projects (selection of appropriate sites; estimating required dimensions) based on the results obtained from the simulations of the SWAT model. The (SWAT-) model-based approach is furthermore an option to at least partly cope with the impact of rather high uncertainty in terms of impacts from climate and land-use changes when considering appropriate scenarios and to react on changing situations (by running SWAT simulations).

1.4 Hypothesis

The KRB is a typical – and drastic – example of many basins in developing countries being confronted with an urgent need for action in terms of water management interventions to cope with changing environments versus a rather limited data and information base.

A combination of hydrological modelling and remote sensing techniques is an appropriate approach to tackle this challenge. Specifically and referring to the KRB, remote sensing techniques, targeted data acquisition on the ground and the hydrological model SWAT can be applied as complementary tools in order:

- to assess the land use/land cover, its spatio-temporal development to understand past changes and to estimate future trends based on MODIS data utilized by a phenology based segregated spatial analyzing approach
- to estimate actual evapotranspiration approximating the current water demand and indicating water stress by the Surface Energy Balance System (SEBS) algorithm
- to simulate hydrographs representing water supply with the SWAT model fed with above-mentioned data derived from remote sensing and utilizing available hydrological data on the ground (after critical review)

The combination of above-mentioned approaches is appropriate to (i) deliver information on water demand- as well as supply in order to enable water management concepts framing the coordination of supply and demand; and to (ii) provide a tool which can be used to adapt and refine water management concepts to future changes coming from climate change and land use dynamics.

1.5 Research objectives

The main objective of this study is therefore to develop a methodology which can identify water availability and demand gaps in the KRB of Afghanistan with minimum ground information.

The specific objectives are:

- To analyze the land use and land cover of the KRB at various spatial and temporal resolutions over the period 2003-2013;
- To estimate the crop-water demand (actual evapotranspiration) across different spatial units of the KRB (main basin, subbasins, provinces) as well as temporal scales (annual, monthly, seasonal) for the period 2003-2013;
- To estimate the water availability across the different spatial and temporal scales in the KRB.

1.6 Dissertation outline

Chapter 1 provides a detailed overview of the issues, challenges and current status of the land and water resources of the KRB. Chapter 2 gives an introduction to the study site, its physiographic conditions while Chapter 3 focuses on the land-use and land-cover analysis at different spatial and temporal scales across the KRB using the MODIS NDVI time series. Chapter 4 provides actual evapotranspiration estimates over different spatial and administrative units (basin, subbasin, and province) as well as temporal scales (monthly, annual, and seasonal) resulting from the use of different remote sensing products.

In Chapter 5, the water availability across the basin as a result of the simulations using the Soil and Water Assessment Tool (SWAT) is discussed. In Chapter 6, summary and conclusions of the overall findings are followed by recommendations for future consideration, policy making and master planning of river basin water resources. Chapter 7 provides a list of the literature consulted regarding the subject and relevant issues.

2 STUDY AREA

2.1 Description of the study area

The Kabul River Basin (KRB) (Figure 2.1), characterized by rugged terrain and an uneven topography, is located between Lat. 36.05^0 N, Lon. 71.72^0 E and Lat. 31.62^0 N, Lon. 67.56^0 E. It forms the western part of the upstream tributary system of the Indus basin which is the hydrological backbone of Pakistan and of high importance for irrigated agriculture as well as for the country's economy. In administrative terms, the KRB is shared by 13 provinces in the central, east and south-eastern parts of Afghanistan. Ghazni province contributes a very small land area based on its natural elevation but has negligible contribution in terms of agriculture and hydrology and is therefore usually excluded from any planning initiative as the majority of the province lies within the Helmand river basin.

The elevation of the KRB is in the range of 400 m (downstream) to 6000 m (upstream) above sea level. The basin hosts around 33% of the total population of the country and provides water for around 10 million people (~138 persons/km^2, based on CSO estimation for 2014-15) (CSO-IRoA, 2015) for their vital daily needs as well as for secondary industrial, agricultural and power production purposes essential to the country's development.

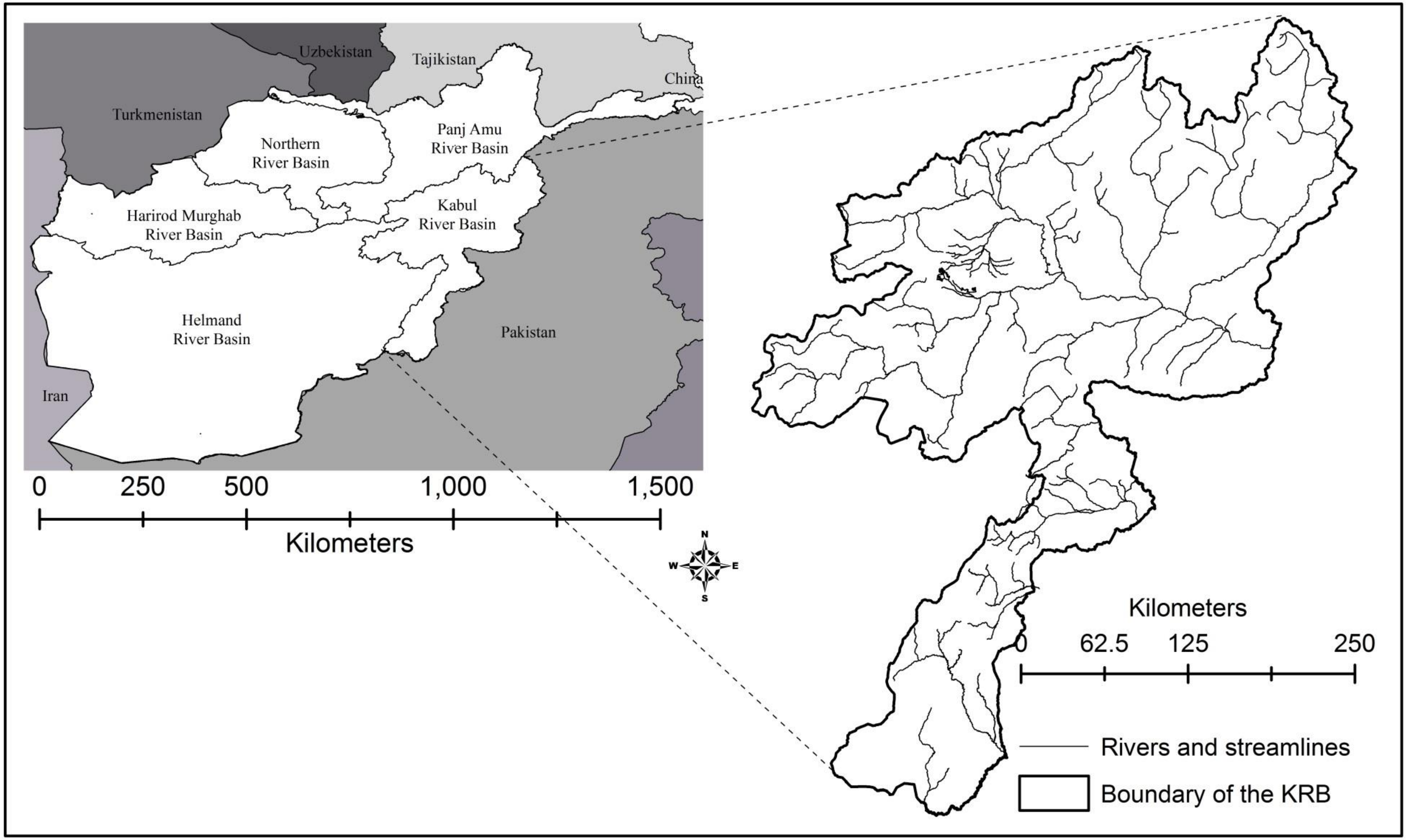


Figure 2.1 Location of the study area and stream/river network

2.2 Drainage area and cropping pattern

The drainage area of the KRB is around 72, 646 km^2 of which approximately 9% (~6,691 km^2) is cultivated in conventional farmland units dominantly with wheat in rotation with maize, rice and sometimes vegetables. Agricultural lands are often located along the meandering routes of rivers and associated tributaries of the basin. The downstream part of the basin usually observes two cropping seasons a year, while in the upstream and central upstream a single cropping season is practiced, usually wheat. The reason is the considerable climatic distinctions between upstream and downstream (mainly due large elevation differences) (Figure 2.4). Besides wheat cropping, the upstream and central upstream parts of the basin are famous for orchards of peaches, grapes and apples etc. while the downstream locations i.e. Nangarhar, Laghman and Kunar provinces feature considerable wheat, maize and rice production together with a large production and supply of vegetables and fruits to the market.

The country's most forested areas are located within the KRB specifically in Khost, Paktya, Paktika, Kunar and Nuristan provinces (Delattre and Rahmani, 2009). The country's poppy cultivation is strongly driven by the prevailing insecurity and takes place mostly in the southern provinces which are partly controlled by anti-state elements. Political situation is also determining poppy cultivation in the districts/provinces of the KRB. From 2003-2013, poppy was cultivated mainly in the provinces Nangarhar, Laghman, Kunar, Kapisa and a small land area in Kabul (UNODC and MoCN, 2013). The extent of poppy cultivation has differed from year to year e.g. in Nangarhar the area was 18,904 ha in 2003, 294 ha in 2009 and 15,719 ha in 2013.

The KRB is subdivided into 7 main subbasins (watersheds). Among them, Ghorband aw Panjshir and Kabul are the biggest subbasins while Alingar is the smallest in terms of drainage area (Table 2-1).

Table 2-1: Major Subbasins of the Kabul River Basin

S. No.	Subbasin	Drainage area (km^2)	Elevation range (m. asl)
1	Alingar	6236	641-5420
2	Ghorband aw Panjshir	12954	1021-5430
3	Chak aw Logar Rod	9958	1777-4283
4	Kabul	12988	378-4719
5	Kunar	11665	501-6077
6	Gomal	9001	1070-3282
7	Shamal	9845	865-4726

2.3 Climate

Afghanistan is regarded as a country with continental climate, however the presence of mountains and foot hills cause numerous and distinct local differences. There is large heterogeneity between the upstream and downstream regions of the KRB in terms of elevation, precipitation and temperature variations. Due to the heterogenic nature of the basin, the cropping pattern, crop growing period and cropping frequency vary between upstream and downstream regions. In 2013 at the central upstream, the mean minimum annual temperature was 6.4 C° and the mean maximum temperature 20 C° (Figure 2.2). The total annual precipitation was 418 mm with a clear concentration of precipitation during the winter months, December to April.

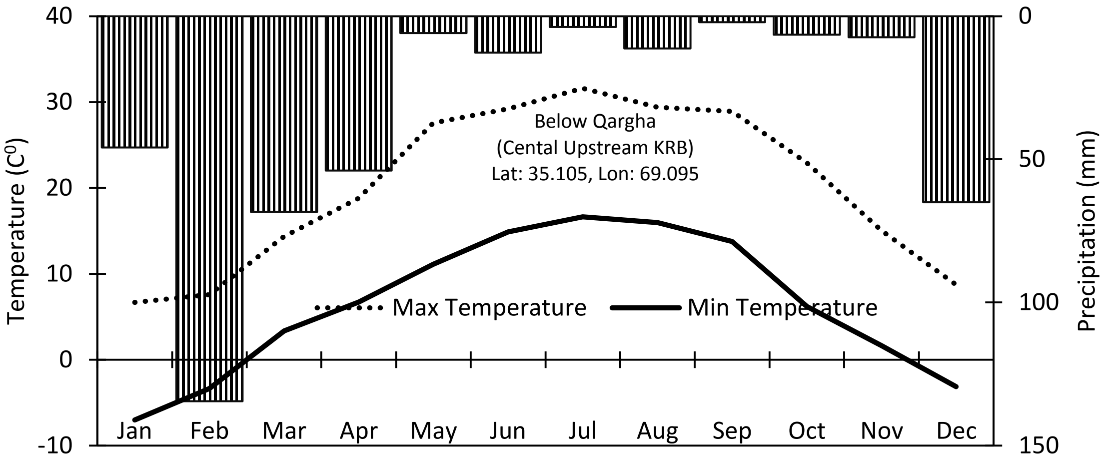


Figure 2.2: Climatograph of the central upstream of the Kabul River Basin

In that year, in the downstream location at Nangarhar the mean minimum and maximum annual temperature was 17 C^0 and 28 C^0 respectively (Figure 2.3). The total annual rainfall recorded at the downstream was 327 mm with highest rainfall in February and March, and slight monsoon shots were observed in June and July. Generally, the eastern and south-eastern border regions (downstream) receive monsoon showers in the months July-September influenced by the South Asian Himalayas (Evans-Pritchard, 1973).

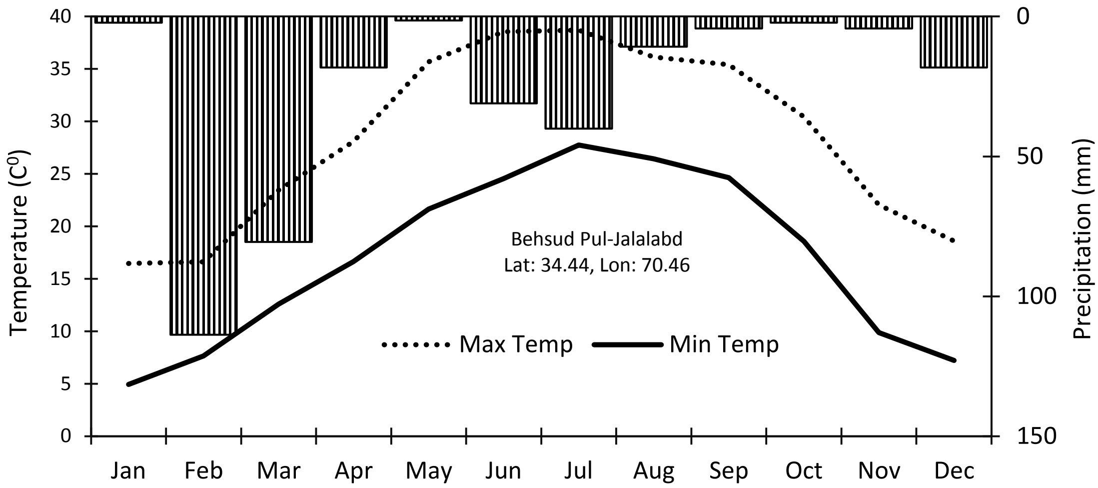


Figure 2.3: Climatograph of the downstream of the Kabul River basin

2.4 Water resources for irrigation

Water availability for irrigation purpose is a function of the seasonal variation of stream flow and groundwater availability. Natural hydrographs (without the artificial impact by water storage in reservoirs) in Afghanistan reach their maximum in the spring and early summer season while a minimum flow is observed in late summer to winter over a large area of the country. Many rivers dry up along sections of their course or are reduced to isolated pools during the minimum-flow period, which is generally not sufficient to fulfil the crop water requirements (Petr, 1999). Natural hydrographs are dominated by snow melt and therefore the cover and thickness of the snow has significant influence on crop yields and in turn on livelihoods and economy.

In addition to merely irrigation, water resources management is also equally important for the domestic and municipal water sector, hydropower development, and industrial uses. Though water consumption in these sectors is substantially less as compared to agriculture sector; yet, economic growth, increasing population and rising water use for mining and other industries are potential threats to water quality and in turn to the environment and on the health of the population. The need to maintain a good water quality for drinking water provision and ensuring ecosystem functioning are likely to put pressure on overall water resources management going beyond consideration of water quantities in future. Furthermore, there is a need to coordinate water use in irrigation and hydropower; although hydropower is a non-consumptive use, periods of peak demand might differ, which for example may lead to release of water I periods without any irrigation demand. This research is focusing on water quantities which provide the base for further water quality explorations due to the fact that any understanding/modeling of water quality requires knowledge on water quantities.

The KRB covers around 12% of the national territory of Afghanistan and generates around 26% of the country's total streamflow (Favre and Kamal, 2004). It hosts an area with the highest population compared to rest of the river basins in the country. The incoming annual flow Afghanistan is receiving from across the Durand line through the Kunar River is estimated to be around 10 km^3 $year^{-1}$ while the outflow of the Kabul River from Afghanistan to Pakistan is estimated to be in the range of 21.5 km^3 $year^{-1}$ (FAO, 2015).

The main sources of irrigation in the basin are streams, springs, *Karezes* as well as extraction from groundwater wells. Irrigated agriculture contributes the most to the food production in the KRB due to the relatively intensive canal networks developed in the eastern provinces (mainly Nangarhar, Laghman and Kunar). There is an additional potential for the enhancement of irrigated agriculture (King and Sturtewagen, 2010) provided modifications in the irrigation infrastructure are implemented and respective economical investments are made (Ward et al., 2008). However, due to inertia in the management system of irrigation canals, there has been little improvement in its extension and consolidation over the course of the last three decades (FAO, 2015a).

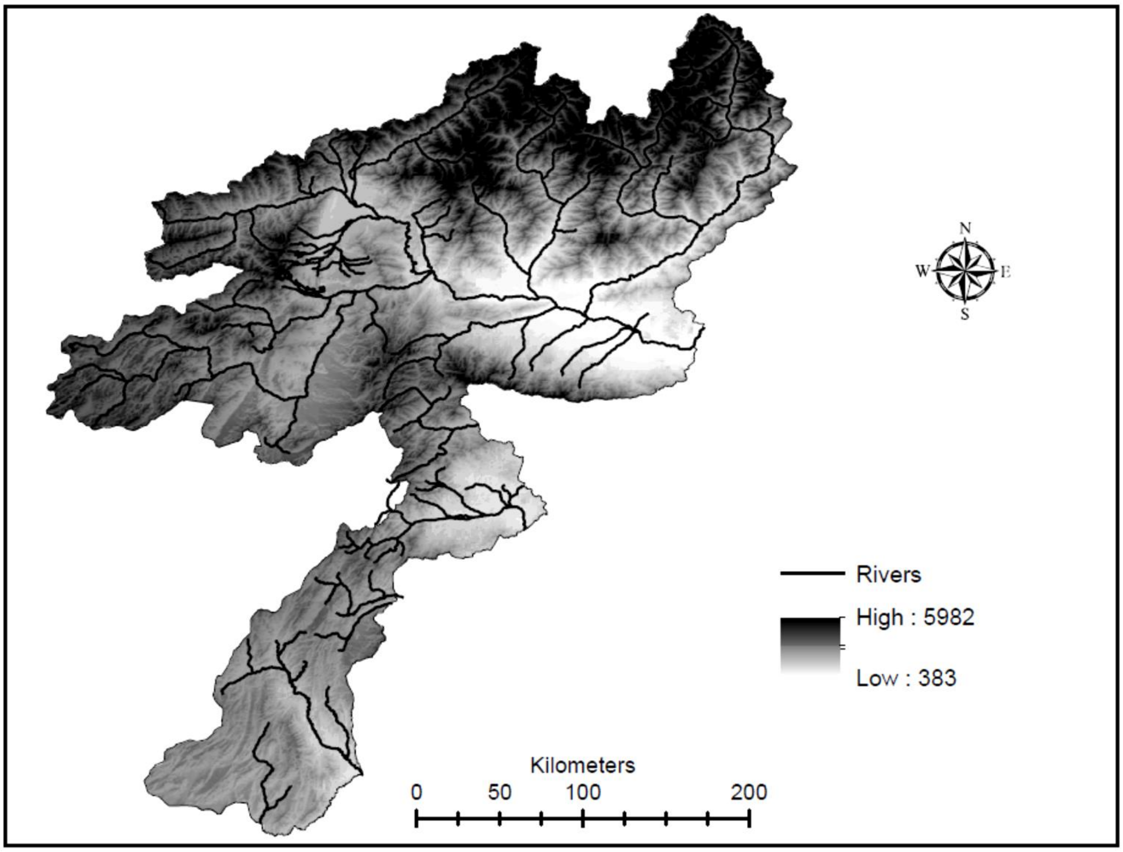


Figure 2.4: Hydrographic and elevation map of the Kabul River Basin

2.5 Institutional structure of water resources management and governance

The government of Afghanistan has legally approved Integrated Water Resources Management (IWRM) as the basic approach for the water resources management at all water resources management units in Afghanistan (Kakar, 2011). For this purpose, a coordination chain (Figure 2.5) was established by the government for establishing river basin agencies at all the major river basins of the country (Kakar, 2011). The sub national offices are based on basin and subbasin delineations. The tasks and responsibilities of the Ministry of Energy and Water (MEW) are an organized focus over the regulatory and managerial roles of the ministry and its basin and subbasin agencies.

The Supreme Council of Water Affairs Management (SCWAM) established in 2005 is the prime body for national level coordination of policy and strategic development. All ministries that are related to water are involved as members of the council, which is chaired by the first vice president. The technical secretariat chaired by the deputy minister for water affairs is responsible for support in terms of technical assistance in preparing strategic and technical documents for review and approval.

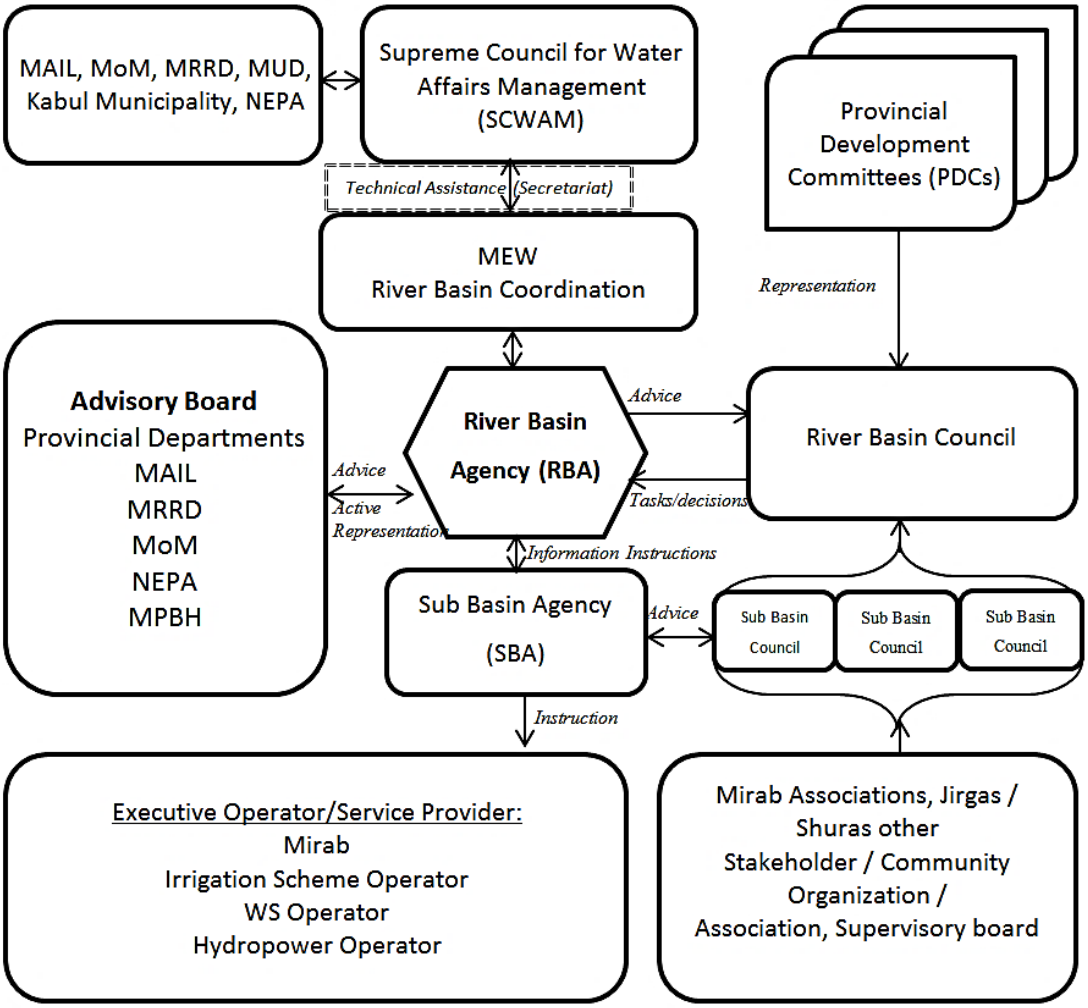


Figure 2.5: Schematic structure of the water resources management of the river basins of Afghanistan (Source: Kakar, 2011)

In the provinces, there is a provincial coordination council, which is chaired by the relevant provincial governor and the representatives are from the provincial line departments which hold monthly meetings. The establishment of the river basin advisory board at the river basin level is in progress. The river basin councils have not been established yet, and water management issues are being handled by the working groups of the river basins which consist of representatives from the community development councils and provincial line ministries as well as representatives of Water Users Associations. Due to poor governance and instability in the country, the entire institutional structure required for the river basin is not yet complete, but the United Nations and other non-governmental organizations play a key role in the identification of sustainable projects and provision of technical expertise as well as monetary assistance and in some cases providing laboratory facilities e.g. water quality testing laboratories etc.

For the implementation of the integrated water resources management approach across the country's river basins, analysis of the cropping pattern, available amount of water for different water use sectors as well as estimation of the agricultural water demand is a requisite for a sound and sustainable distribution, governance and management of water resources at different administrative units of water management.

3 LAND USE AND LAND COVER ANALYSIS

3.1 Introduction

Due to internal developments and because of the transboundary nature, the Kabul River Basin (KRB) is of great strategic importance for Afghanistan and beyond. The KRB received a large number of Afghan repatriates in the post-2001 period due to relatively better security conditions, services and resources availability compared to the rest of the country. Having been already overwhelmed by the existing population, the current food production in the KRB does not meet the requirements of the local inhabitants, this being confirmed by the fact that 30% of the population is food insecure consuming less than 2100 kcal/day (UCDAVIS, 2013b). Coping with the food insecurity issues requires maximum information regarding land use and land cover (LULC) of the target area; yet, the existing data deficiency in general and especially the insufficient knowledge on the LULC restricts effective planning, management and proper development of the national water resources in Afghanistan. Current data and information deficits further limit the prospects for the advancement of a rational coherent policy on trans-boundary river basins (King and Sturtewagen, 2010). For this reason a national level land-cover atlas of Afghanistan was drafted in 2010 by the Food and Agriculture Organization of the United Nations (FAO) and Global Land Cover Network as a follow up on the land cover mapping of Afghanistan conducted in 1993 (FAO, 1993) which provides information on the aggregated land cover distribution in Afghanistan (FAO, 2012). However, a basin-wide study of LULC specifically targeting the key variation in the land use and land cover of the major crops in the KRB is yet to be carried out. From the perspective of integrated water resources management, it is highly important to have a segregated study of the cropping pattern at the provincial level whilst utilizing remote sensing products in order to support creating a preliminary base profile of the local water requirements not only for agriculture as the biggest consumer of water resources (Qureshi, 2002), but also for industrial, municipal, sanitation and drinking purposes.

Before going into the details, it is fundamental to distinguish between the land use and land cover because in many existing classification systems documented so far, both the terms mentioned are sometimes confused and misunderstood. Therefore both the terms used in this research follow the basic definition by (Di Gregorio and Jansen, 2000) and are elaborated as follow:

Land cover is considered to be the observed (bio)physical cover on the earth's surface. The land cover in a very pure and strict sense could be described as the vegetation and man-made features. Consequently, the areas where the surface consists of bare rock or soil are described as land itself rather than land cover. It is also debatable to admit that water surfaces are real land cover. However, in practice, generally the scientific community defines those features under the term land cover.

Land use is characterized by the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it. With this definition, land use forms a direct linkage between the land cover and peoples' actions in their environment.

To date, several studies have been conducted which have highlighted the diverse impacts of LULC change on the socio-economic development in regional ecosystem services, biodiversity, land surface temperature, as well as the influence on runoff characteristics (Xiao and Weng, 2007; Sulieman and Elagib, 2012; Wu et al., 2013; Sajikumar and Remya, 2015). The analysis of the LULC is vital for adequate diagnosis of its influence on the changes in atmospheric dynamics in different climatic regions (Kharol et al., 2013). The dynamics of global change in the LULC is driven by various factors, ranging from war and recurrent conflicts (Delgado-Matas et al., 2015), rising population (Jayne et al., 2014), changes in institutional and socio-economic conditions (Niedertscheider et al., 2014) to sharp urbanization (Rutten et al., 2014; Deng et al., 2015; van der Sluis et al., 2015). In the meantime, a move towards food security, depending upon the economic status of the countries, has significant influence over the LULC systems and associated changes (Badami and Ramankutty, 2015). An LULC analysis helps very much to improve the local policies of natural resources conservation especially in the areas where LULC and socio-economic conditions are swiftly changing (Scullion et al., 2014). Therefore it is very important to thoroughly examine the LULC analysis at various spatial and temporal scales in order to be able to answer questions related to the interactions between population and environment especially in an agrarian environment (Walsh et al., 2001). The LULC and climate change are considered to be important drivers of variation in stream-flow (Niraula et al., 2015) thereby underscoring its importance for effective natural resources management aimed at providing detailed and precise information regarding LULC of the target region (Cheema and Bastiaanssen 2010; Sajikumar and Remya 2014; Singh et al., 2015).

Various techniques are used for the estimation of the LULC applying several criteria ranging from the use of phenological status of the crops (Reed 2006; Cheema and Bastiaanssen 2010; Kiptala et al., 2013; Dong et al., 2015; Yan et al., 2015) to expert knowledge (Conrad et al., 2012; Mwaniki and Möller 2015), and decision tree based classification (Friedl and Brodley 1997; Punia et al., 2011; Chasmer et al., 2014). However, phenologically based crop classification has become popular due to its ability to capture various types of agricultural land cover and use which is usually not possible with other classifications systems. The intra-(as well as the inter-) seasonal fluxes of water, energy and carbon between the land surface and atmosphere are strongly driven by crop phenology (Ganguly et al., 2010; Chen et al., 2015; Pan et al., 2015). In crop phenology, relevant information is imperative for various applications such as the diagnosis of ecosystem response to global change; it plays a key role in understanding how ecosystems are structured and how they function (Cleland et al., 2007) under different geographic and climate conditions. Phenology of different land covers varies greatly over large geographic gradients and elevation, according to different climate zones as well as vegetation types. Furthermore, considerable inter-annual variability in the start and end of the growing season, and thus growing season length, is observed as a result of year-to-year variability in weather (Richardson et al., 2013). For the classification of various crops through remote sensing, several researchers used phenological techniques at large river basin scales but without considering the phenological variations of individual crops in different agro-eco systems (Funk and Budde, 2009; Leinenkugel, et al., 2013; Pervez et al., 2014).

For an improved accuracy in the LULC classification of the KRB with high variability between the upstream and downstream regions, a more detailed analysis is required (Reed et al., 1994). Therefore, in this study, an innovative approach is introduced where a large river basin (KRB) is segregated into provincial units based on their respective cropping calendars differing from each other due to physiographic conditions. The study focuses on the phenological trends of the dominant crops in the KRB by applying the MODIS NDVI product due to its substantial intra-class variability driven by the regional changes in the climate and management practices (Wardlow et al., 2007). Poppy cultivation, a major concern of both, the government of Afghanistan and the international community, is also an integral part of the LULC analysis of the KRB.

The objective of this study was to develop a cropping calendar for individual provinces followed by developing LULC maps of the KRB for the period 2003-2013 as well as of the changes in the extent of land cover of the major agricultural crops i.e. wheat, maize, barley and rice. Furthermore, a correlation is established between the NDVI curves and various physiographic attributes including elevation, temperature and precipitation. The comprehensive analysis of the LULC under this research paves a reliable base for future studies with relevance to the agricultural land cover and crop water demand in data scarce river basins of Afghanistan.

3.2 Material and methods

3.2.1 Development of the cropping calendar

The cropping calendar is a tool providing timely information on various crop development stages from sowing until harvest and assists in planning the management strategies required for sound agricultural practice and yield production. It supports farmers and agricultural extension workers in taking proper decisions on relevant crops and their sowing period, while considering the agro-ecological dimension. It also offers a solid base for emergency planning of the rehabilitation of farming systems after disasters (FAO, 2017). The development of a cropping calendar is based upon the suitability of the climate for a certain growth stage of crop such as sowing, germination, flowering and harvesting etc. Prior studies (Funk and Budde 2009; Kiptala et al., 2013) illustrate the importance of the cropping calendar in the appropriate identification of the trends of the NDVI curves of different crops extracted from the phenologically-tuned MODIS NDVI products.

There are considerable temporal variations in the cropping calendar of the upstream and downstream regions of the KRB. In this study the cropping calendar of all the provinces of the basin was developed by considering the pre-studies (UCDAVIS, 2013a) as well as information collected from the Ministry of Agriculture, Irrigation and Livestock (MAIL) of Afghanistan. Information regarding the conventional practices of local farmers was also incorporated.

3.2.2 Land-use and land-cover classification 2003-2013

The choice of using the MODIS-NDVI in this study is due to the fact that it is phenologically tuned and provides consistent, spatial and time series comparisons of global vegetation environments which can be used for the monitoring of the Earth's terrestrial photosynthetic vegetation activities in support of phenology, change detection and biophysical interpretations (Solano et al., 2010).

For an LULC classification of the KRB, the MODIS NDVI images of MOD13Q1 and MYD13Q1 were downloaded and stacked year wise covering a period of 2003-2013. After this step, each province was segregated from the layer stack and an unsupervised classification (ISODATA clustering algorithm) was carried out for each individual province. Followed by this, the NDVI curves were extracted for identification of the relevant crop based on its phenology. Beside the individual class refinement and supervised classification, the resultant LULC map was checked for accuracy using the ground truth points collected from the field. The step-by-step process of this study is illustrated in Figure 3.1.

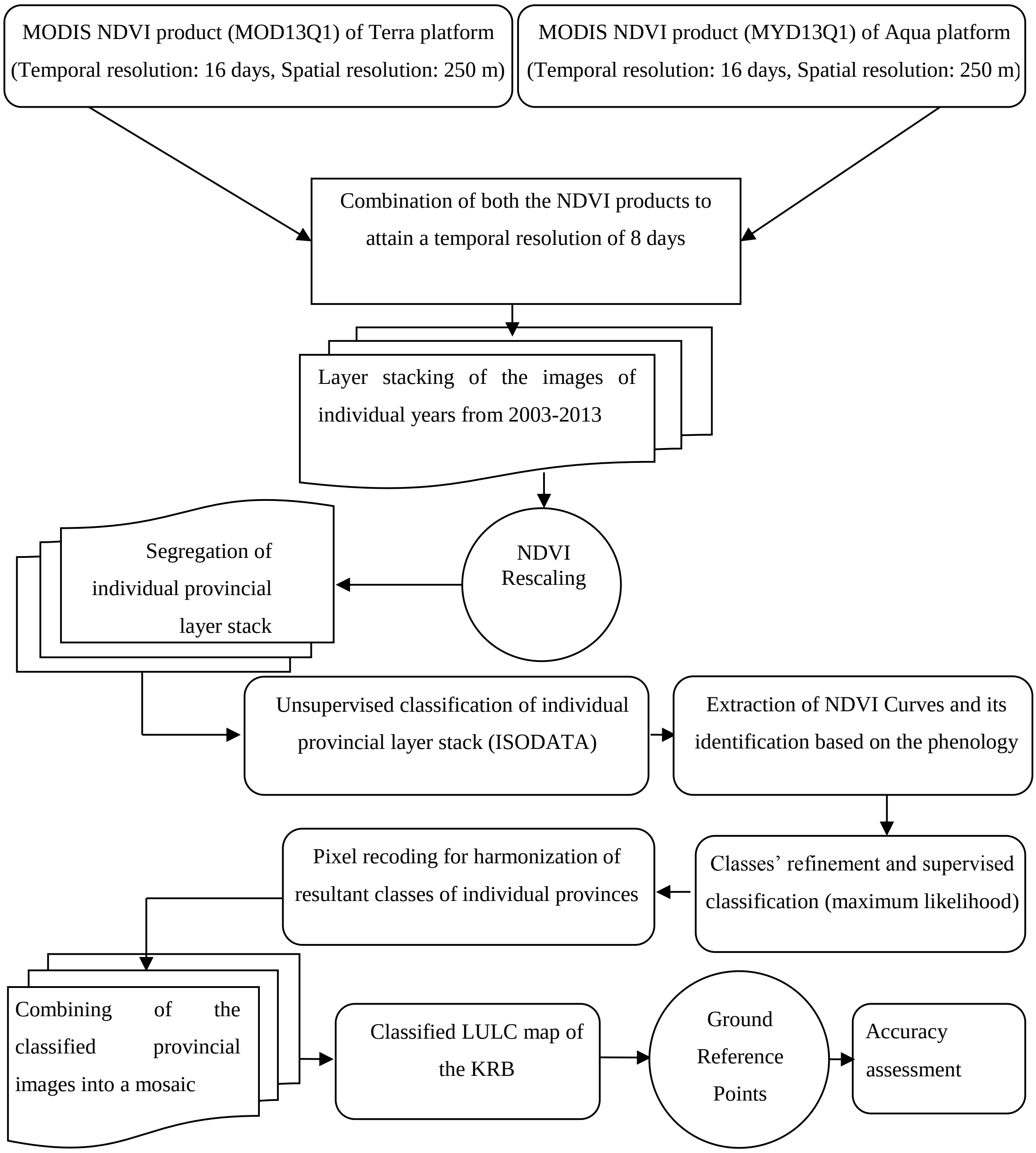


Figure 3.1 Methodological framework for land use and land cover mapping of the Kabul River Basin

Classification approach

Preparation of the MODIS datasets

The Moderate-resolution Imaging Spectroradiometer (MODIS) is a payload scientific instrument launched into the earth orbit by NASA in 1999 on board the Terra (EOS AM) Satellite, and in 2002 on board the Aqua (EOS PM) satellite. The orbit of the Terra is timed in such a manner that in the morning it passes from north to south across the equator, while in the afternoon, Aqua passes south to north over the equator. The local equatorial passing time of the Terra is approximately 10:30 a.m. in a descending node with a sun-synchronous, near-polar, circular orbit. Similarly, the local equatorial crossing time of the Aqua is 1:30 p.m. in an ascending node with a sun-synchronous, near-polar, circular orbit. To view the entire earth surface, Terra MODIS and Aqua MODIS requires between one and two days respectively.

In order to cover the period 2003-2013, the on-demand smoothed satellite time series of MODIS Vegetation Indices (MOD13Q1 and MYD13Q1) filtered by University of Natural Resources and Life Sciences, Vienna (BOKU) (Vuolo et al., 2012) covering the KBR was downloaded. The output format was selected to be GeoTIFF (.tif). The choice of the smoothed images was due to the fact that the overall performance with the field-based error matrix is comparatively better than non-smoothed MODIS time series (Fritz et al., 2008).

Unsupervised classification

In order to provide high temporal resolution, images from both sensors of the MODIS satellites (Aqua and Terra) were combined for a closer portrayal of the crop phenological development and stacked into a single image (*.img) file, to get a temporal resolution of 8 days, by using Erdas Imagine software (Erdas, 2010). The MODIS vegetation indices' products were converted to Normalized Difference Vegetation Index (NDVI) by dividing these over a scale factor 10,000.

The layer stack was imported into ERDAS Imagine software for unsupervised classification, and 30 classes were produced. ERDAS Imagine software has been chosen because it is using the iterative Self Organizing Data Analysis Technique (ISODATA) algorithm for the creation of unsupervised classification; this method enables to set a limit for the number of clusters. This is because of ISODATA algorithm's capability to perform cluster deletion, splitting, and merging between iterations being performed. Moreover, ISODATA algorithm uses the minimum spectral-distance method for clusters' formation and it starts either with arbitrary cluster means or the means of present signature-set. When each time the clustering repeats the means of these clusters are changed. The new cluster means are used for the next iteration. Another reason of the selecting the ISODATA algorithm embedded in ERDAS Imagine is that it repeats the clustering of the image until either a maximum number of iterations has been completed, or a maximum percentage of unchanged pixels has been reached between any two iterations (Erdas, 2010).

A convergence threshold of 0.975 was used which denotes that the maximum percentage of pixels whose cluster assignments can go unaltered between several ongoing iterations. After this, masks of individual provinces of the KRB mask were used to subset the output and keep it limited to the boundaries of the study area. A similar approach was utilized for the unsupervised classification of individual provinces with different cropping calendar and phenological development.

Plotting of the NDVI time-series data generates a temporal curve which sums up the different growth stages defined by the relevant cropping calendar that green vegetation goes through during a complete growing season. The key phenological variables regarding a certain season and metrics were extracted by analyzing such curves. By using the zonal mean function through the model maker, the NDVI values were extracted into a spread sheet at both the KRB and provincial levels. The NDVI values were transformed into graphical form in order to be identified and nominated for a certain crop against the relevant cropping calendar of the respective province.

Based on studies conducted on the NDVI of crops (Gamon et al., 1995; Funk and Budde 2009; Kiptala et al., 2013; Bao et al., 2015), a high peak level in the NDVI curve denotes the maximum photosynthetic activity at the relevant crop growth period. Keeping in view their relevant cropping calendar, a crop/feature name was assigned to each class behaving as portrayed by the relevant cropping calendar. During the refinement and identification process 17 main classes were labeled representing the LULC of the study region. The unique class names and associated short labels with a basic introduction of the class were used for a better overview (Table 3.1).

Table 3-1: Major LULC classes of the Kabul River Basin

S. No	LULC Code	Class Name	Class Description
1	SW	Snow or Water	Land use with negative sign (-), e.g. snow glaciers and water storage dams
2	BF	Barley-Fodder	Barley and fodder cultivated in rotation
3	PV	Poppy-Vegetables	Poppy and vegetables cultivated in rotation
4	M	Maize	Winter maize for fodder
5	MF	Maize+Fodder	Maize and fodder intercropped
6	BV	Barley-Vegetables	Barley and mix vegetables cultivated in rotation
7	B	Barley	
8	EVGF	Evergreen Forest	Includes, Cedrus deodara (Cedar), Picia smethiana (Spruce), Pinus wallichiana (Bhutan pine), Abies spectabilis (East Himalayan fir), Pinus gerardiana (Chilgoza pine)
9	F	Fodder	Alfalfa, clover and other forage types
10	P	Poppy	Opium poppy
11	O	Orchards	Grapes, apples, plums and melons etc.
12	WM	Wheat-Maize	Wheat and maize cultivated in rotation
13	DF	Dense Forest	Deciduous forest trees, e.g. walnut and other nut species
14	SF	Sparse Forest/vegetation	Perennial vegetation and re-grown logged forest trees
15	BL	Bare Land	Land cover without intentional cultivated greenery, e.g. settlements, roads, deserts etc.
16	W	Wheat	Mono-cropped wheat crop
17	WR	Wheat-Rice	Wheat and Rice cultivated in rotation

Supervised classification and pixel recoding

Upon finalization of the class refinement, a supervised classification was run over the KRB as well as at the provincial level. To this process, the refined signatures were utilized using the parametric rule of "Maximum Likelihood" for an improved classified map by providing supplemental information such as spatial land use information, crop phenology and NDVI limits etc. (Manandhar et al., 2009). The resultant classes were harmonized through pixel values recoding in Erdas Imagine (Erdas 2010). For a representative expression similar classes were merged into each other through signature editor. After this, classified images of individual provinces were combined into a mosaic for a basin-wide LULC map covering the KRB region.

Accuracy of the land use and land cover classification

Calibration is required for the assessment of the data accuracy in order to provide logical corrections for realistic results. The results are compared with an accepted reference measured or estimated values for ensuring that the considered measurements comply with the requirements. For the sake of data calibration, the estimated quantitative cropland data on the provincial level was collected from the Central Statistics Organization (CSO-IRoA, 2014) and cross-checked against the results observed from the LULC classification map thus generated. The global positioning system (GPS) was used to collect around 358 ground truth points (GTPs) from homogenous land covers in a randomized manner. The minimum number of GTPs was 5 from the barley-fodder rotation cover and the maximum GTPs from wheat and wheat-rice land covers were 53 and 31, respectively. In some classification studies, the minimum number of sample reference points per land use system was 8 (Thenkabail et al., 2005), 3 (Kiptala, et al., 2013) and 20 (Maingi and Marsh, 2002). The ground truthing campaign covered two cropping seasons, i.e. May to September (summer season) and October– April (winter season). The field campaign was driven by the cropping calendar as well as to some extent by the local security conditions.

The ground truth data along with remote sensing data were then used to build the error matrix. The error matrix is a key criterion for the assessment of the quality of classified maps developed through remote sensing. The overall accuracy, the user and producer accuracies and the Kappa coefficient (K) were employed to assess the accuracy of the developed LULC for 2003 - 2013. The K coefficient is another measure of the agreement between the classification map and the reference data which is derived from the error matrix for the measurement of the classification accuracy of imagery. It shows agreement between two categorical datasets corrected for the agreement as expected (van Vliet, et al., 2011) by chance which depends only on the distribution of class sizes in both datasets. The *K* coefficient is more reliable as it incorporates the chance agreement (Viera and Garrett, 2005).

The general equation for *K* is:

$$K = \frac{P(o) - P(c)}{1 - P(c)}$$ Equation .(1.1)

where P(o) is the percentage observed agreement while P(c) shows the hypothetical probability of chance agreement. In case of complete agreement K would be equal to 1 however, in case of disagreement other than what would be expected by chance K shall be equal to 0.

The overall accuracy was achieved by dividing the number of correct pixels by the total number of pixels in the error matrix. This does not indicate how well the individual classes are classified. Therefore, the respective accuracies of the producers and users were estimated to provide the quality of the classification of individual classes.

Evaluation of the estimated land cover of major crops in Kabul River Basin

For the authenticity of the quality of the produced results, beside the error matrix, Afghan government estimates of the extent (ha) of the main crops (wheat, barley, maize, rice) (CSO-IRoA 2014) at the provincial level were used. The term “estimated” was used for the results of this study while the term “actual” represents the cropping extent reported for different years by the central statistics organization of Afghanistan (CSO). Since the statistical data from the CSO are rough estimates not supported by physical or remote sensing measurements, the overall agricultural area have been compared with the estimates of the land cover atlas of Afghanistan (FAO, 2012) as the main yard stick and the most reliable resource so far. The at las used high resolution SPOT 4 images and the accuracy is high enough to relate the estimates carried out in this study.

Correlation of the Normalized Difference Vegetation Index with different physiographic attributes

The normalized difference vegetation index (NDVI) is an impressive indicator of the crops' spatial density distribution (Wang et al., 2001; Suzuki et al., 2001) and growth status as well as its phenology (Pan et al., 2015) and yield (Quamby, 1993). The crop NDVI is directly affected by various physiographic variables e.g. precipitation (Wang et al., 2003), temperature (Fu and Burgher 2015), altitude (Li et al., 2015) etc. Therefore, the correlation between these attributes and NDVI trend throughout the crop growth period was studied and recorded.

3.3 Results and discussion

3.3.1 Cropping calendar for the Kabul River Basin

Based on the field data collected from the local farmers and published literature, 7 cropping calendars were developed which represent the phenology-based crop development stages from sowing till harvesting within the 13 provinces comprising the KRB (Figure 3.2). The cropping calendar clearly visualizes that most of the south-eastern provinces (Laghman, Nangarhar, Kunar and Logar) with similar climate conditions follow almost the same cropping calendar. The south-eastern provinces Paktia, Paktika and central province Panjshir follow the same cropping calendar due to similarities in the climatic conditions. The cultivation of wheat in rotation with maize and rice dominates in Nangarhar, Laghman, Kunar and Khost provinces. In Nuristan province crop rotation is observed but in fewer areas as the hilly and rocky undulating shady terrain means shorter growing degree days and mono-cropping is common here. The cropping calendar indicate that Kabul, Kapisa, Parwan and Maidan Wardak are dominantly mono-cropping provinces due to relatively lower temperatures (Fang et al., 2015) leading to comparatively short growing degree days.

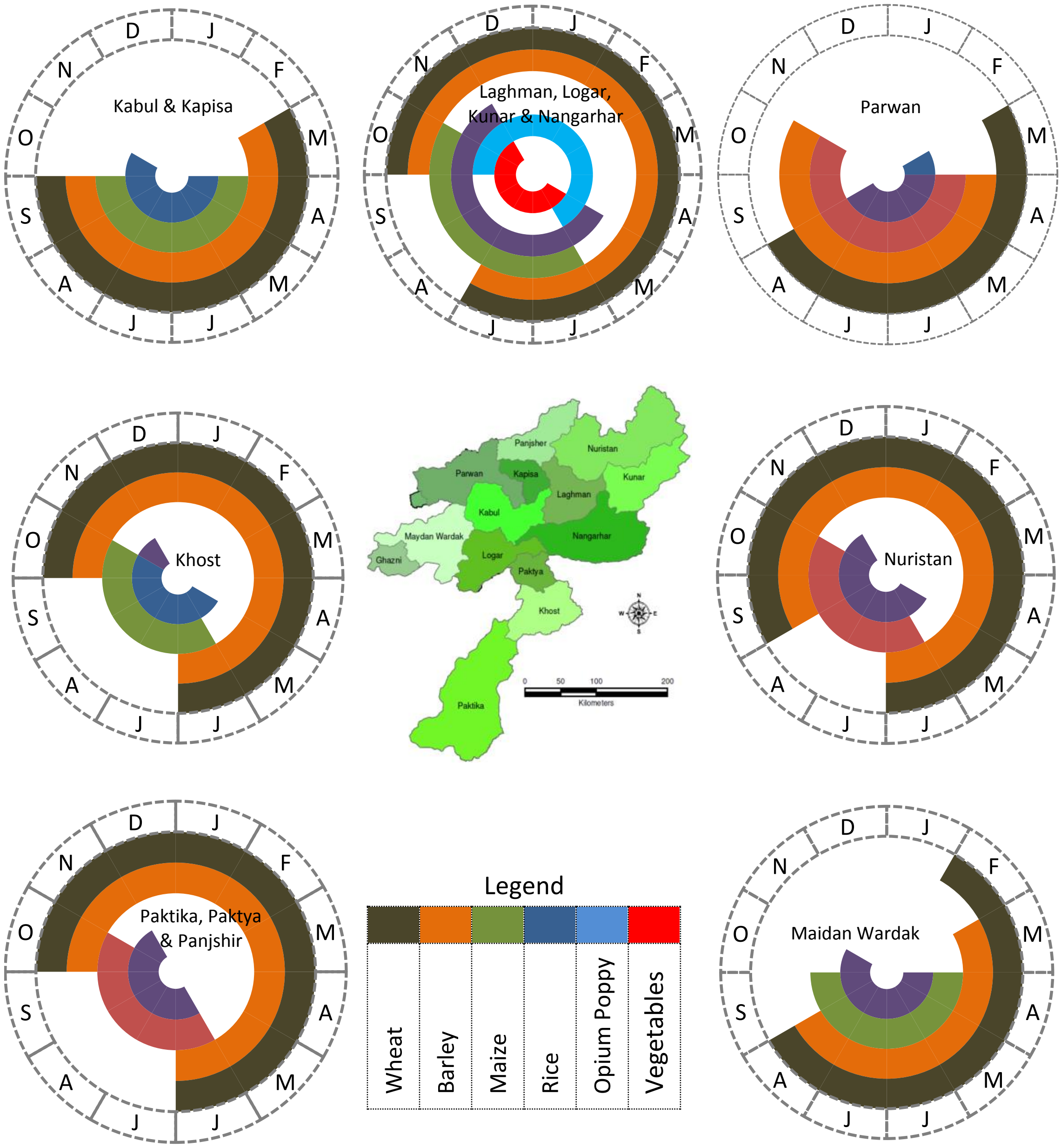


Figure 3.2: Cropping calendar of the Kabul River Basin

Classifying the land use based on phenological variations in different provinces

After the unsupervised classification of the 13 segregated provinces of the KRB, the representative NDVI graphs (Figure 3.3-3.8) show that throughout the KRB 17 distinct land cover types exist. These land-cover types range from bare and fallow land to cultivated land, as well as deciduous and evergreen forests. Due to the uneven terrain and smaller farmland units with large differences between upstream and downstream in terms of dates of sowing, harvesting, crop development, temperature and precipitation (mainly driven by elevation) , it was difficult to identify an individual representative NDVI curve for a specific crop throughout the KRB. In order to provide an impression of the KRB level NDVI curve, a comparison was made with the segregated provincial NDVI curves. Since the NDVI trend and profile of an individual crop at provincial level usually remains the same irrespective of the area being equipped with it, therefore only 2013 year's NDVI profile was selected as representative of the respective crops in later years.

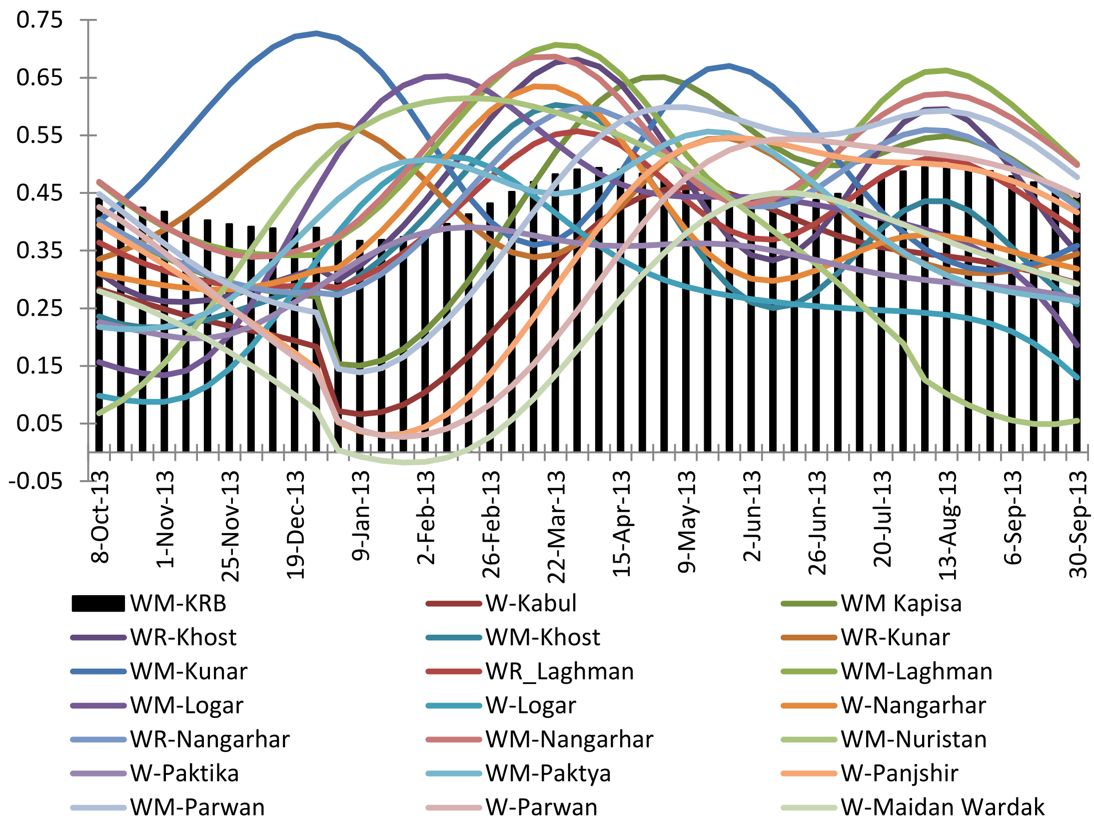


Figure 3.3: Comparison of the trend of mean Normalized Difference Vegetation Index- of wheat crop at provincial level with that of Kabul River Basin (KRB) level

Out of the 17 classes identified, comparison of the dominant crops such as wheat, maize, rice and barley were made between provincial and the basin level curves. It was difficult to generalize the basin level mean NDVI curve of certain crops driven by different crop calendars in the up- and downstream provinces while segregated provincial level curves were rather easily identified in reference to its phenology and crop development stages.

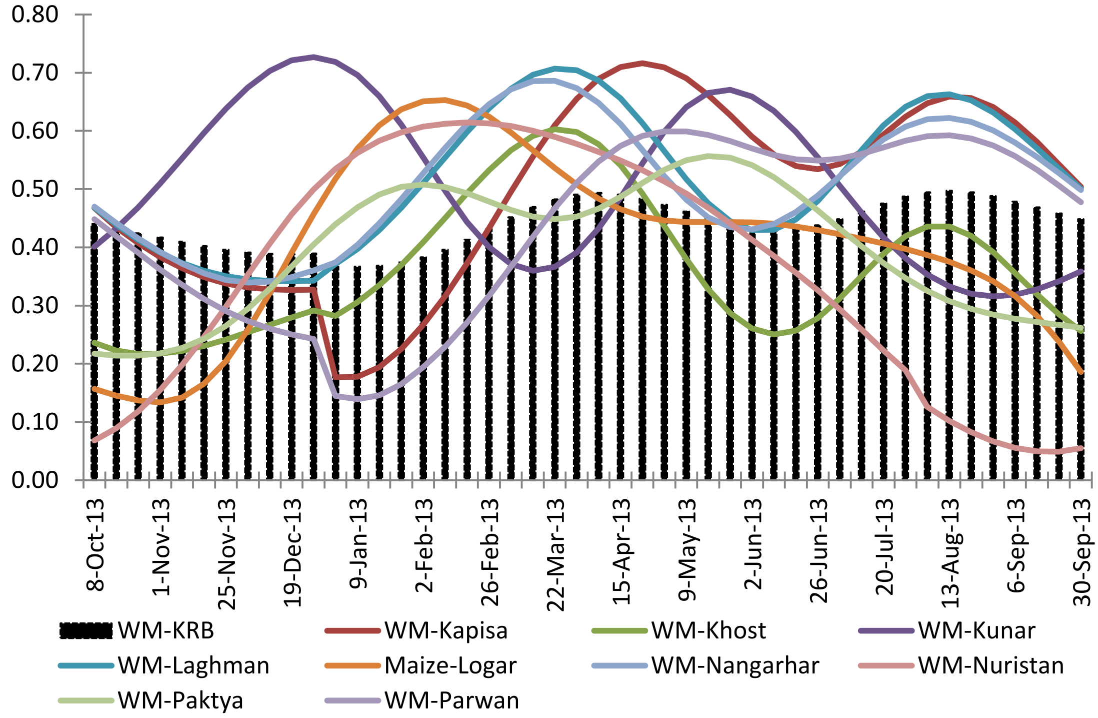


Figure 3.4: Comparison of trend of mean Normalized Difference Vegetation Index of maize crop at provincial level with that of Kabul River Basin (KRB)

A single peaked NDVI indicate a single cropping season annually while two peaked NDVI curves in one annual cycle reveal crop rotation especially in irrigated areas (Figure 3.5). The start- and end-points of these NDVI curve peaks differentiate the main crops being cultivated in the study area from one another. Figure 3.5 illustrates a typical example of the NDVI profile of wheat-maize rotation in Kunar province where the peaks and depressions give a clear understanding of the different growth stages of the relevant crops.

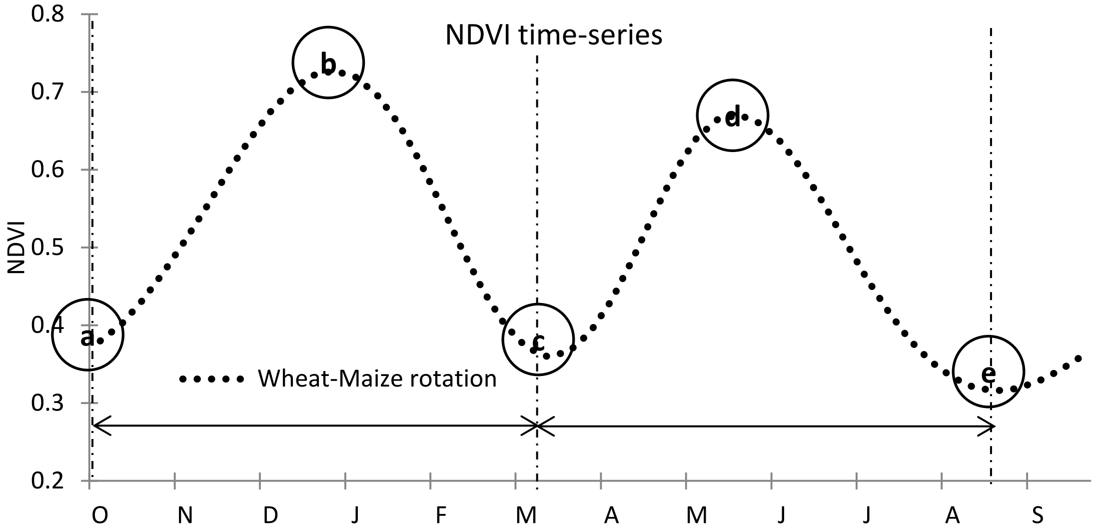


Figure 3.5: Phenology based NDVI time-series of crop growth stages during wheat-maize crop rotation at the downstream KRB: (a) germination/initial stage (b) mid-season, the period between (a) to (b) is the crop development stage, (c) late season or harvesting of wheat and plantation of maize and rice, (d) mid-season of maize and rice and (e) late season or harvesting of maize; the same cycle is being followed in the following year as well

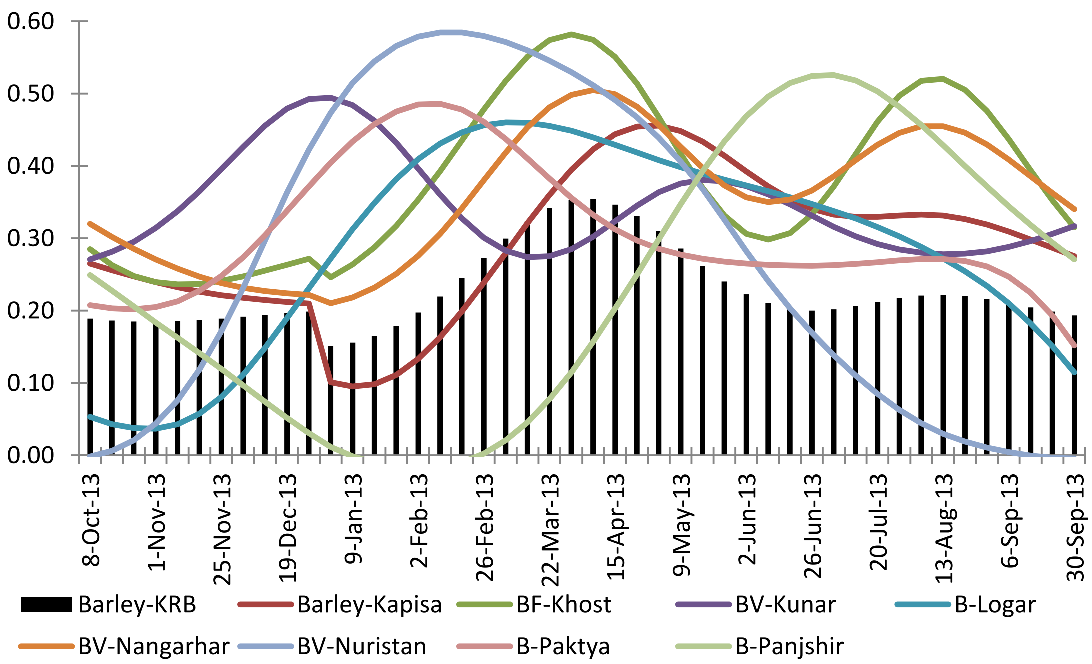


Figure 3.6: Comparison of the trend of mean Normalized Difference Vegetation Index of barley crop at provincial level with that of Kabul River Basin (KRB) level

The NDVI curves with negative values especially between the months of December and February show the snow cover or water. The usual straight NDVI curve throughout the year denotes the evergreen forests dominant in Kunar, Nuristan and Paktya provinces whereas in the case of deciduous forests, the NDVI curve remains consistent from April-October and then clearly declines during autumn when the leaves fall.

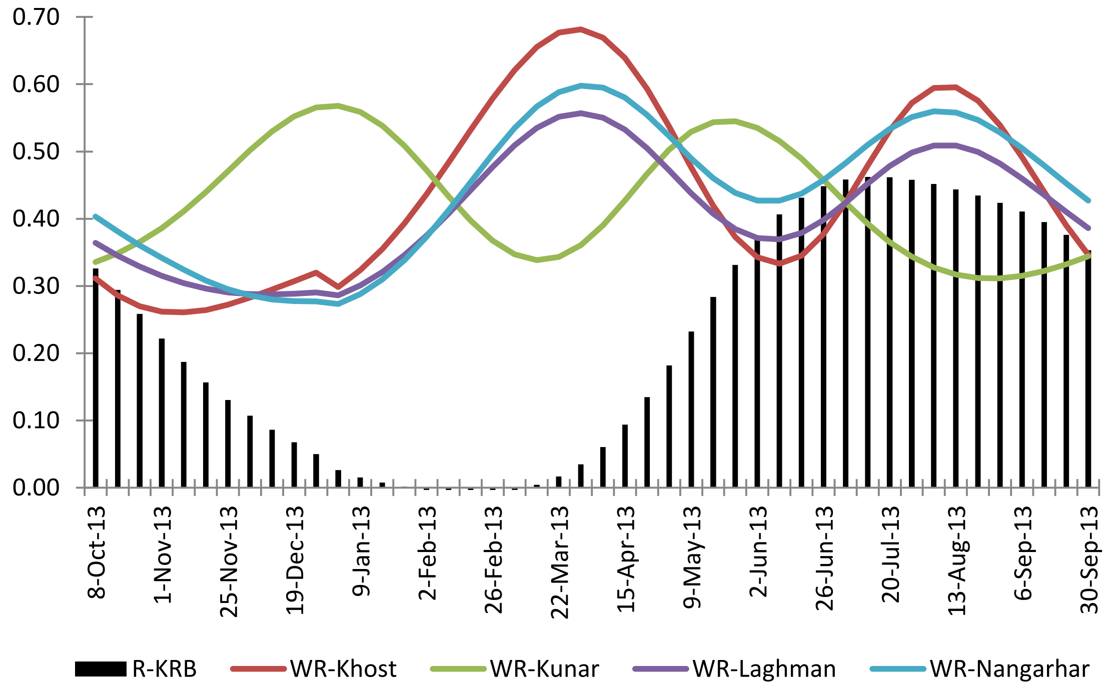


Figure 3.7: Comparison of the trend of Normalized Difference Vegetation Index of rice crop at provincial level with that of Kabul River Basin (KRB) level

The curves of the identified classes derived from the individual provinces of the KRB were split in two main categories, namely, non-vegetated (mean maximum NDVI ≤ 0.22) and vegetated features (mean maximum NDVI > 0.22). The vegetated features were further categorized as the evergreen forest with a rather smoothened NDVI (mean maximum NDVI = 0.47) and the seasonal vegetation (mean maximum NDVI = 0.30 - 0.54) that changed in different times of the season/year. The seasonal vegetation was further categorized as sparse vegetation (NDVI=0.30), dense vegetation (NDVI = 0.50) and crops (wheat, maize, rice, barley) (NDVI = 0.54) (Figure 3.8).

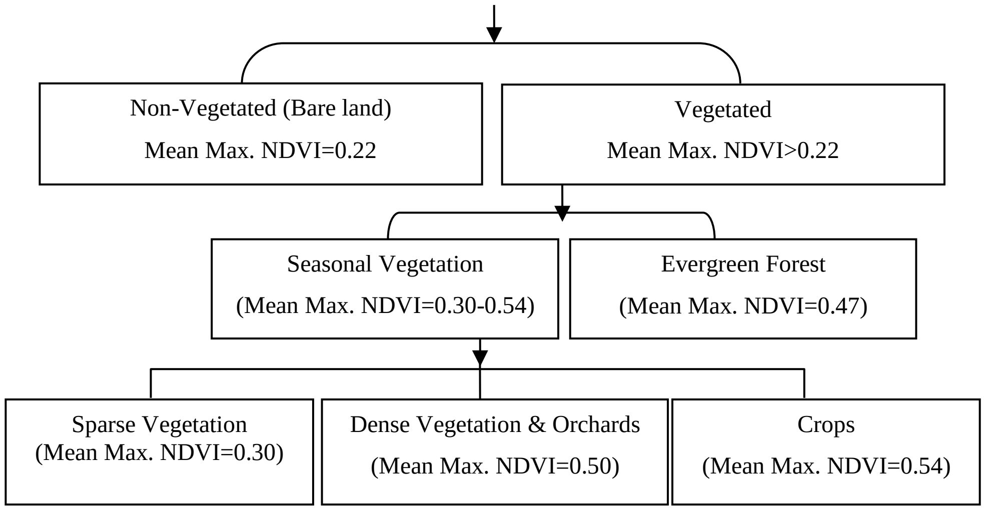


Figure 3.8: Categorization of the Normalized Difference Vegetation Index of vegetated and non-vegetated areas in the Kabul River Basin

After refining the individual signatures at provincial level, a supervised classification was run resulting in 17 major land covers. As shown over the LULC maps, forests dominant in Nuristan, Paktya and Khost provinces, while irrigated agriculture dominates in Nangarhar, Kunar, Laghman and Khost provinces.

3.3.2 Land use and land cover mapping of the Kabul river basin from 2003-2013

The segregated provincial level analysis of the KRB was due to variations between upstream and downstream provinces with varying physiographic conditions. This analysis shows that in most of the eastern provinces, i.e. Kunar, Laghman, Nangarhar and the southeastern Khost province cropping coverage dominates compared to the other provinces where bare land or other land-cover types are prevailing (Figure 3.9). Based on the amount of precipitation, each year there is a usual shift locally from one land cover to another e.g. wheat to barley or vegetables, rice to maize or other vegetables having similar a cropping calendar. The choice of farmers on what to grow is also partially influenced by the farmers’ access to irrigation water since MAIL has started initiatives of lining the water channels across the country for raising the land and water productivity (MAIL, 2016).

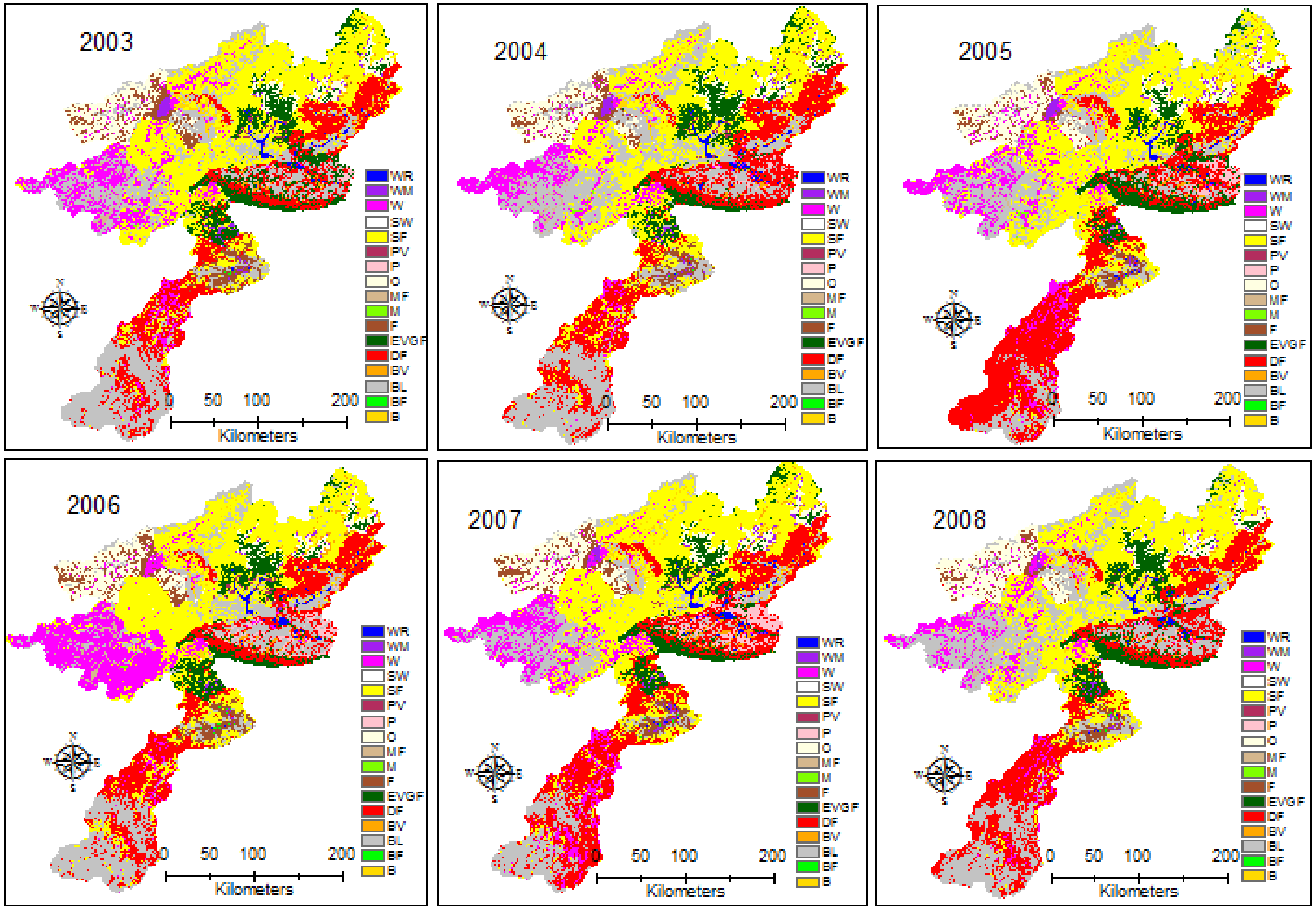


Figure 3.9: Temporal variations of the land use and land cover in Kabul River Basin 2003-2013

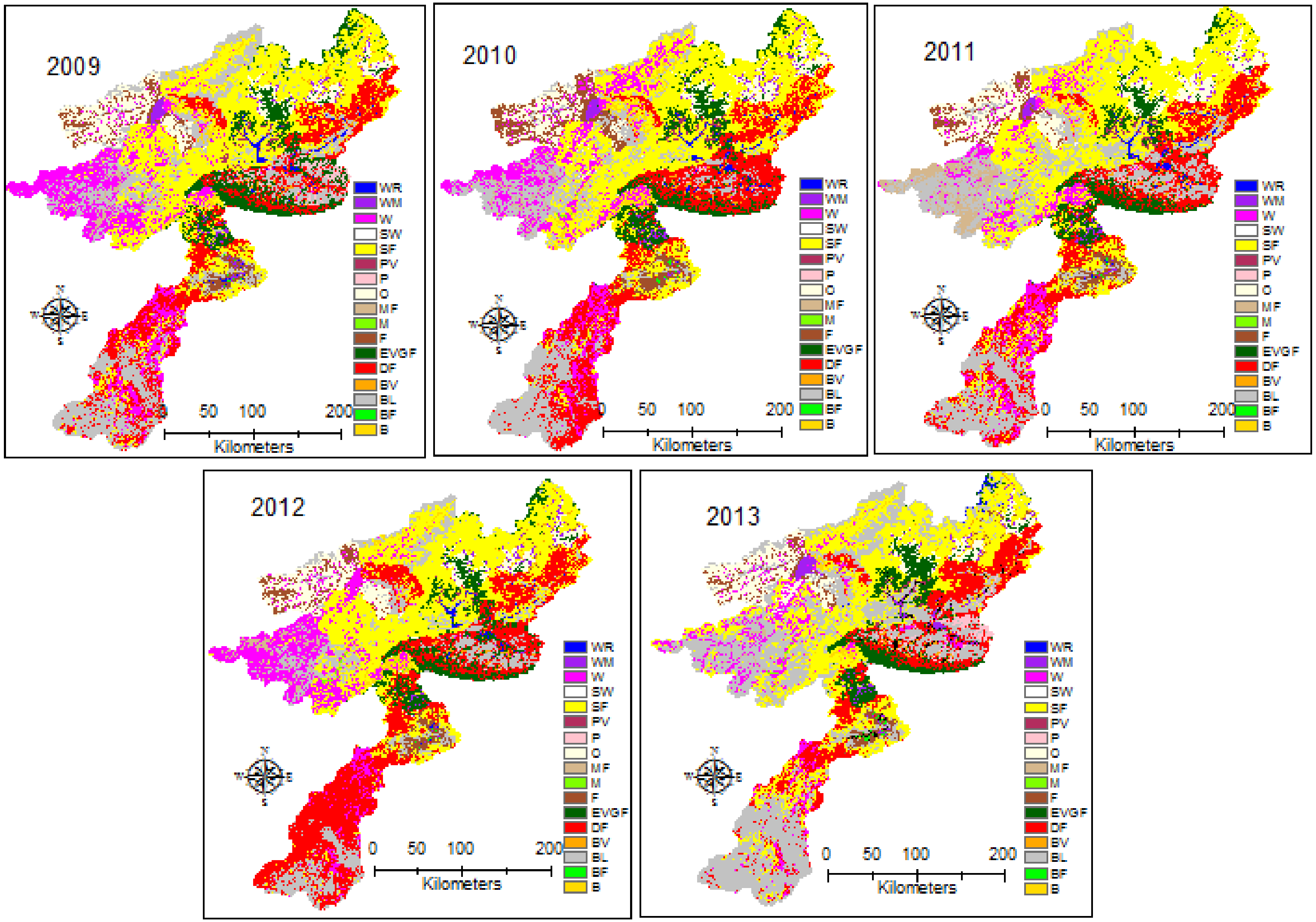


Figure 3.9: continued

The NDVI product of MODIS used in this study typically aimed at the estimation of the agricultural area required later for analysis in reference to water demand, and water availability. Therefore the major crops in Afghanistan were considered in this study that mainly contributes to the local food demand of the population in(out)side the KRB.

While studying the LULC changes over the study period, 2003-2013, it was found that the LULC types SW, SF, DF, EVGF, O and BL experienced almost no change throughout the period (Figure 3.10). However in contrast there were significant changes in the major crop classes i.e. wheat, maize, barley and rice. This can be attributed to the rising local food demand due to increasing population, mainly repatriation of refugees from the neighboring countries as well as the strategic move of the relevant governmental institutions towards food security across the country and self-sufficiency in the local grain production.

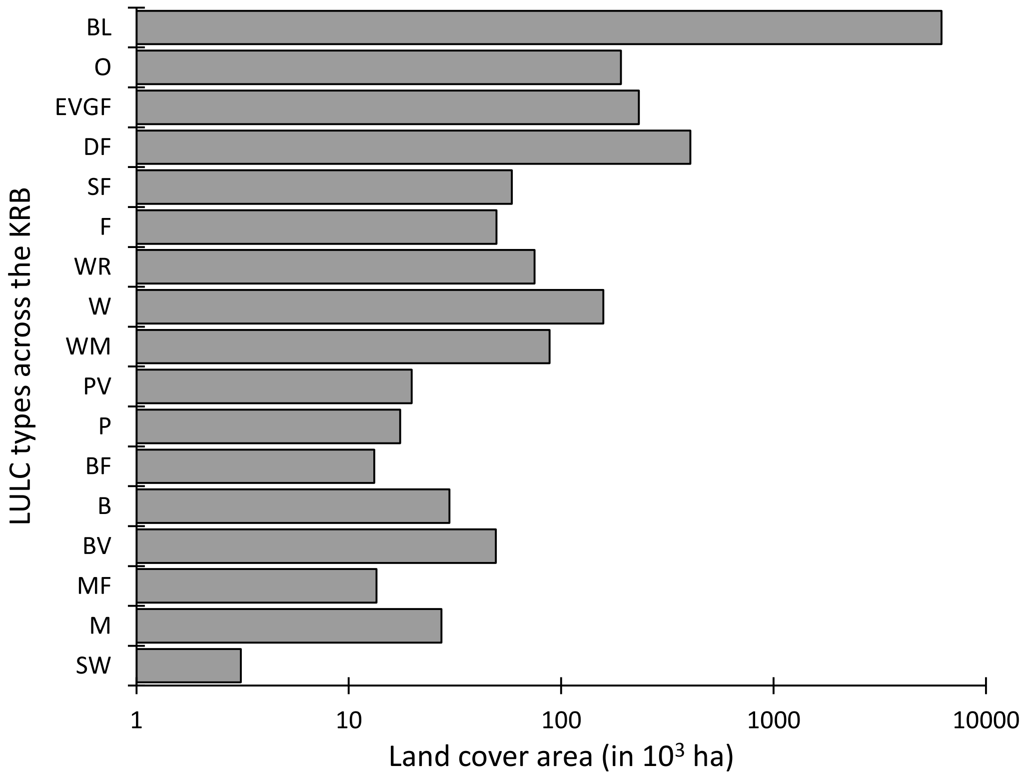


Figure 3.10: Areal extent of LULC types in the Kabul River Basin

The temporal behavior of the wheat cultivation estimation as a result of the disaggregated study shows that the mean land area of wheat in Nangarhar province during the period 2003-2013 was 64000 ± 12000 ha, where the minimum area was in 2003 (42331 ha) while the highest in 2006 (80200 ha) (Figure 3.11). The reason behind the lowest coverage in 2003 was the drought prevailing across the country in late 2002 that discouraged the cultivation of wheat and other crops.

Overall, the year-to-year expansion/shrinkage was driven by the moisture availability for irrigation during the wet and dry years across the country. The overall wheat cultivation was 14600±5300 in Kabul, 24600±4000 in Kapisa, 27300±4200 ha in Khost, 18100±2100 ha in Kunar, 22000±2000 ha in Laghman, 16127±2300 ha in Logar, 24702±6000 ha in Nuristan, 7800±4775 ha in Paktika, 5300±2000 ha in Paktya, 4188±700 ha in Panjshir, 30000±4200 ha in Parwan and 29000±5000 ha Maidan Wardak. In the case of crop rotation, the wheat cover area, other than for drought reasons, is sometimes replaced by for example, maize or rice which are mainly cultivated in rotation with wheat. In such situations merely a shift took place from one crop to another based on the local market demand and climatic conditions.

A variation is often observed in provinces with lower temperatures and undulating terrain with a single cropping season e.g. Maidan Wardak, Panjshir, Paktika, Paktya and Parwan provinces. The variation in cropping cover among different years can be explained by the non-uniform (in terms of land cover) and small sized farm units as well as the use of moderate spatial resolution (250 m) of the MODIS NDVI analyzed in this study.

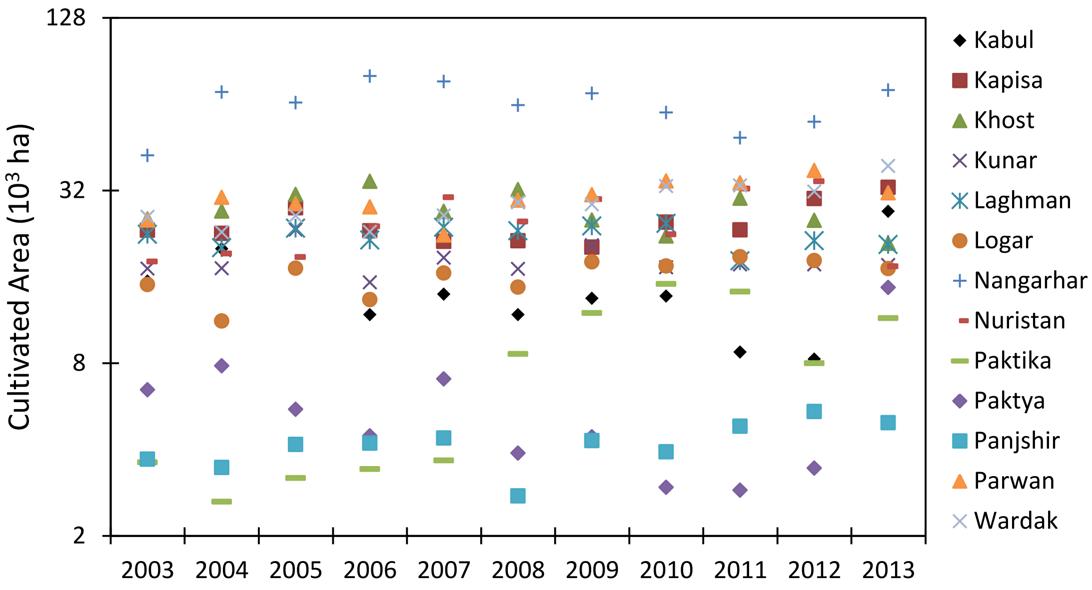


Figure 3.11: Inter-annual variability of wheat coverage in different provinces of Kabul River Basin 2003-2013

As mentioned earlier, throughout the KRB, Nangarhar province is the major crop production unit famous for cereals, vegetables and fruit production. Any changes in the land cover area in Nangarhar are relatively more influential compared to other provinces of the KRB. Winter wheat and barley follow the same crop calendar and therefore contrary to the wheat cultivation in 2003, part of the land area had been replaced by barley cultivation. Throughout the study period 2003-2013 in Nangarhar province, the minimum area of barley was recorded in 2004 (16481 ha), while the largest area was recorded in 2010 (25194 ha) (Figure 3.12). The mean area covered by barley during the study period 2003-2013 was 7300±2600 ha in Kapisa, 10800±3000 ha in Khost, 9506±906 ha in Kunar, 5500±1400 ha in Laghman, 7100±900 ha in Logar, 22400±2700 ha in Nangarhar, 21200±6100 ha in Nuristan, 5700 ha in Paktya, 8100±1500 ha in Parwan and 8400±4000 ha in Maidan Wardak. There seems to be no major shift from year-to-year except in occasional cases that are driven either by drought conditions, market demand or otherwise the use of medium resolution (250 m) NDVI product of MODIS which might also influence the estimation of an individual crop grown in relatively smaller farm units across the KRB.

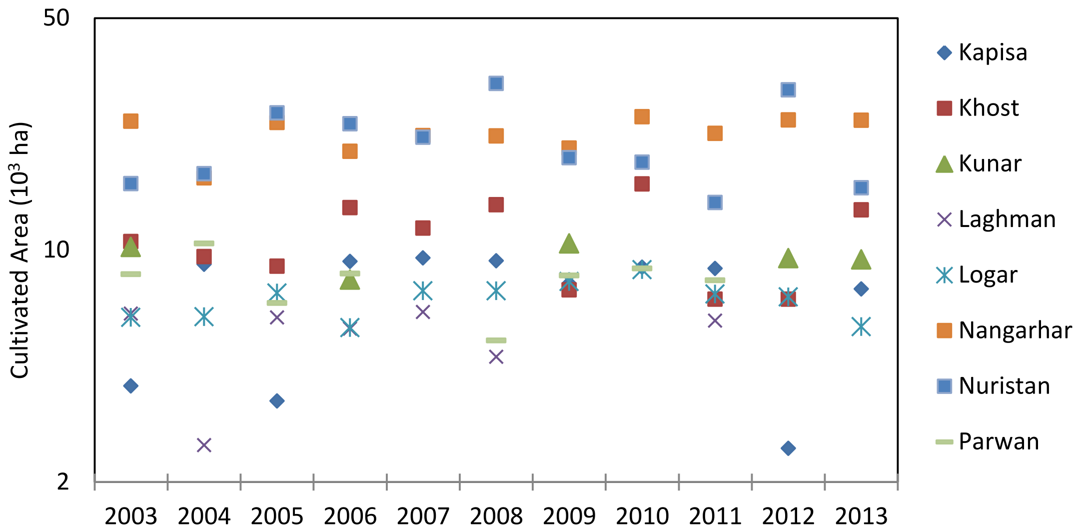


Figure 3.12: Inter-annual variability of barley coverage in different provinces of Kabul River Basin 2003-2013

Maize is another major product widely consumed in Afghanistan. The crop is usually grown in rotation with wheat or barley. In 2006, the overall extent of maize decreased because of the dry conditions but during the rest of the years the trend hasn't been steady for wet and dry years, but rather a shift between different crops is resulted described by the aforesaid factors. The mean ground coverage in different provinces of the KRB during the study period was 13150±1900 ha in Kapisa, 13100±3800 ha in Khost, 9425±1000 ha in Kunar, 9300±1700 ha in Laghman, 5700±1500 ha in Logar, 23600±5500 ha in Nangarhar, 23000±5000 ha in Nuristan, 5000±3000 ha in Paktya, 8375±2400 ha in Panjshir, 18800±3500 ha in Parwan and 9400±1700 ha in Maidan Wardak provinces (Figure 3.13). The base period of this study 2003, most crops severely affected by the drought conditions in 2002, in late 2003 and then again in 2004.

Beside wet and dry climate conditions, another reason for non-steady extents of cropping area during the study period 2003-2013 is the existence of mixed pixels of maize and other vegetables grown in the same season in smaller farming units. This applies typically to the upstream provinces e.g. Kabul, Parwan and Panjshir etc. with undulating rocky terrain where the farming units are relatively small and the focus is more on orchards of grapes, melons and apples etc. that brings a cash return in a short time. Based on the local market demand, intercropping is also practiced.

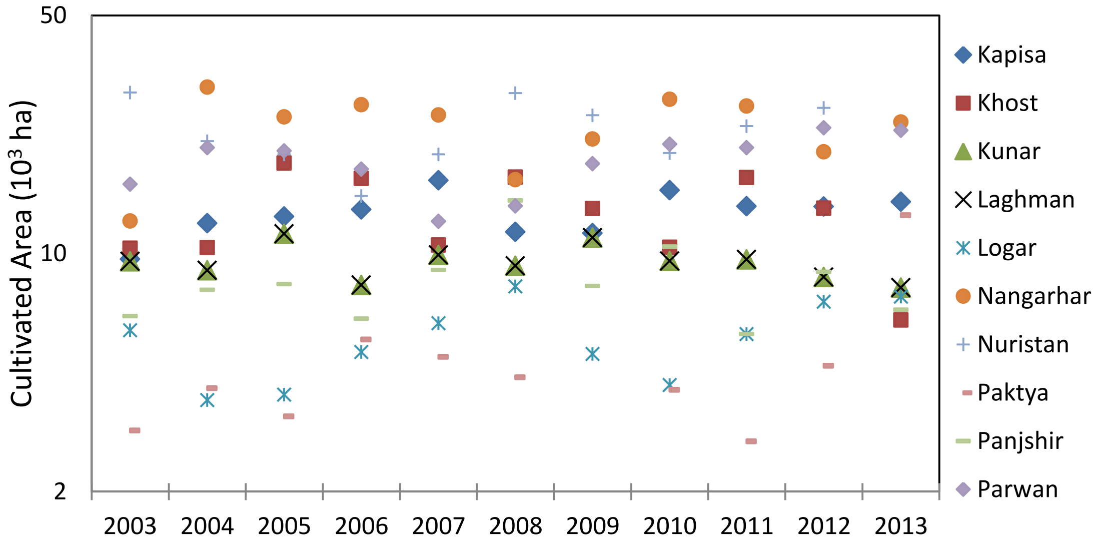


Figure 3.13: Inter-annual variability of maize coverage in different provinces of Kabul River Basin 2003-2013

In the subtropical semiarid climate, rice is the third major crop after wheat and maize grown in Afghanistan (FAO, 2002). In the KRB, the main producing provinces are Nangarhar, Laghman, Kunar, Kapisa and Parwan. Due to lower temperatures on the high elevations of Kabul, Nuristan, etc., rice is rarely grown in these provinces. The mean area cultivated with rice in the study period 2003-2013 was 4300±1000 ha in Kapisa, 13000±2800 ha in Khost, 8700±1300 ha in Kunar, 12900±2500 ha in Laghman, 26400±5000 ha in Nangarhar and 4000±1800 ha in Paktya province (Figure 3.14).

Since the rice land cover dominates in Nangarhar province, the standard deviation is also higher e.g. ±5000 ha, while the provinces with smaller rice areas (mainly due to lower water availability or missing canal network) have considerably lower standard deviations. However, throughout the study period, there was no consistent expansion or shrinking of any major land cover in general but rather a shift from one to another and vice versa, which was driven by farmers' decision or market demand as well as by climatic conditions.

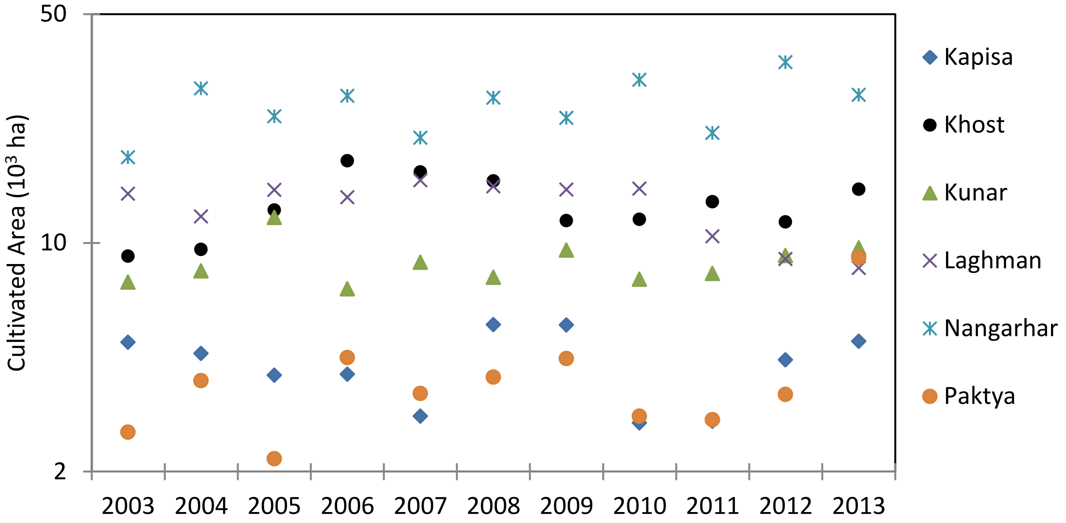


Figure 3.14: Inter-annual variability of rice coverage in different provinces of Kabul River Basin 2003-2013

The uneven rocky terrain with diversified smaller farming units in the provinces Paktika, Khost and Kapisa resulted in mixed pixels with puzzling NDVI response due to fodder and vegetables especially pulses grown in the respective season.

Accuracy assessment

The reliability of the quality of a map is a function of the accuracy of the classification performed (Foody, 2002). Therefore the choice of accuracy assessment method and its implementation matters very much (Lyons et al, 2012). In this section a statistical evaluation was performed referring to the user and producer accuracies of individual land cover classes of the LULC maps for 2003-2013. Producer accuracy specifies the probability of a ground reference datum which has been correctly classified and it is a measure of the omission error. It is calculated to know how well an area can be classified by dividing the diagonal number from a class's column by the sum of the entire column including the number within the diagonal of an error matrix (Jensen, 2005). While the user's accuracy indicates the probability of how well the classified sample represents what is found on the ground. It is calculated by dividing the diagonal values of a class by the total of the numbers within the row of that class in the error matrix (Jensen, 2005).

The user and producer's accuracies provide relatively reliable land-cover specific information compared to the overall or generalized accuracy. The overall mean accuracy obtained throughout the study period was 68.15%±9.45; the highest accuracy of 82.4% was attained in 2013 reaching (Figure 3.15). The mean producer and user accuracies for all the land cover classes were 75.9±11.3% and 76.4±11.2%, respectively. The dominant land cover classes of barley (B), maize (M), maize-fodder (MF), wheat-maize (WM) and wheat-rice (WR) rotation have a higher mean accuracy (both user and producer) (>65%) as well as lower variability in user and producer accuracies compared to the other classes. The reason for relatively larger variability in the remaining classes might be the mixed cropping, snow cover at higher altitudes especially in the areas where EVGF exists. Another reason might be the development of orchards in later years which had been previously used for fodder or mixed land covering with vegetables etc. Compared to the major cropping areas, most of the areas e.g. EVGF, P and SF were difficult to access for taking the ground reference data and the reasons were prevailing insecurity in most of those areas.

As a result of the error matrix, the mean Kappa coefficient (*K*) was 0.66 for the entire study period which is acceptable. The *K* coefficient may range from 0 (disagreement other than what would be expected by chance) to 1 (complete agreement), the values of the current study are more towards complete agreement. Spruce et al (2011)'s classification of the MOD02 NDVI 250 m image threshold classification resulted with Kappa coefficient of 0.76 while 0.33 for MOD13 NDVI 250 m unsupervised classification. Similarly, using the MODIS NDVI, Shao et al. (2010) reported the *K* coefficient in the range of 0.67-0.74 in different ecoregions.

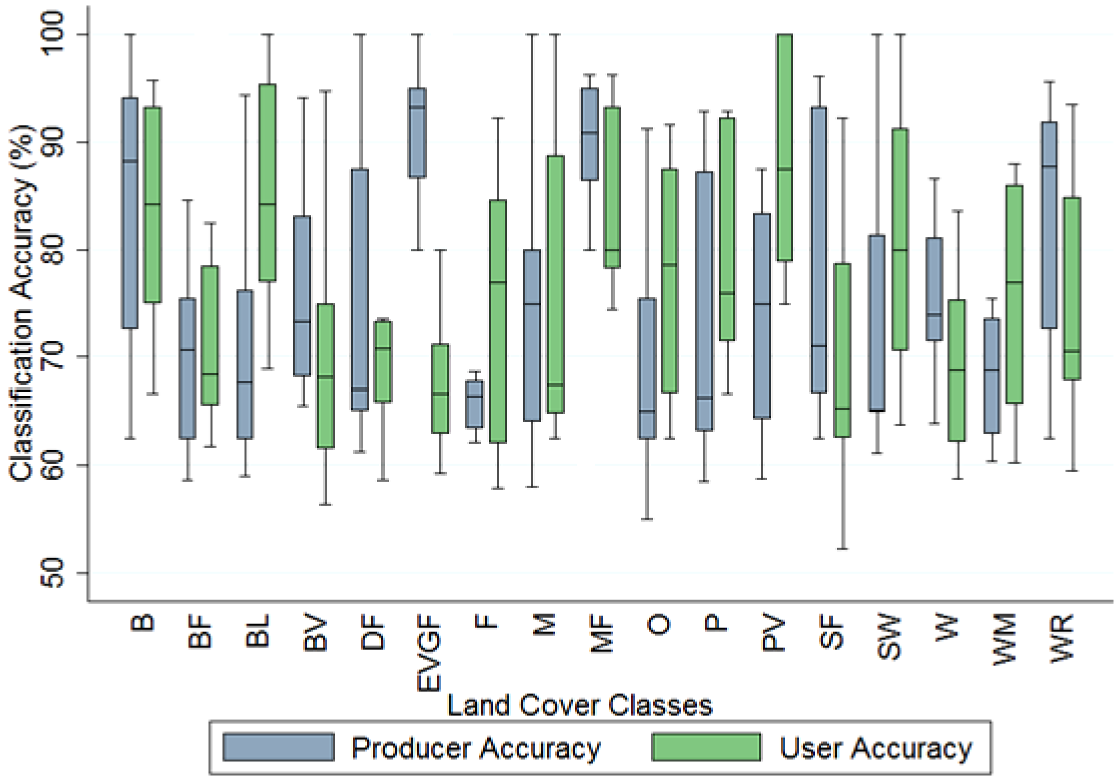


Figure 3.15: Mean classification accuracy of individual land cover classes 2003-2013

The individual class accuracy is also driven by the spatial resolution of the remote sensing product and frequency of the features under study as well as geographic variability. Therefore, high variability is seen among the relevant user and producer accuracies of the classes EVGF, DF and F. The reason is the non-homogeneity of the availability of these classes. In classes PV, F and EVGF, there is large variation in the user accuracy while producer accuracy does not vary in the same pattern. This can be explained by the heterogeneity of features due to mixed pixels and smaller farm units which yield relatively inconsistent user and producer accuracies. Sometimes fodder (F) is intercropped with maize as well as within smaller farm units of vegetables which has no strategic consistency from year to year and therefore results into larger variation between user and producer accuracies.

The MODIS NDVI moderate spatial resolution product has been used in studies on forests, grassland, water, peat land and settlement resulting in an overall accuracy range of 67-79% (Nitze et al., 2016) which testifies the quality of user and producer accuracies attained in this study. A similar experiment with MODIS NDVI for the analysis of LULC changes but at a very large scale, i.e., deciduous forests, conifers, agriculture, etc., produced an accuracy of 88% (Lunetta et al., 2006). In similar studies, in the US central plains, the product showed an overall accuracy of 90.9% for cropping areas. Here, producer and user accuracies were 87.3% and 96.5% for the crop class and 97.4% and 83.2% for the non-crop class, respectively (Wardlow and Egbert, 2008). Using the same product for rice field classification in Bali, a 66.63% overall accuracy was attained (Nuarsa et al., 2011).

Evaluation of estimated land-use and land-cover 2003-2013 against estimates of other sources through different approaches

There is substantial significance in the use of remote sensing products to study thematic changes, e.g. LULC dynamics driven by environmental variables such as elevation, precipitation and slope, etc. This information is vital for water resources planning and environmental policy and management decisions on the wider river basin level. A variety of remote sensing products and methods has been used for change detection (Lu et al., 2016; Lunetta et al., 2006; Lu et al., 2004), but in the case of the KRB only two options were available to evaluate the quality of the results: (1) the estimates of the central statistics organization (CSO) and (2) the Afghanistan land cover atlas (FAO, 2012) based on the satellite data for the year 2010. The first are only lump sum estimates and the quality could be still be questioned due to the fact that data is not supplemented by physical or remote sensing technologies

For the extent of individual land cover class estimated in this study, the estimates of the central statistics organizations (CSO) were used to see how far they match or differ from each other. The CSO data was the only available resource that could be used and it only starts from 2008 unlike the estimations of this study which cover the period 2003-2013.

Results of the trend analysis of the major land cover classes (Table 3-2) i.e. wheat, maize, barley and rice, show that in 2006 compared to the base year 2003, there was an increase in the land coverage of wheat (17%), maize (7%), barley (8%), and rice (33%). According to the FAO (2008), there was an almost 100% increase in cereal production in 2006 in Afghanistan compared to 2001, which justifies the estimations in this study to some extent. In 2009, there was a considerable expansion in the cultivation of all the major crops compared to the base year 2003, e.g. the areal extent of wheat increased by 24%, barley by 11% and rice by 23% relative to 2006. This drastic increase compared to the base year could partly be attributed to the fact that 2009 was a wet year and almost the entire river basin received maximum precipitation, which was sufficient for soil moisture provision for crops cultivation. The CSO reported an increase in wheat, maize and rice area by 22%, 56% and 7%, respectively, with a decrease in barley cultivation by 8%. This decrease may be attributed to the increase in wheat coverage due to the fact that these two crops follow the same cropping calendar. The analysis of the cropping area in 2013 (wet year) shows once again an increase in areal coverage of wheat by 31%, barley by 7% and rice by 32%; with the increase in rice, maize following the same cropping calendar, was replaced by rice due to irrigation water availability and as a result there was no change in the maize area as compared to that in the base year of the study. However, in contrast to these results, the CSO estimates show a drastic expansion in maize area by around 143% compared to 2008 without providing any special reason or active plan behind this increase. Against the increase in wheat and maize area, the CSO reports shrinkage in the barley and rice area by 21% and 1%, respectively but is contradicted by the results of this study.

Table 3-2: Comparison of agricultural land-cover estimated in this study with estimates by Afghan Central Statistics Organization (CSO; www.cso.gov.af)

Land-cover	Estimates of this study				Estimates of the CSO			
	2003	2006	2009	2013	2008	2009	2011	2013
	Area (10^3, ha)	Change (%)	Change (%)	Change (%)	Area (10^3, ha)	Change (%)	Change (%)	Change (%)
Wheat	244	+17	+24	+31	256	+22	+26	+35
Maize	92	+7	-3	0	22	+56	+10	+143
Barley	120	+8	+11	+7	65	-8	+20	-21
Rice	57	+33	+23	+32	48	+7	+13	-1

Note: Positive sign (+) indicates increase, negative sign (-) indicates decrease

Qualitative assessment of agricultural land cover derived from MODIS NDVI

As mentioned above, the main cereals of Afghanistan are wheat, maize, barley and rice which are widely grown and consumed across the country. The imports of these cereals into the country have been driven by the local water availability (reduced availability) for irrigated and rain-fed crops and their relevant production (reduced production). In this study the land cover trend for 2003-2013 was analyzed, the comparison of the individual cereal crop areas have already been performed in the previous section to those estimates which have been made by the CSO (www.cso.gov.af). However, for the qualitative assessment of the overall main cereal cover, the estimates in this study are compared to those of the FAO in the land cover atlas of Afghanistan for the year 2010 (FAO, 2012) where SPOT 4 images with high resolution were used and which are the most reliable resource available at the country level so far. In the land cover atlas, the provincial agricultural area (both irrigated and rain-fed) has been estimated which is compared with the findings of this research in this section, comparison is drawn to the sum of estimates in this study regarding main cereals that comprise of wheat, maize, barley, rice and in some provinces of poppy. The correlation established below is between the individual years from 2003-2013 to that of 2010 (land cover atlas) in order to determine the inter-annual variability of land cover with reference to the quality presentation of FAO (2012).

In order to check the quality of the agricultural cover estimated in this study, the areal agricultural cover estimated by the FAO (2012) for the year 2010 was used. The comparison with estimates in this study shows a remarkable fitness for 2005 (R^2=0.88) and 2006 (R^2=0.90) (Figure 3.16).

The fitness coefficient for 2003 and 2013 was R^2=0.79 and R^2=0.87 respectively. Furthermore, the coefficient for 2009 and 2011 was R^2=0.79 and R^2=0.78, respectively, which is almost the same as that of 2003 highlighting no major shift towards the overall agricultural area in the KRB except a partial increase in the area of wheat, barley and rice. The slight increase or decrease in the R^2 coefficients over the course of the study period could be attributed partially to the use of the medium resolution product of MODIS NDVI as well as a response to the increased food demand locally and potentially improved food security conditions compared to a decade ago.

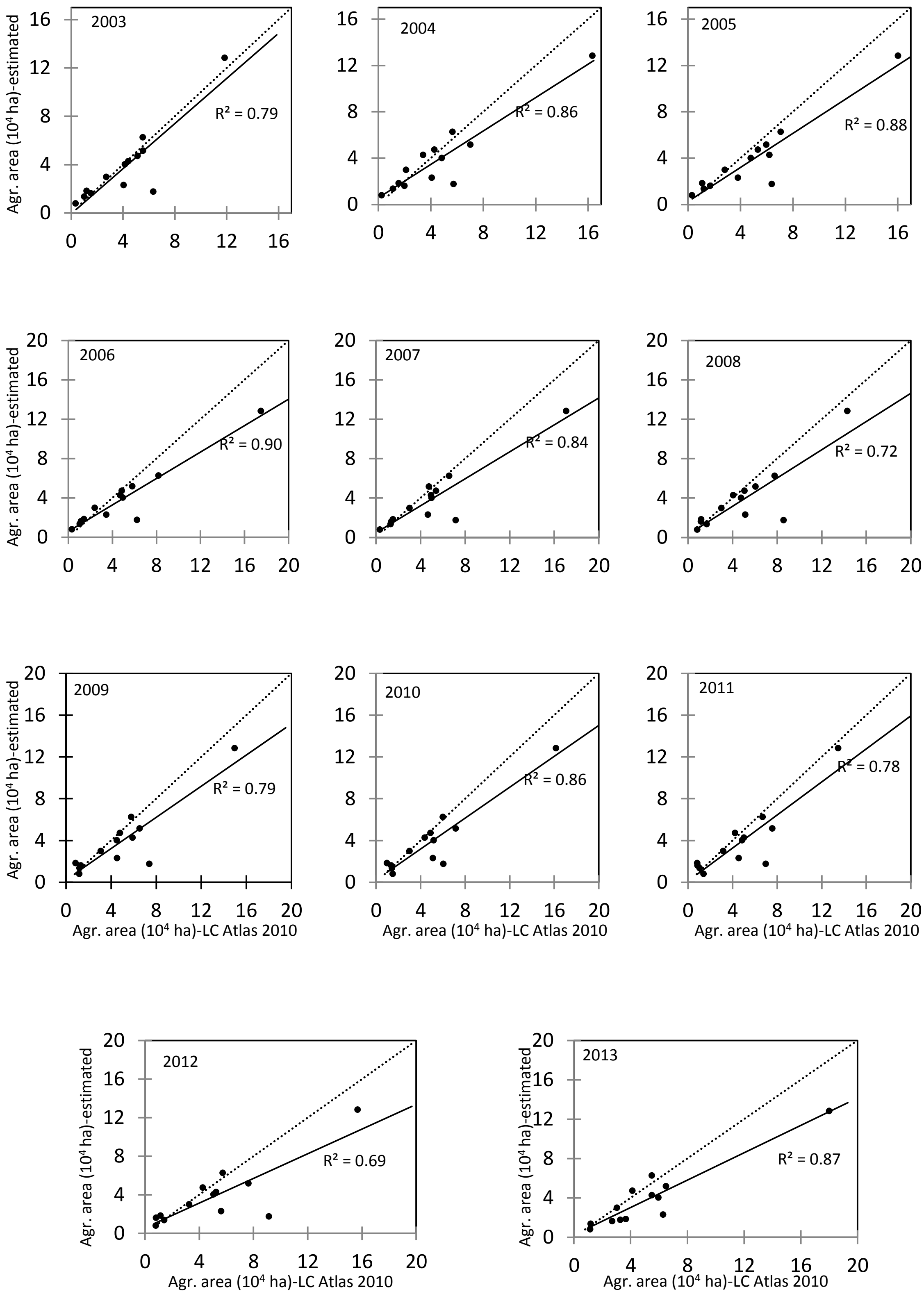


Figure 3.16: Comparison of the MODIS NDVI derived agricultural area and SPOT 4 derived land cover of 2010 (LC Atlas 2010, source: FAO, 2012)

3.3.3 Correlation of the Normalized Difference Vegetation Index with different physiographic attributes

The KRB is characterized by undulating valleys with cropping intensities varying between up- and downstream regions. Temperature and precipitation patterns vary as well as elevation which ranges throughout the basin from 383 to 5,982 m (Figure 3.17). Recent studies show that the variations in temperature, precipitation as well as elevation have a strong relation with Normalized Difference Vegetation Index (NDVI) responses (Raynolds et al., 2006; Campo-Bescós, 2013). These physiographic attributes directly or indirectly drive the NDVI response of the crops as explained below:

Effect of elevation on the NDVI

The elevation of an area has a strong correlation with the NDVI response of the crops grown in the respective areas (Li et al., 2015 and Zhan et al., 2012). Studies revealed that elevation is the dominant factor in determining the vertical distribution of vegetation in an area (Jin et al., 2008). Therefore it is important to analyze the NDVI-elevation relationship; in particular while considering an area with huge elevation differences between the upstream and downstream regions as in the KRB (Figure 3.17).

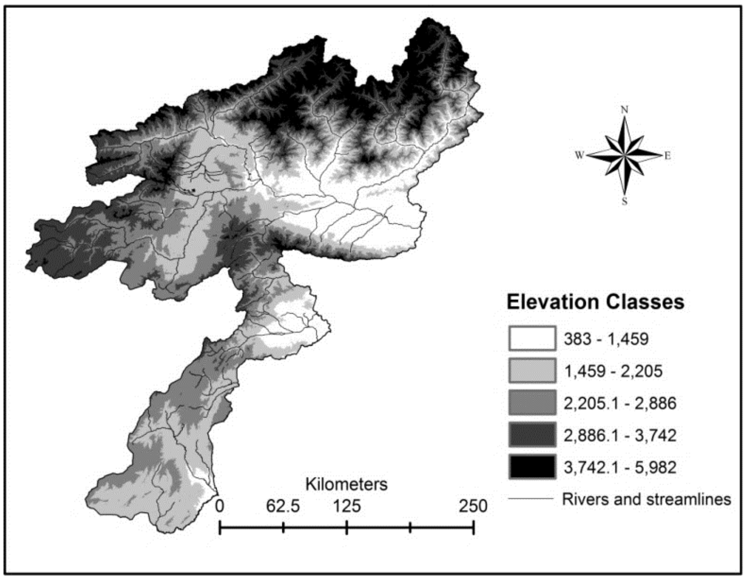


Figure 3.17: Elevation (m) map of Kabul River Basin

At high elevations (Parwan, Panjshir, Kabul), the NDVI values were lowest on average for most of the crops cultivated (Figure 3.18) throughout the season (Kileshye Onema and Taigbenu, 2009). In contrast, the areas of lower elevation and flatter terrain resulted in higher values of NDVI and vice versa.

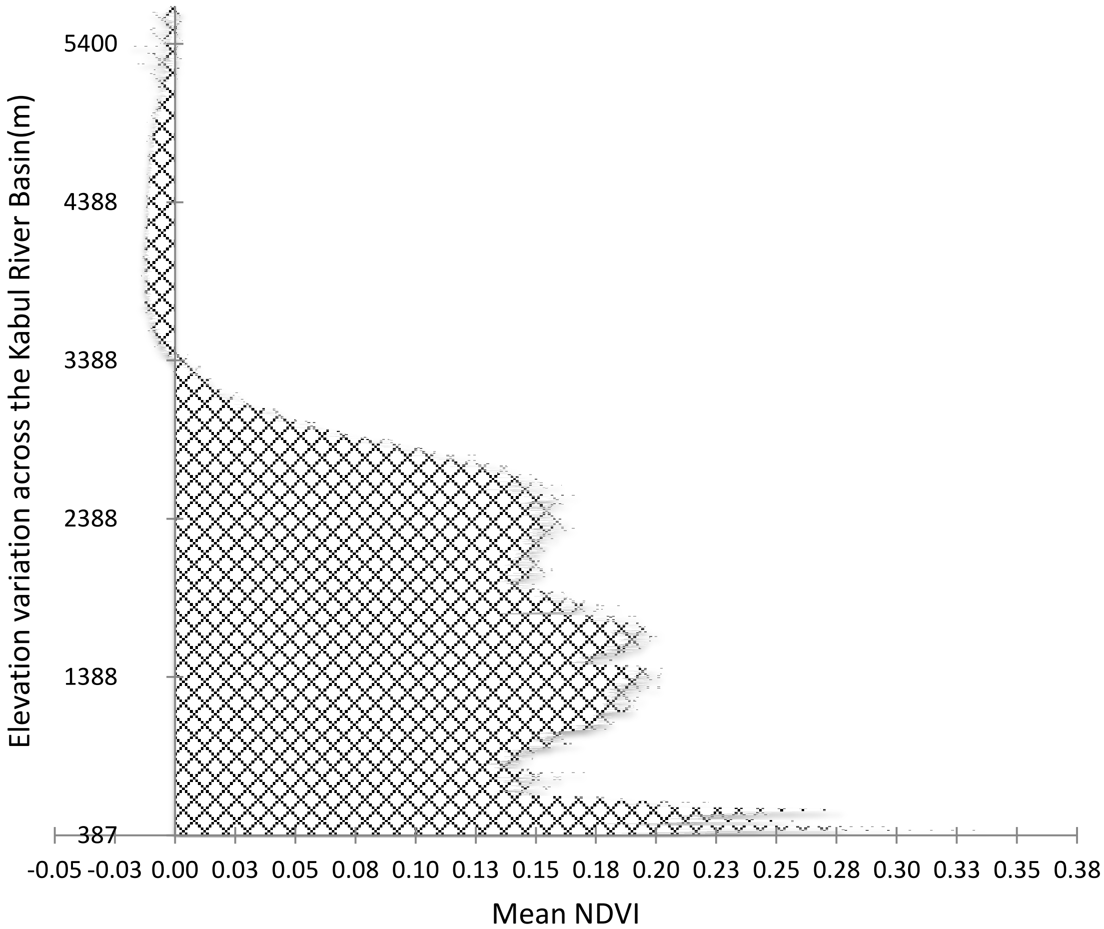


Figure 3.18: Relationship between elevation (m) and NDVI of the Kabul River Basin

When comparing the specific land cover types to elevation it can observed that poppy, followed by wheat, maize and rice crops were cultivated for the most part at lower elevations especially at the very downstream provinces of Nangarhar, Kunar, Khost and Laghman (Figure 3.19). Contrary to this, provinces with higher elevation i.e.

Kabul, Parwan, Panjshir and Nuristan, had a rather smooth NDVI curve, which accounts for most of the snow-cover as well as orchards.

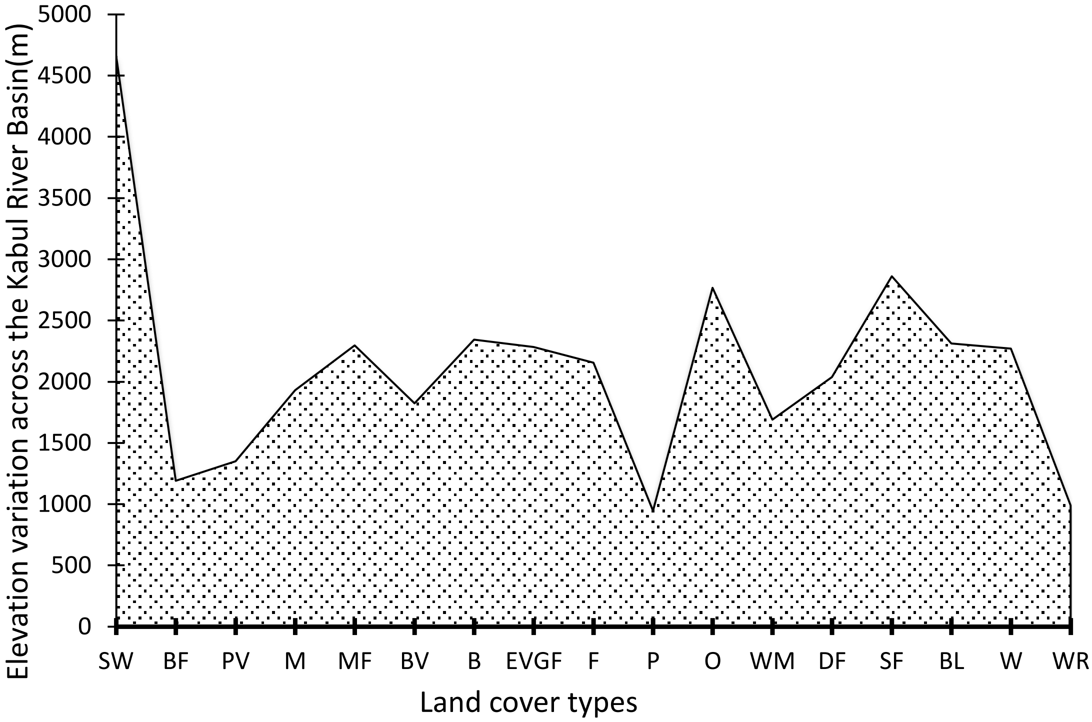


Figure 3.19: Elevation map of the individual land-cover in the Kabul River Basin (KRB)

Effect of temperature on the NDVI

There is a clear relationship between the temperature, which is a limiting factor for plant growth, and the NDVI of the crops. At higher altitudes the temperature is usually lower compared to the lower altitude regions (Cheema and Bastiaanssen, 2010); therefore vegetation in cold regions is shown to be limited by temperature (Schultz and Halpert, 1993) yielding to low peaked NDVI especially at the maximum crop development stage. Global studies on the NDVI trend show that NDVI increases with raise in temperature (Ichii et al., 2002; Julien and Sobrino, 2009; Cheema and Bastiaanssen, 2010 and Xu et al., 2011). The downstream provinces in this study feature higher average temperature compared to that at the upstream provinces; thus there were more growing degree days received by the crops resulting in higher NDVI values.

Effect of precipitation on the NDVI

Prior studies on the response of NDVI towards climate parameters have shown that NDVI has a strong relationship with the amount of precipitation (Wang et al., 2001; Wang et al., 2003; Cheema and Bastiaanssen, 2010 and Herrmann et al., 2016). The response of vegetation NDVI to temperature and precipitation is most well-defined in the autumn season (Cui and Shi, 2010). With high rainfall events, the NDVI curves respond quite sharply especially at the early crop development stage till maximum growth or maturity. In this case, with the heavy precipitation in the downstream of the KRB in Dur-Baba, the NDVI responded very positively with a lag of 10-15 days (Figure 3.20) which has already been observed in other studies of the region (Cui and Shi, 2010).

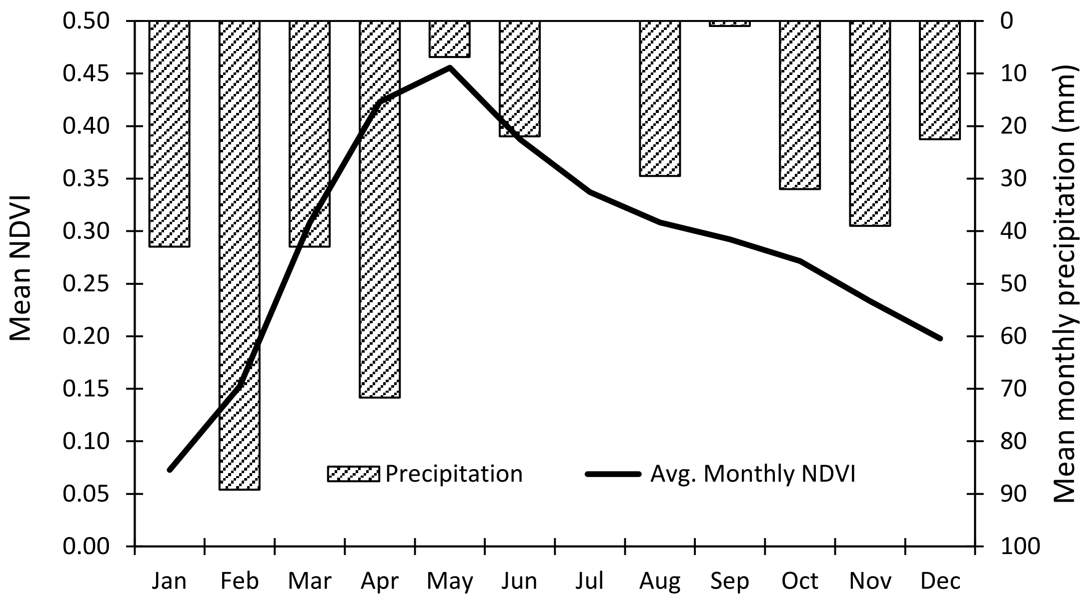


Figure 3.20: Normalized Difference Vegetation Index’s response to precipitation

As a typical response of NDVI to precipitation, the NDVI values of crops are driven by the precipitation amount within a threshold (Schultz and Halpert, 1993), in areas with high altitudes, the temperatures are often low as in the case of the KRB (upstream of INDUS basin) where higher snow-cover undermined the vegetation cover and distorted the natural response of the NDVI (Cheema and Bastiaanssen, 2010), thus resulting in lower NDVI values and rather blunt peaks at the maximum crop development stage. Similarly, the NDVI decreases in semi-arid regions due to a precipitation decrease (Ichii et al., 2002). According to Purevsuren et al. (2012), the NDVI has a maximum response to precipitation with a time lag of 10-20 days but in this study the response of the NDVI was observed with a time lag of 12 days after receiving 74 mm of rainfall in April in Kabul province. Before that, due to continuous rain showers from January to March, the NDVI trend was rather steady prior to the crop reaching its maximum development stage. Beside rainfall, the storage characteristics of the soil also influence the moisture level and eventually the crop’s response as well as a delay to it.

4 ANALYSIS OF SPATIAL DISTRIBUTION OF ACTUAL EVAPOTRANSPIRATION

4.1 Introduction

Almost all of the five river basins of Afghanistan are characterized by improper management and scarcity of data on locally available water resources (Hanasz, 2011). Irrigated agriculture is by far the largest contributor to the country's GDP and national employment which is in the range of 60-70% from urban to rural areas, respectively (MOEC, 2014). Deterioration of irrigation infrastructure in the past decades of civil unrest in the country, intermittent severe droughts and flood fluctuations across the country have further exacerbated the inadequacies in the development of Afghanistan's water resources sector (Farrell and Thorne, 2004; Roe, 2015; Shi et al., 2015).

Meanwhile, repatriation of the Afghans living in exile has further challenged the land and water productivity in this basin thereby putting great strain on the existing water resources. Heightened attention is required for water resources management in order to meet the rising food production and water demand. Investments in the post-2001 period, aimed at the recovery and rehabilitation of the hydraulic structures and canalization network, compared to the extent of losses experienced in the years of conflict, have proven inadequate to meet the local needs required for paving preliminary arrangements for a food secure Afghanistan.

To date, an estimated 99% of the surface water withdrawal is devoted solely to agricultural consumption nationwide (Qureshi, 2002). Currently, the industrial and municipal sectors are the least thirsty consumers of water in Afghanistan; yet, it is projected that this will change rapidly due to the strategic empowerment and development of these sectors planned in the near future (ANDS, 2008). Due to the predicted future rise in inter-sectorial competition for water use, it is of vital importance to ensure water security for the country's agriculture and to estimate the crop water needs with a high degree of accuracy. In the KRB (as well as further resolution going to the provincial and subbasin level), updated knowledge on actual evapotranspiration (ET_a) for various land use systems is missing; the estimation of which is a prerequisite for the safe and secure distribution of water among different users in a sustainable manner because the water demand by irrigated and rainfed agriculture consists of actual evapotranspiration (Li et al., 2015). In such cases, a holistic based approach of integrated water management is pivotal and direly needed that may incorporates the ET_a estimation with a highest possible degree of accuracy.

Various models have been developed for the estimation of ET_a at various scales that use a combination of diversified temporal and spatial resolution remote sensing data inputs as well as meteorological parameters. Surface energy balance models, using remote sensing data include SEBAL (Bastiaanssen et al., 1998), SEBS (Su, 2002), S-SEBI (Roerink et al., 2000), SEBI (Menenti and Choudhary, 1993) and METRIC (Allen et al., 2007) etc. The SEBS model has been utilized for the estimation of turbulent fluxes and ET_a estimation in a variety of land use systems ranging from forests (Rwasoka et al., 2011, Hu et al., 2015), wetlands (Álvarez, 2007), crops (Pardo et al., 2014), barren lands (Xin, 2007), fodder crops, grasses (Wang et al., 2013) and sparse to dense vegetation (Byun et al., 2014). Among many other models using surface energy for ET_a estimation, SEBAL (Bastiaanssen et al., 1998) can be useful as it only has minimum ground based data requirement and doesn't require exact atmospheric corrections and can thus be successfully applied in flat areas, which is not the case with the KRB. Similarly, the S-SEBI model (Roerink et al., 2000) does not require ground-level data but its accuracy can be questioned and therefore cannot be generalized. METRIC (Allen et al., 2007) could not be employed in all areas as a consequence of ambiguities in its behavior in relation to anchor pixel determination (Liou and Kar, 2014).

For this study, the Surface Energy Balance System (SEBS) algorithm (Su, 2002) in combination with Moderate Resolution Imagine Spectrometer (MODIS) satellite data was used for the first time in the KRB. Although this approach requires a lot of input data and is comparatively complex, the uncertainties in the estimated heat fluxes are comparable to in-situ measurement (Su,, 2002) which can be seen as a clear advantage of the approach. Instead of using fixed values, roughness height for heat transfer in this case is also computed explicitly. There is a scarcity of ground-level physical data available in the KRB. In such cases, water resources and climate relevant research for future planning and management is entirely dependent on global remote sensing data sets (Mauser and Schädlich, 1998; Senay et al., 2007; Hwang and Choi, 2013).

The objective of this study was to analyze the long term trends of actual evapotranspiration in the KRB at detailed spatial and temporal scales. Therefore, SEBS was used to estimate the ET_a at the main basin (KRB) level and subbasins as well at the provinces on a monthly, seasonal and annual basis for the period 2003-2013. ET_a can also be utilized as an indicator to assess performance of irrigation and water allocation/management in general. The long term analysis results can be used by policy makers and water managers in the region to strategically plan land and water resources to mitigate the surface water scarcity and to optimize the available land and water resources. In addition, the ET_a derived under this research could be used in comparisons to future studies on the effects/impacts of climate change on ET_a.

4.2 Materials and methods

4.2.1 Methodological framework and description of Surface Energy Balance System (SEBS)

For the estimation of the ET_a, SEBS was used while incorporating the Global Land Data Assimilation System (GLDAS) and MODIS satellite data (Figure 4.1):

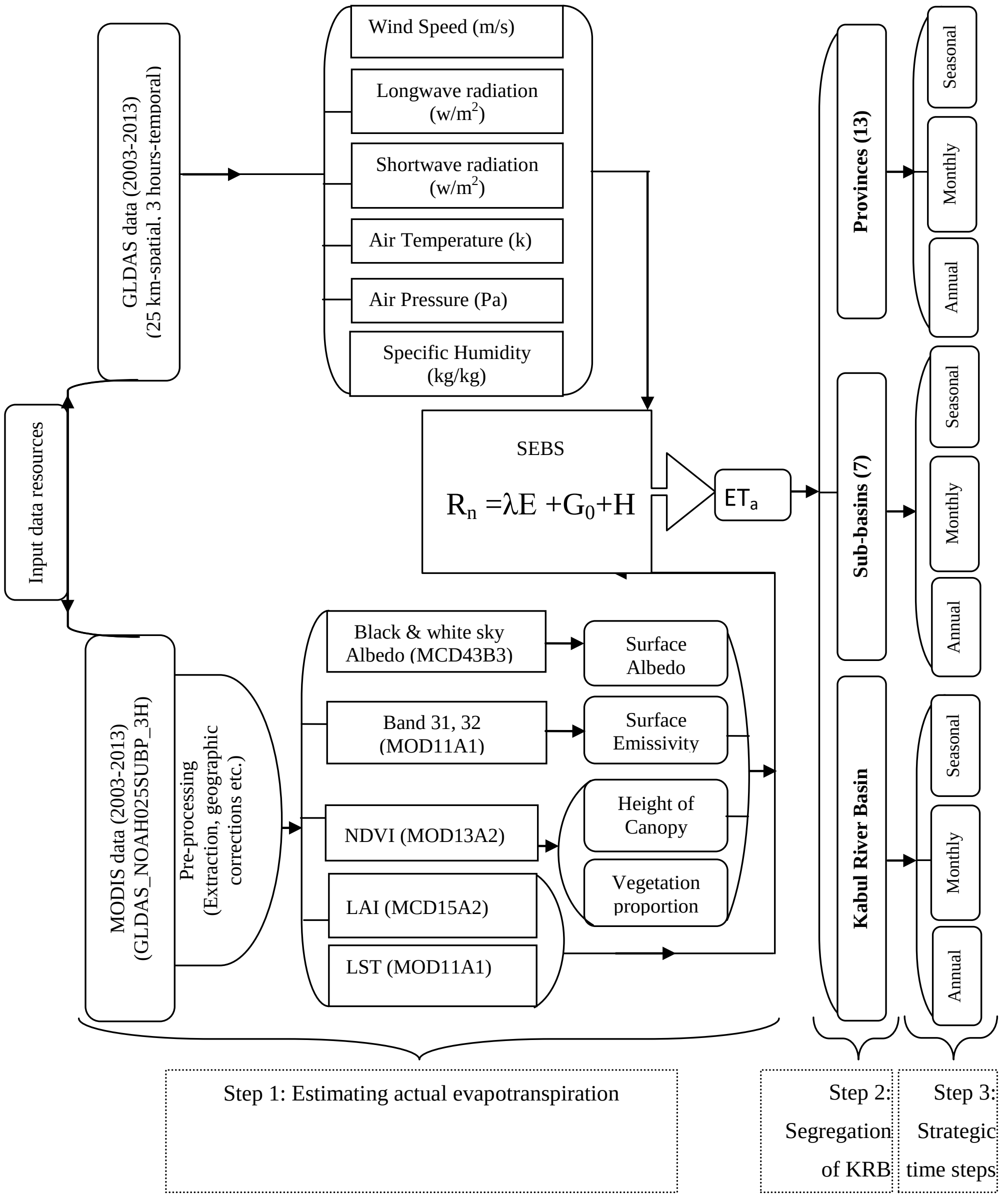


Figure 4.1: Methodological framework to estimate ET_a in different spatial units of the KRB with strategic time steps

The SEBS algorithm (Su, 2002) is a single-source model used for the estimation of atmospheric turbulent fluxes and surface evaporative fraction from remote sensing data. SEBS has been proven to be a very credible evapotranspiration model based on the remote sensing data and has been successfully used over various ecosystems under different climate and geographic conditions (Liaqat et al., 2014; Su et al., 2005; Zhou et al., 2006). It employs meteorological and satellite spectral reflectance and radiance data for the estimation of the turbulent heat fluxes and is based entirely on the rational of the basic equation (4.1) used for the computation of the surface energy balance, given below:

$$R_n = G_0 + H + \lambda E$$ Equation (4.1)

where R_n is net radiation (Wm^{-2}), G_0 is soil heat flux (Wm^{-2}), H is the sensible heat flux (Wm^{-2}), λE is the turbulent latent heat flux (Wm^{-2}), λ is the latent heat of vaporization (Jkg^{-1}) and E is evapotranspiration. R_n is further expressed as:

$$R_n = (1-\alpha) \cdot R_{swd} + R_{lwd} - R_{lu}$$ Equation (4.2)

where the R_{lu} (longwave upward radiation) was calculated using the procedure recommended by Allen et al., (2007). $R_{lu} = \varepsilon \cdot \sigma \cdot T_0^4$, here ε is the air emissivity determined using the Brutsaert (1975) approach i.e. ε =1.24.$(e_a/T_a)^{1/7}$ *and* σ is the Stefan–Boltzmann constant (5.67 x 10^{-8} $Wm^{-2}K^{-4}$) , T_0 is surface temperature (K), α represents the albedo, R_{swd} denotes the incoming shortwave radiation (Wm^{-2}), R_{lwd} is the downward longwave radiation (Wm^{-2}),

The soil heat flux, was calculated using the fractional vegetation cover (f_c,) with constants for full vegetation canopy (Γ_c= 0.05) (Monteith, 1973)and bare soil (Γ_s = 0.315) (Kustas and Daughtry, 1990). The equation used was:

$$G_0 = R_n \cdot [\Gamma_c + (1-f_c) \cdot (\Gamma_s - \Gamma_c)]$$ Equation (4.3)

The fractional vegetation cover f_c was linearly interpolated between the bare soil and full vegetation canopy conditions using the NDVI minimum (NDVImin) and NDVI maximum (NDVImax) values from the given image. The equation used for f_c calculation was:

$$f_c = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \qquad \text{Equation (4.4)}$$

To derive sensible heat flux (H), the similarity theory was applied. The choice of using either the Monin–Obukhov Similarity (MOS) theory (Monin and Obukhov, 1954) for Atmospheric Surface Layer (ASL) or otherwise BAS theory (Brutsaert and Stricker, 1979) depends on the height at which the measurements are taken. In this study, since the measurements were taken in the Atmospheric Surface Layer (ASL), the (MOS) functions were used to derive H from the available energy through an iteration procedure (Su, 2002):

$$H = \frac{ku_{*}\rho C_p(\theta_s - \theta_a)}{\left[\ln\left(\frac{z-d_0}{z_{0h}}\right) - \psi_h\left(\frac{z-d_0}{L}\right) + \psi_h\left(\frac{z_{0h}}{L}\right)\right]} \qquad \text{Equation (4.5)}$$

where z represents above surface height, u_* is the friction velocity and k = 0.4 is von Karman's constant, d_0 is zero plane displacement height, z_{0m} denotes the roughness height for momentum transfer, ϑ_s is the potential temperature at the surface, ϑ_a is the potential air temperature at height z, while z_{0h} is the scalar height for heat transfer, Ψ_m and Ψ_h are the stability correction functions for momentum and sensible heat respectively, L represents the Obukhov length, C_p shows the specific heat capacity of air at constant pressure, g is the gravitational acceleration (9.8 ms^{-2}) (Su, 2002).

The value of H was calculated by considering the limiting values under the wet and dry limits (energy balance at limiting cases). At the dry moisture limit, latent heat (λE_{dry}) becomes equal to zero and sensible heat (H_{dry}) would be at its maximum value. By definition, from Eq. (1), it follows that:

$$\lambda E_{dry} = R_n - G_0 - H_{dry} \equiv 0 \qquad \text{Equation (4.6)}$$

or

$$H_{dry} = R_n - G_0 \qquad \text{Equation (4.7)}$$

At the wet-limit, sensible heat flux (H_{wet}) has the minimum value and the evapotranspiration occurs at the potential rate, (λE_{wet}), bounded by the available energy only. In this case the equation would be as given below:

$$\lambda E_{wet} = R_n - G_0 - H_{wet} \qquad \text{Equation (4.8)}$$

or

$$H_{wet} = R_n - G_0 - \lambda E_{wet} \qquad \text{Equation (4.9)}$$

The energy used for the evapotranspiration process (evaporative fraction, Λ) is divided by the total available energy (R_n–G_0) and expressed as:

$$\Lambda = \frac{\lambda E}{(R_n - G_0)} \qquad \text{Equation (4.10)}$$

By rearranging the above equation, the latent heat was determined by $\lambda E=\Lambda\cdot(R_n\text{-}G_0)$. The actual evapotranspiration (ET_a) was then calculated by using the formula $ET_a=\lambda E/\lambda\cdot_{\rho w}$, where ET_a is the actual evapotranspiration in mms^{-1}, λ (latent heat of vaporization in Jkg^{-1}), and ρ_w denotes the water density in kgm^{-3}.

The latent heat flux drives the total vapor flux into the atmosphere which is shown as the energy. In conditions of cloud-free sky, the evaporative fraction (Λ) known to be conservative in a diurnal cycle is assumed to be representative of daily energy partitioning. Due to this assumption, instantaneous evaporative fraction (Λ) during the satellite overpass time was used to compute instantaneous evapotranspiration at annual, monthly as well as seasonal timescales. The ET_a was scaled up to daily values, $ET_{a_{24}}$ *(mm/day)*, by estimating averaged 24-h net radiation (R_{N24}) (Hou et al., 2014; Jia et al., 2009). The instantaneous ET_a (mm s^{-1}) values were then combined to obtain a daily total ET_a (mm/day), for this reason the instantaneous ET_a values were summed up over 24 hours. This adaptation was based on the assumption that the evaporative fraction remains almost constant though the sensible and latent heat fluxes may vary strongly during a day (Sugita and Brutsaert, 1991). Considering this, the following equation was used for a total daily ET_a:

$$ET_{a_{daily}} = \sum_{i=0}^{24} \left[\Lambda . \frac{R_n - G}{\lambda \rho_w} \right] i \qquad \text{Equation (4.11)}$$

$$ET_{a_{daily}}(\text{mm/day}) = 8.64 \times 10^7 . \left[\Lambda . \frac{R_{ndaily} - G_{daily}}{\lambda \rho_w} \right] \qquad \text{Equation (4.12)}$$

where R_{ndaily} represents the daily average net radiation, ρ_w is the density of water in kg m^{-3}, G_{daily} is the daily average soil surface heat flux and λ is the latent heat of water taken as 2.47×10^6 (J kg^{-1}) (Jia et al., 2009).

4.2.2 Main input data characteristics

Global Land Data Assimilation System (GLDAS)

The Global Land Data Assimilation System (GLDAS) is a unique uncoupled land surface modeling system that drives the multiple models and integrates a large quantity of observed data purposed to ingest satellite and ground based data; it runs globally with a spatial resolution of 0.25^0 with 3 hours step information (Rodell et al., 2004). GLDAS uses sophisticated land surface modeling and data assimilation techniques and generates optimal fields of land surface states and fluxes in the near-real time typically in a time span of 48 hours.

The GLDAS data is courtesy of the National Aeronautics and Space Administration (NASA) available online for public non-commercial use with no cost applied. This data is widely used around the world for the initialization of weather and climate prediction models, and promotes various hydro-meteorological studies and applications ranging from the diagnosis of the strength of soil temperature in land atmosphere interactions (Liu et al., 2015), evaluation of soil moisture (Dorigo et al., 2015), integrated modeling of aerosols (Peters-Lidard et al., 2015), estimation of groundwater estimations (Fatolazadeh et al., 2015) and other diverse analyses (Amatya et al., 2015; Qin et al., 2015; Watkins et al., 2015). The use of GLDAS datasets is rather impressive when dealing with areas where there is data scarcity or missing ground climatic information (Armanios and Fisher, 2012; Cai et al., 2013; Kiptala et al., 2013).

For running the SEBS algorithm, the following meteorological variables were extracted from the Goddard Earth Sciences Data and Information Services Center (GES DISC- http://disc.sci.gsfc.nasa.gov/hydrology), for sinusoidal tile grids H23V5 and H24V5 (covering the study area, more specifically GLDAS model (GLDAS_NOAH025SUBP_3H) (Rodell and Beaudoing, 2007) which contains a series of land surface parameters simulated from the NOAH 2.7.1 model in the GLDAS (Table 4-1):

Table 4-1: Characteristics of the climate parameters downloaded from GLDAS

S. No	Data Type	Source	Variable	Spatial Resolution	Temporal Resolution	Temporal Coverage
1	GLDAS	NOAH	Wind Speed (m/s)	25km	3- Hours	2003-2013
2			Long-wave Radiation (W/m2)	25km	3- Hours	2003-2013
3			Air Temperature (K)	25km	3- Hours	2003-2013
4			Short-wave Radiation (W/m2)	25km	3- Hours	2003-2013
5			Air Pressure (Pa)	25km	3- Hours	2003-2013
6			Specific Humidity (Kg/Kg)	25km	3- Hours	2003-2013

Moderate resolution Imaging Spectroradiometer (MODIS) data

The three important surface variables for the determination of heat and water exchanges between land surface and the overlying atmosphere and the partitioning of available energy between soil and vegetation are land surface temperature, land surface albedo as well as vegetation cover (Jia et al., 2009). For use in the SEBS algorithm, aimed at ET_a estimation, the user-friendly data of MODIS was downloaded for a study period 2003-2013 from the Land Processes Distributed Active Archive Center (LP DAAC) of the United States Geological Survey (USGS) (https://lpdaac.usgs.gov/products/modis_products_table). The downloaded meteorological variables were interpolated in a linear way between 0600 and 0900 Coordinated Universal Time (UTC) to match the MODIS temporal resolutions over pass time over the KRB which is around 10:00 am according to local time (GMT 04:30).

While using the MODIS re-projection tool (https://lpdaac.usgs.gov/tools/modis_reprojection_tool), the downloaded data sets (Table 4-2) were re-sampled using the nearest neighbor interpolation method.

The tiles covering the KRB were H23V5 and H24V5 for which the relevant data given in Table (4-2) was downloaded. The MODIS land surface temperature data or emissivity (MOD11A1) is a daily (instantaneous) product, while the leaf area index (LAI) (MOD15A2) is an 8-day composite dataset. Because land surface status defined by LAI and surface reflectance or surface albedo (MCD43B3) does not change significantly over short periods, an 8-day interval is sufficient to portray the land surface properties (Jia et al., 2009). The regional land cover product (MCD12Q1) was used with a spatial resolution of 500 m with a temporal coverage of 2003-2013. The land cover map was applied in the analysis of the evaporative behavior of different land cover types in the KRB.

Table 4-2: Characteristics of the MODIS products used in the estimation of ET_a for 2003-2013 across the Kabul River Basin (KRB)

S. No.	Data Type	Source	Variable	Spatial Resolution	Temporal Granularity	Temporal Coverage
1	Satellite Land Surface Data	MODIS	Emissivity/LST (MOD11A1)	1km	Instantaneous	2003-2013
2			NDVI (MOD13A2)	1km	16-day	2003-2013
3			LAI (MCD15A2)	1km	8-day	2003-2013
4			Albedo (MCD43B3)	1km	8-day	2003-2013
5			Land Cover (MCD12Q1)	500 m	annual	2003-2013

4.2.3 Segregation of Kabul River Basin into different spatial management units for actual evapotranspiration estimates

The latest iteration of the Water Law of Afghanistan (GoIRA, 2009) places emphasis on the equitable and needs-based participation of stakeholders in water resources management in an integrated manner in all the five river basins of Afghanistan (Rout, 2008). Integrated Water Resources Management (IWRM) has been legally approved as the basic approach for the water resources management at all water resources management units in Afghanistan (Kakar, 2011). For this purpose, a coordination chain was established by the Government of Afghanistan for establishing river basin agencies in all major river basins (Kakar, 2011). Estimation of the agricultural water demand is the key prerequisite for a sound and sustainable distribution and management of water resources at these management units. Consequently, these units were considered in addition to the KRB as spatial units for the ET_a-analyses. The KRB is divided into seven subbasins and 13 provinces for strategic and operational planning and management of the available water resources.

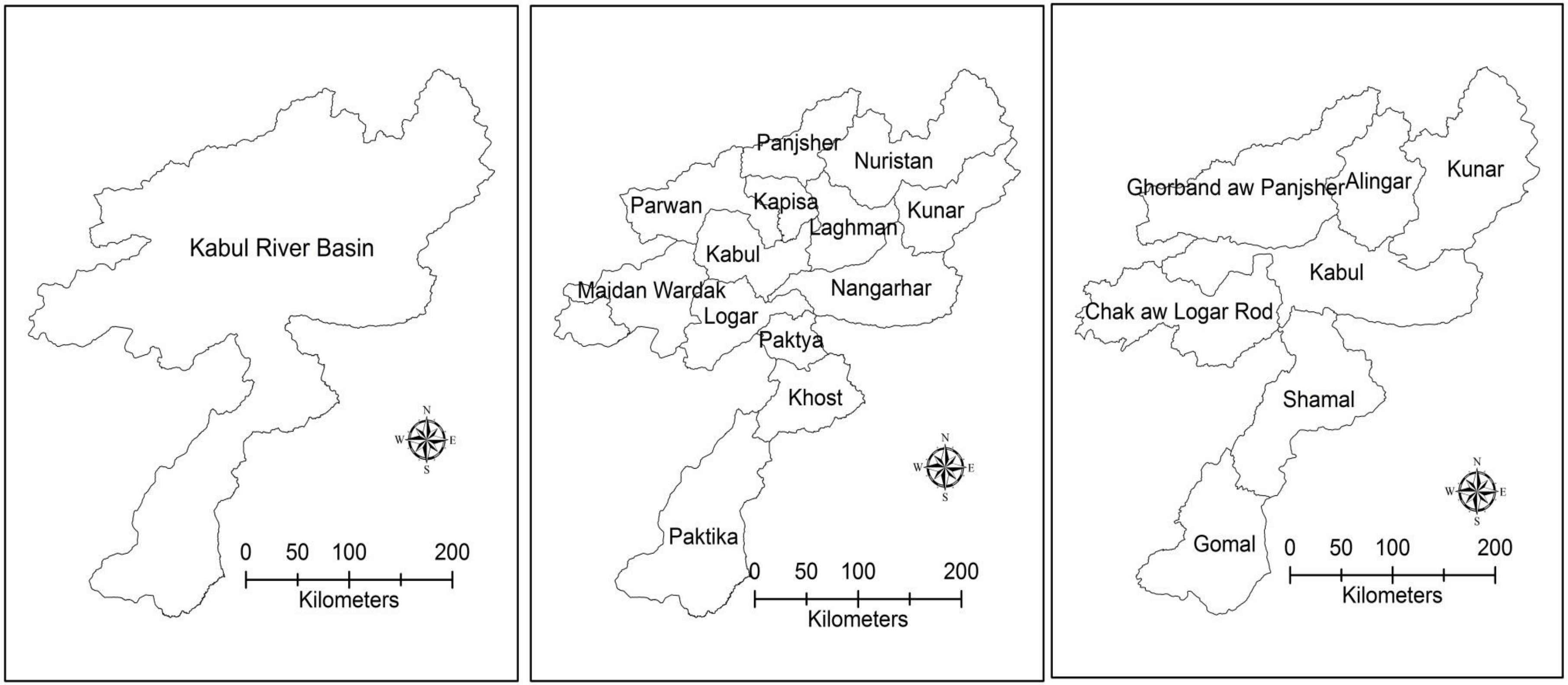


Figure 4.2: Segregating the (a) Kabul River Basin into (b) provincial and (c) subbasin boundaries

Strategic planning of water resources based on actual evapotranspiration estimates at crucial time steps

Generally, plant cell growth is the physiological process centrally triggered by the water content in the plant tissues absorbed from the crop root zone (González et al., 2015). Therefore, providing availability of water to crops (via the soil as storage) is essential for scheduling irrigation in agriculture especially at the crucial crop development stages (Akhtar et al., 2013). The knowledge on agricultural water demand for strategic planning is not possible without prior information on the crop phenology. For this reason a crop calendar was established in this study for identification of the temporal boundaries of winter and summer crop seasons at various spatial administrative units. Under this strategic planning, the consumptive water use of crops, being of paramount importance for a holistic basin-wide water resource management, has been calculated in detail at annual, monthly and seasonal time spans. The decentralized estimation of the ET_a is pivotal for the development of key thematic areas in different watersheds across the KRB. Therefore, ET_a was estimated using the SEBS model for each individual year ranging from 2003 to 2013 at annual, monthly and seasonal scales.

Actual evapotranspiration estimates for different crops

Due to its influential magnitude on the water demand side, estimating the ET_a of land use and land cover is a key requirement for water resources planning and management. Therefore, the LULC maps from 2003-2013 were used in this study; the KRB was divided into 17 main LULC classes ranging from the dominant wheat, maize and rice crops to evergreen forests in the east of the country.

The cropping calendar developed for the KRB (Chapter 3, Figure 3.2) identified two distinct growing seasons, from May-September (summer) and October–April (winter) which provided the base for the estimation of the ET_a. The individual land cover based ET_a was determined using the LULC maps (Chapter 3, Figure 3.9). In the KRB, most of the central and upstream region grow one crop per year with occasionally two crops at very small scale, whereas the downstream parts dominantly cultivates two crops in rotation, i.e. usually wheat-rice, wheat-maize.

4.2.4 Evaluation of the actual evapotranspiration (SEBS ET_a) through advection-aridity model (AA):

The advection-aridity model (AA model) is an energy balance model (Brutsaert and Stricker, 1979) used here to estimate the actual evapotranspiration from the meteorological data of two stations (Nangarhar and Kunar provinces) randomly picked up from the KRB for which the data for the year 2003 was available. The results of the AA model have been employed to evaluate the estimations of SEBS model for the KRB at various spatial and temporal units. The choice of using the AA model is because of its suitability under arid and semi-arid conditions (Yang et al., 2016; Liaqat et al., 2014; Szilagyi et al., 2009). The main benefit of the Advection-Aridity complementary method is that it does not require any information on plant canopy resistance, stomatal resistance properties of the vegetation, soil moisture or other measures of aridity, because it depends mainly on meteorological parameters (Brutsaert, 2005; Brutsaert and Stricker 1979). The details of AA model have been elaborated in several studies under various geographic and climatic conditions (Rwasoka et al., 2011; Crago and Brutsaert, 1992; Liu and Sun et al., 2004).

Brutsaert and Stricker's (1979) proposed AA model for regional evapotranspiration estimation; which is based on Bouchet's (1963) complementary relationship, and expresses the actual evapotranspiration ET_a as a combination of the wet environment (ET_w) and potential evapotranspiration (ET_p) (Equation 3.13):

$$ET_a = 2ET_w - ET_p \qquad \text{Equation (3.13)}$$

ET_a is the actual evapotranspiration

ET_w is the evapotranspiration under wet surface

ET_p is the potential evapotranspiration

For the calculation of the wet surface evapotranspiration (ET_w) (Equation 3.14) and Potential Evapotranspiration (ET_p) (Equations 3.15) in the above equation (Z), AA model uses the Priestley and Taylor (1972) and Penman (1956) equations respectively.

$$ET_w = \alpha_e \frac{\Delta}{\Delta + \gamma} (R_N - G) \quad \text{Equation (3.14)}$$

$$ET_p = \frac{\Delta}{\Delta + \gamma} (R_N - G) + \frac{\gamma}{\Delta + \gamma} \times E_r \quad \text{Equation (3.15)}$$

In Equations (3.14) and (3.15), R_n-G is the net available energy: R_n represents the net radiation near the surface expressed in terms of equivalent vaporization rate (mm) and G is the heat flux into the ground

α_e is the Priestley-Taylor coefficient (α_e =1.26),

γ is the psychrometric constant which is a function of temperature too

Δ is the slope of saturated water vapor pressure curve at current air temperature (k Pa $^0C^{-1}$)

E_r is called as the drying power of the air, and is a production of the vapor pressure deficit and wind and is expressed as in equation (3.16)

$$E_r = f(u) \times (e_s - e_a) \quad \text{Equation (3.16)}$$

Where *f(u) is the wind function,* e_s is the saturation vapor pressure (kPa) and e_a is the actual vapor pressure in (kPa).

Penman (1948) originally suggested the *f(u)* to be calculated as below

$$f(u) = 0.26(1 + 0.54u_2) \quad \text{Equation (3.17)}$$

Where u_2 is the wind speed in (m s^{-1}) and denotes the wind speed measured at a reference height (2m) from the ground surface.

The complementary relationship between ET_a and ET_p introduced by Bouchet (1963) was combined by Brutsaert and Stricker (1979) while combining equation (3.14) to equation (3.17) as follows:

$$ET_a = (2 \propto_e - 1)\frac{\Delta}{\Delta+\gamma}(R_N - G) - \frac{\gamma}{\Delta+\gamma} \times 0.26(1+0.54u_2) \times (e_s - e_a)$$ Equation 3.18

The input data for the AA model (in Equation. 3.18) consists of air temperature, relative humidity, wind speed, and net radiation. Since the observed net radiation (R_n) is not readily available, therefore the FAO-crop evapotranspiration method (Allen et al., 1998) was used to estimate the net radiation from meteorological observation data.

4.3 Results and discussion

4.3.1 Estimation of actual evapotranspiration across the Kabul River Basin (KRB) at different strategic time steps

Inter-annual variation in actual evapotranspiration across the Kabul River Basin (KRB)

As an overall finding of the analyses carried out under this study, an increment of around 9% in the mean annual ET_a of the KRB from 2003 till 2013 was detected. The LULC analysis and data available from the government (CSO-IRoA, 2014) shows that from 2003-2013 there was an increase in the cultivation of wheat across the country. During this period, the mean minimum annual ET_a estimated was 471 mm in the year 2004 (Figure 4.3). The year 2004 was the driest years during the study period across the country (Pervez et al., 2014). Therefore, relatively less precipitation and the high temperatures around the dry years caused accelerated rates of ET_a (Falamarzi et al., 2014; Kimball and Bernacchi, 2006; Trajkovic, 2005)

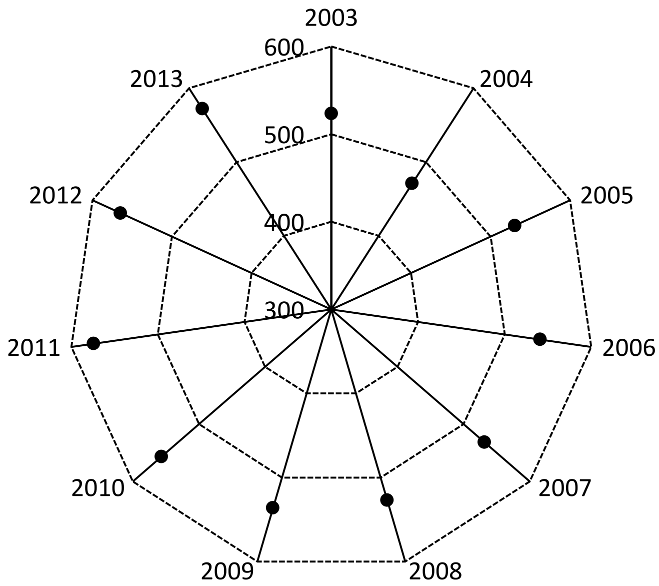


Figure 4.3: Mean annual variation of actual evapotranspiration (mm) in Kabul river Basin 2003-2013

The annual ET_a maps of the KRB from 2003-2013 show a rise in crop annual water consumption in 2011 and 2013 of 574 mm and 572 mm, respectively, compared to that of 2004 (Figure 4.4).

The increase in ET_a in 2011 was contributed by the increase in wheat, maize and rice by 17%, 23% and 11% respectively. The increase in wheat cultivation is partly explained by the reduction in barley (11%) compared to the base year 2003. Moreover, wheat is often irrigated across the basin unlike barley. In 2013, the ET_a rate was around 572 mm which can be justified by the relevant increase in the irrigated area of wheat by 31%, maize by 16% and rice by 21%, whereas barley area decreased by 5%.

The increase in cropping area especially in areas with double cropping had multiplied effect in terms of high water consumption by the crops. Since the farm irrigation across the country is fully supply based rather than demand-aware, the increase in the irrigation frequency lead to raised soil moisture levels (in the range of field capacity) which tends to enhance ET_a.

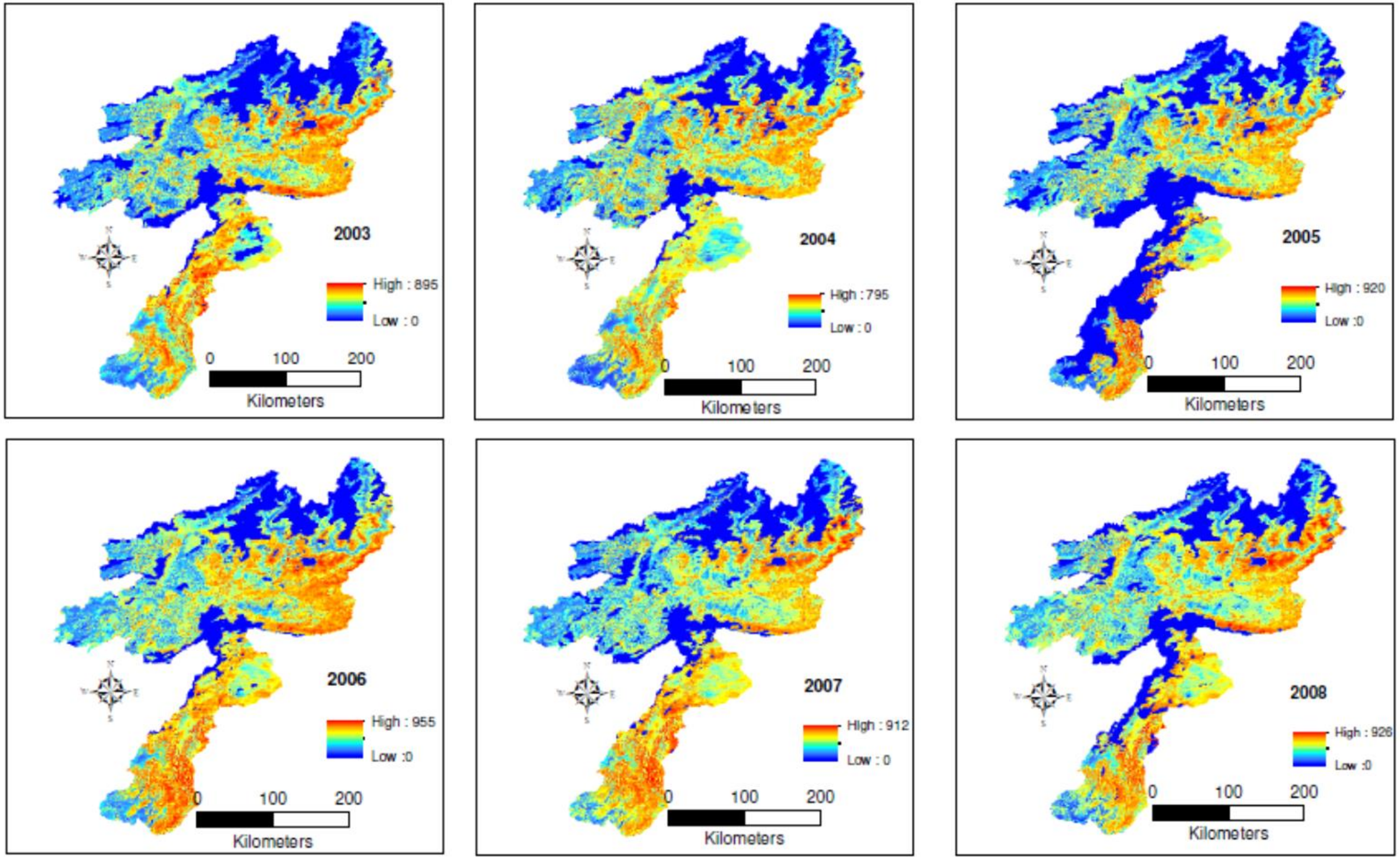


Figure 4.4: Spatial distribution of inter-annual variation of actual evapotranspiration) in the Kabul river Basin (KRB) 2003-2013

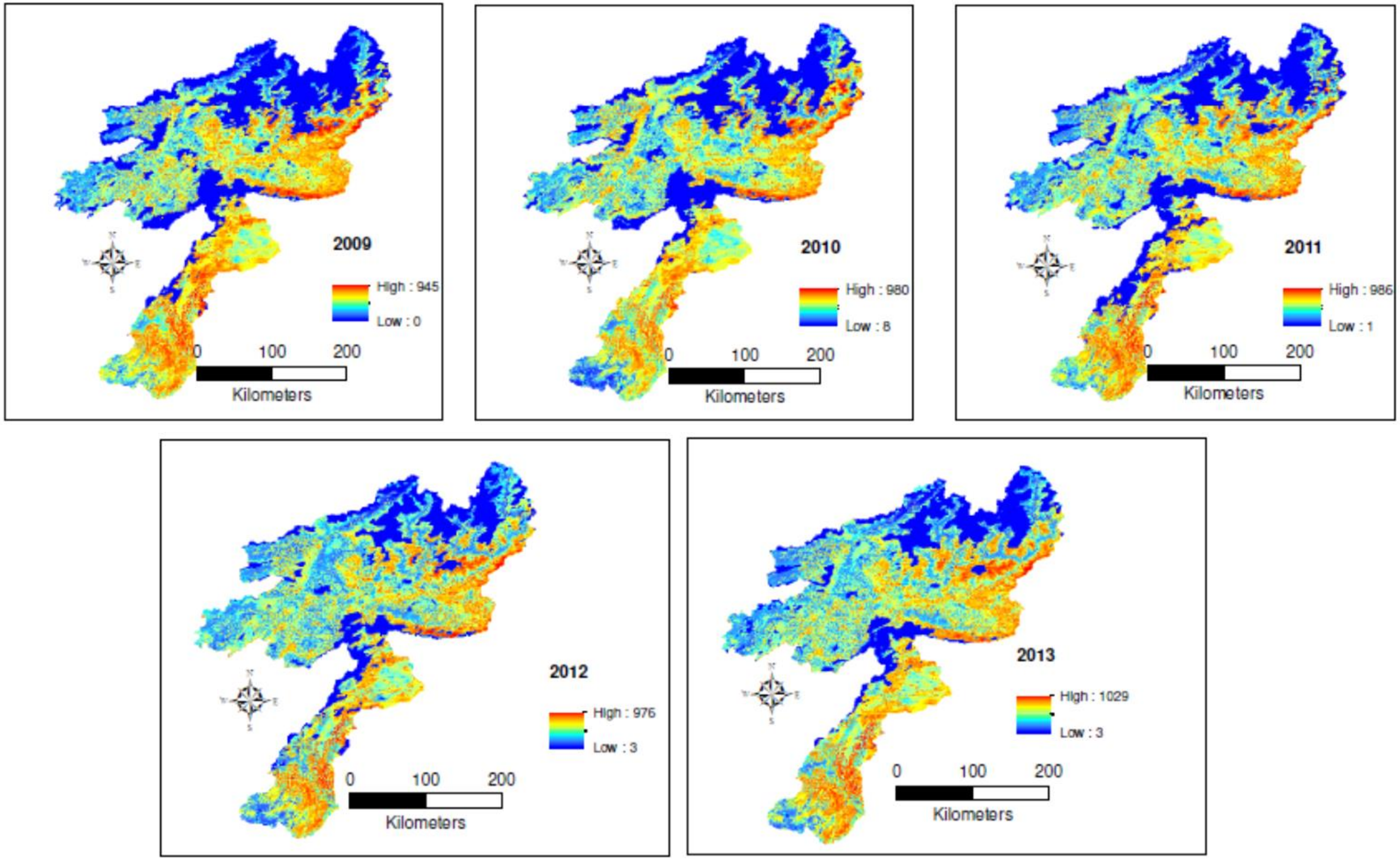


Figure 4.4: Continued

Monthly variation in actual evapotranspiration across the KRB from 2003-2013

The monthly-variability of ET_a throughout the study period showed an ET_a of 9 mm in January, 2004. The lowest ET_a values throughout the year 2004 were triggered by the drought conditions affecting the water availability in the basin (WFP, 2004). The overall minimum average ET_a throughout 2003-2013 was estimated for the month of December (10±2 mm), which is one of the coldest months. For the remaining years, the average annual variation was consistent on average basis i.e. the average ET_a for the months January, February, March, April, May, June, July, August, September, October and November were (14±2), (28±4 mm), (49±4 mm), (62±5 mm), (72±4 mm), (70±5 mm), (73±5 mm), (67±5 mm), (48±4 mm), (31±3) and (16±3), respectively. The larger fluctuation in evapotranspiration is often observed in semi-arid regions with sparse vegetation (Wang et al., 2013 and Gokmen et al., 2012). The annual average (2003-2013) ET_a shows that the usually highest values of ET_a across the KRB are reached in the months of May-August with a magnitude in the range of 70 mm; these are the hottest months across the entire KRB and are relatively less humid.

Seasonal variation in actual evapotranspiration across the KRB from 2003-2013

The seasonal variability in the ET_a in the summer season (May-September) across the KRB stays almost consistent with a decadal mean ET_a of 333±19 mm. The maximum ET_a was experienced in the winters of 2010-2011 (223 mm), 2011-2012 (223 mm) and 2012-12 (220 mm). Among decadal winters, 2003-2004 experienced the lowest ET_a of 188 mm. The minimum ET_a was experienced in the summer 2004 (288 mm) (Figure 4.5). In the case of seasonal variation in the ET_a in the winter season (October-April), the decadal mean ET_a was 207±12 mm. The considerable reduction was contributed by the drought in 2004 that hit most of the country with loss to plant and animal species (WFP 2004).

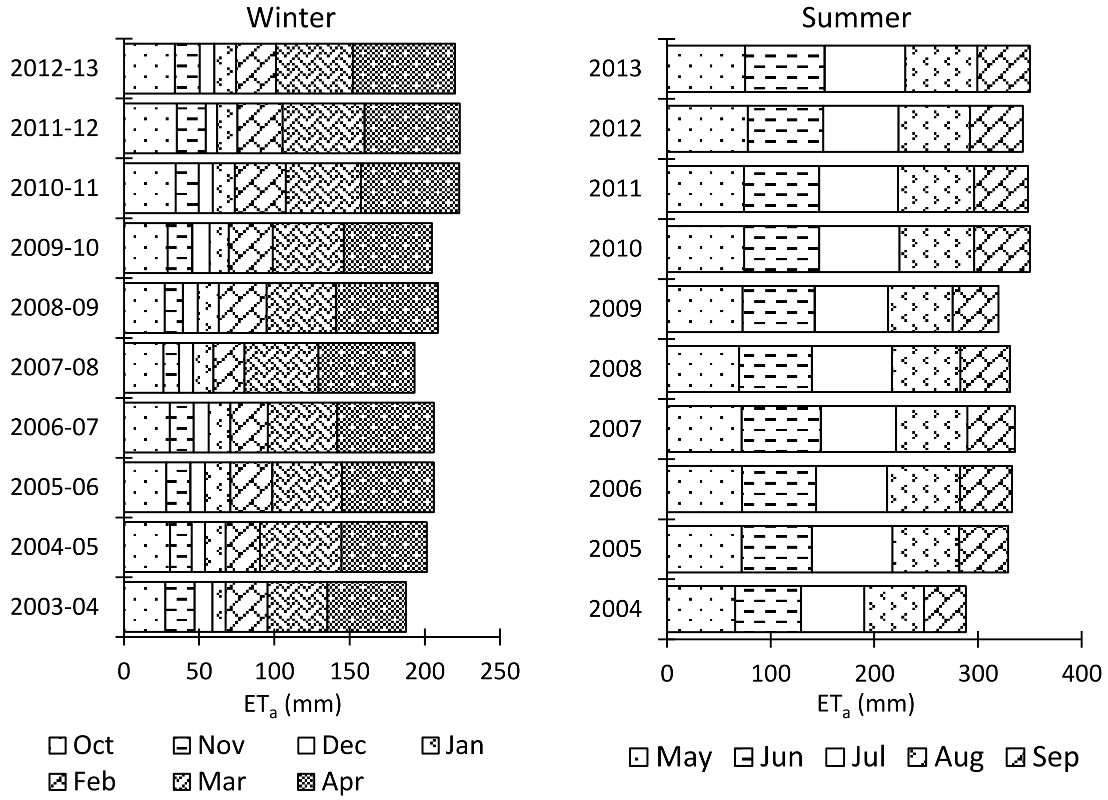


Figure 4.5: Monthly and seasonal variation of actual evapotranspiration during different years (2003-2013) across the Kabul River Basin

4.3.2 Estimation of actual evapotranspiration at subbasins of the Kabul River Basin (KRB) at different strategic time steps

Annual variation in actual evapotranspiration across the subbasins from 2003-2013

By applying the SEBS algorithm over the spatial subbasin administrative units (subbasins), the maximum mean annual ET_a across the KRB throughout the study period was observed in the Shamal and Kunar subbasins with 522 mm each (Figure 4.6), while the minimum value was estimated for the Chak aw Logar subbasin which was roughly 420 mm. The mean annual ET_a across the subbasin of the KRB was 486 mm with a standard deviation of ±45 mm; which can be explained by the heterogeneity in the physiographic attributes of the subbasins i.e. rainfall, temperature, elevation etc. In general, the maximum ET_a in all subbasins was observed in the months of May, June, July and August. These are the months which experienced the maximum temperatures throughout the study period. As visible from the below graph, the impact of the 2004 drought conditions is quite obvious in all subbasins of the KRB (Figure 4.6).

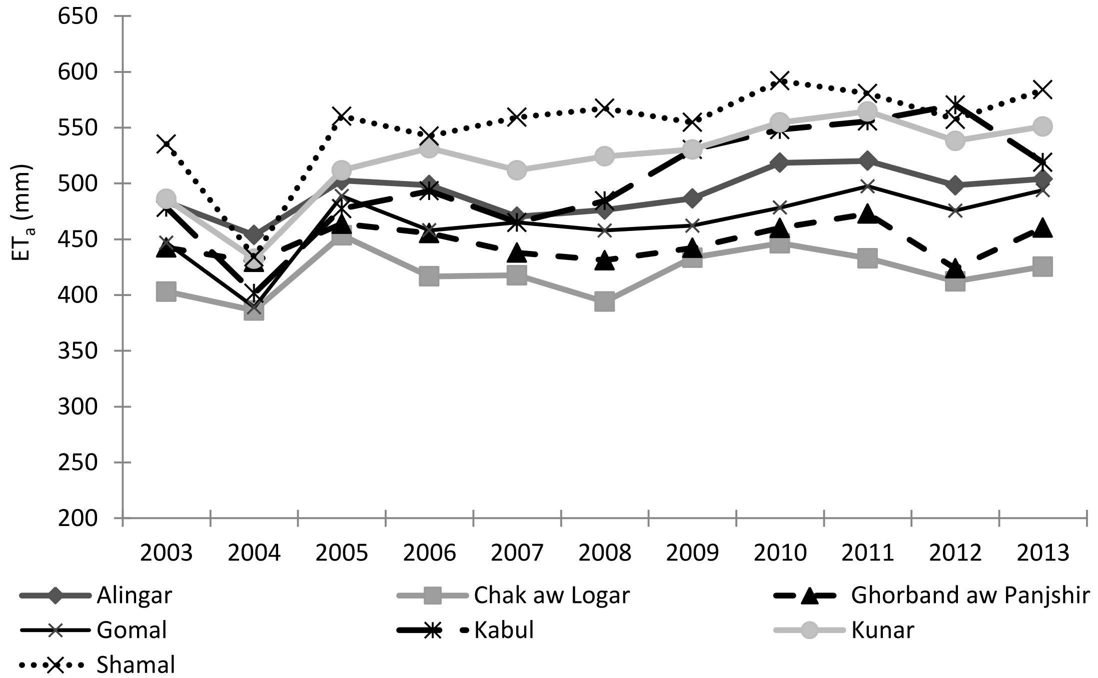


Figure 4.6: Annual variation of actual evapotranspiration in different subbasins of the Kabul River Basin 2003-2013

Monthly variation in actual evapotranspiration in the subbasins from 2003-2013

The average monthly variation in ET_a across the subbasins of the KRB (Figure 4.7) showed the lowest value (4 mm) throughout 2003-2013 in the month of January at the Chak aw Logar subbasin, while the maximum ET_a was experienced in Gomal and Shamal subbasin with 13 mm each. Throughout the study period the minimum monthly mean ET_a was experienced in the months of December (7±1 mm) and January (9±3 mm) across all the subbasins of the KRB. The highest decadal mean ET_a for all subbasins was in the months of May (67±5 mm), June (66±4 mm), July (68±6 mm) and August (62±8 mm).

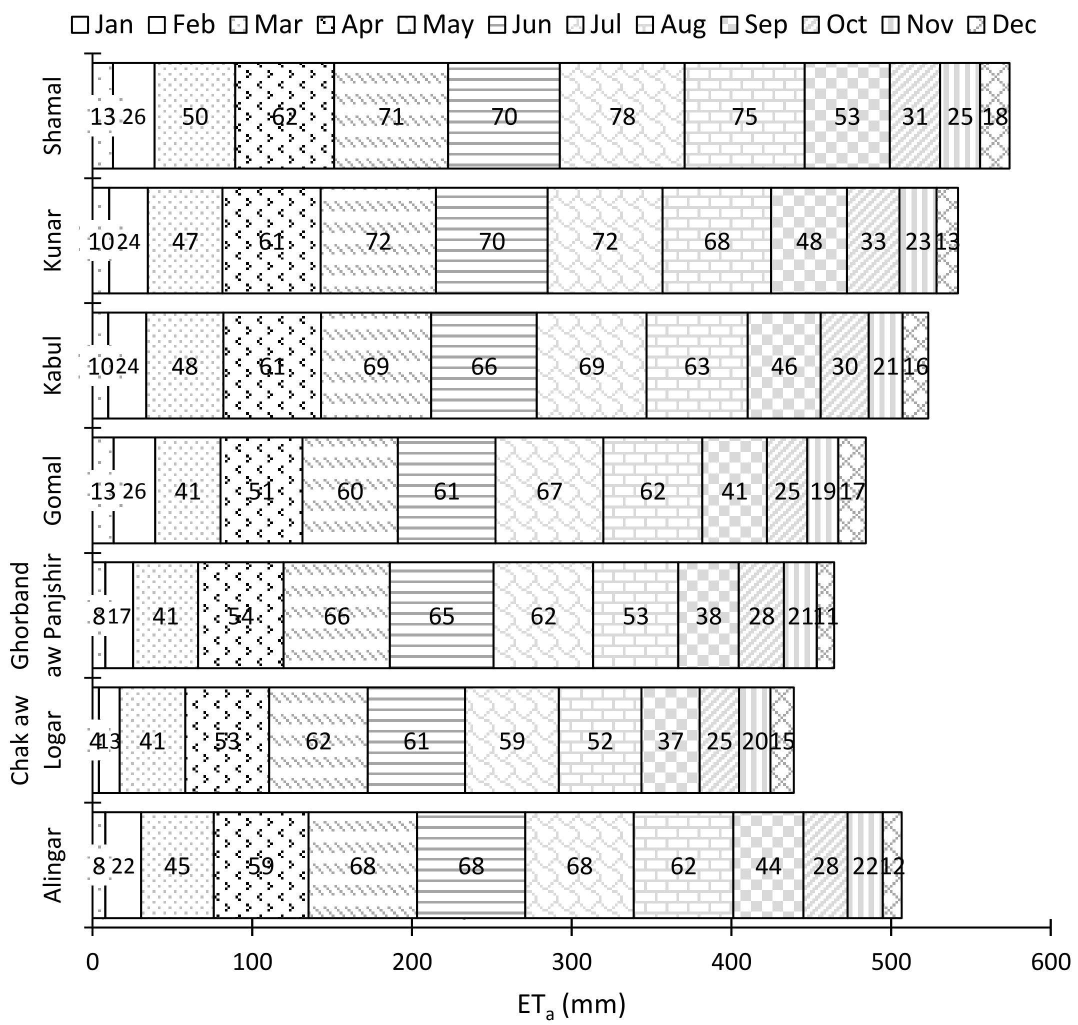


Figure 4.7: Mean monthly variation (2003-2013) of actual evapotranspiration in different subbasins of the Kabul River Basin

Seasonal variation in actual evapotranspiration across the subbasins from 2003-2013

The inter-annual seasonal-variability in the subbasins of the KRB showed a mean ET_a in the winter season in Alingar, Chak aw Logar, Ghorband aw Panjshir, Gomal, Kabul, Kunar and Shamal was estimated as (201±60 mm), (151±11 mm), (162±10 mm), (173±16 mm), (188±26 mm), (193±15 mm), and (201±16 mm) respectively. For the summer season, the mean ET_a estimates were (311±12 mm), (271±12 mm), (287±11 mm), (292±16 mm), (316±29 mm), (332±25 mm) and (351±29 mm), respectively (Figure 4.8).

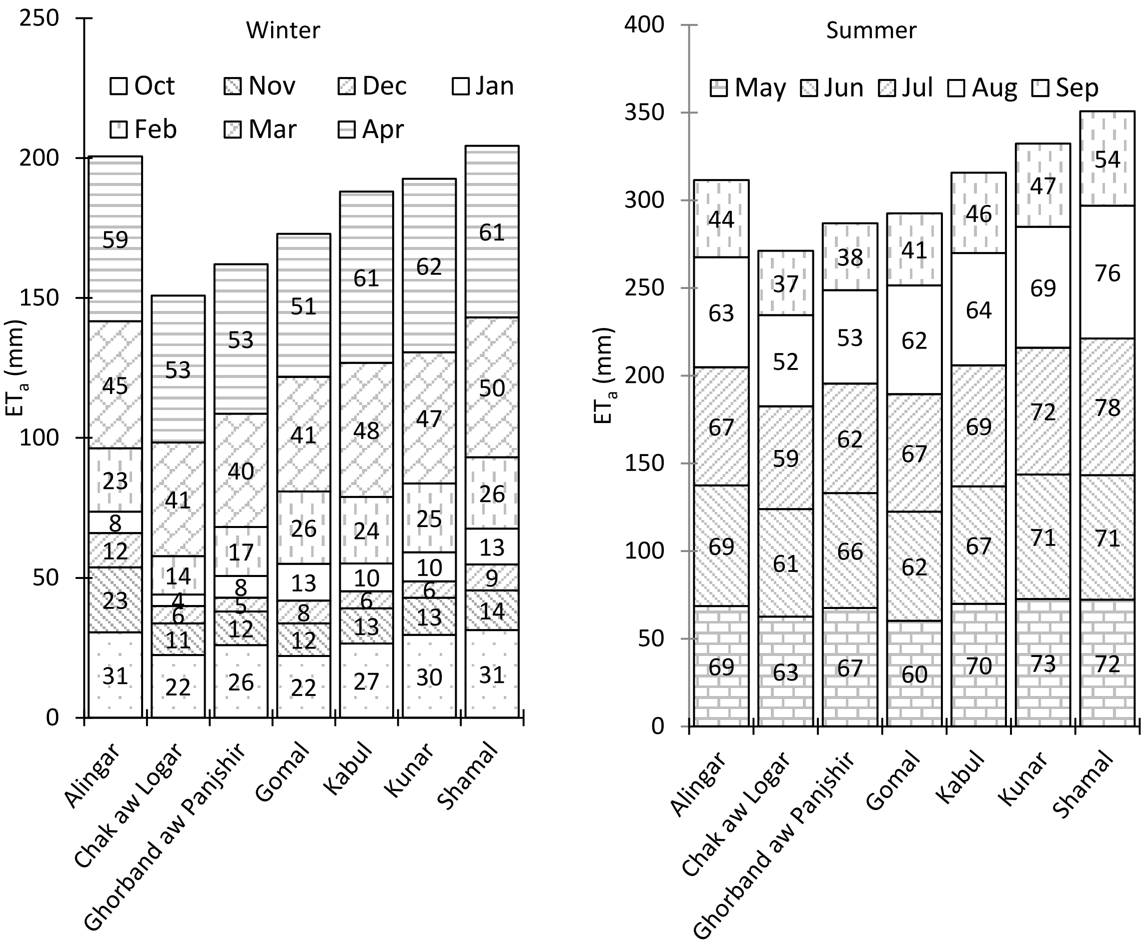


Figure 4.8: Mean seasonal (2003-2013) variation of actual evapotranspiration in different subbasins of the Kabul River Basin

4.3.3 Estimation of actual evapotranspiration across the provinces of the Kabul River Basin in different strategic time steps

Annual variation in actual evapotranspiration across the provinces of Kabul River Basin from 2003-2013

At provincial level the decadal mean maximum and minimum annual ET_a throughout 2003-2013 was observed in Kunar (546 mm) and Panjshir (353 mm) provinces (Figure 4.9). Within this period the mean minimum annual ET_a across all the provinces of the KRB in 2004 was 406±28 mm. This overall lowest ET_a is due to the fact that Afghanistan was hit by a severe drought in that year (WFP, 2004) and therefore lost most of its cultivated crops and livestock.

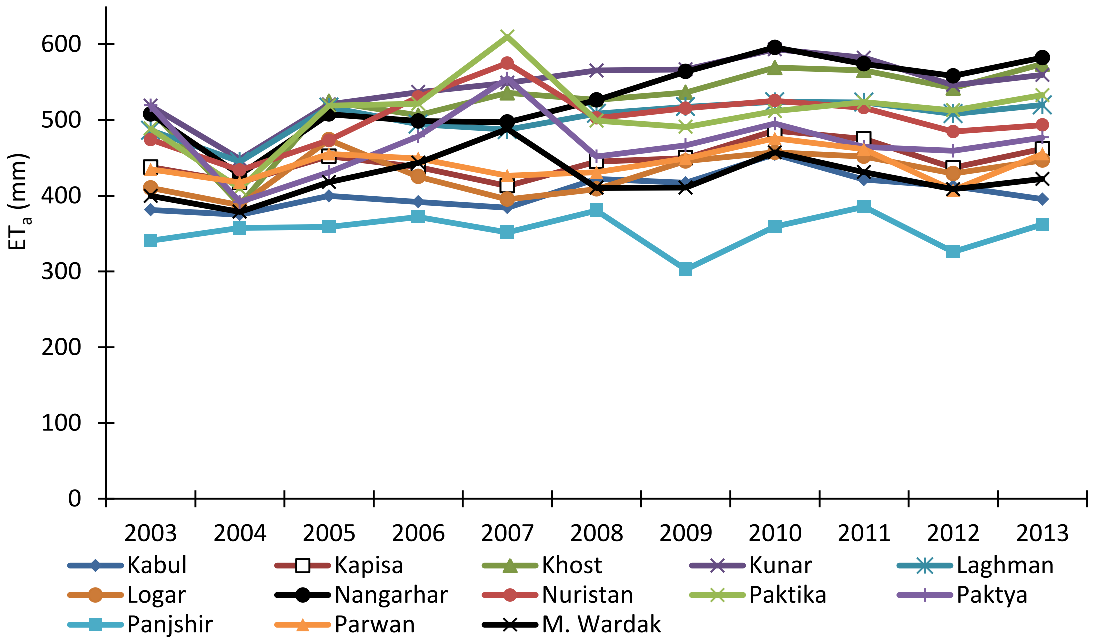


Figure 4.9: Annual variation (2003-2013) of actual evapotranspiration across provinces of the Kabul River Basin

Seasonal variation in actual evapotranspiration across the provinces of Kabul River Basin (KRB) from 2003-2013

Analysis of the season temporal behavior showed that in winter season Kunar, Khost and Nangarhar provinces experienced the highest mean ET_a of 196 mm 193 mm and 192 mm respectively throughout the study period while Panjshir province experienced the least ET_a of 85 mm. Similarly, in summer season, Kunar and Nangarhar provinces experienced the highest mean ET_a of 351 mm and 340 mm respectively, the reason behind this is the large irrigated areas with crop rotation in these provinces. The least ET_a in summer season was experienced by Panjshir (268 mm) and Kabul (270 mm) provinces (Figure 4.10-4.11).

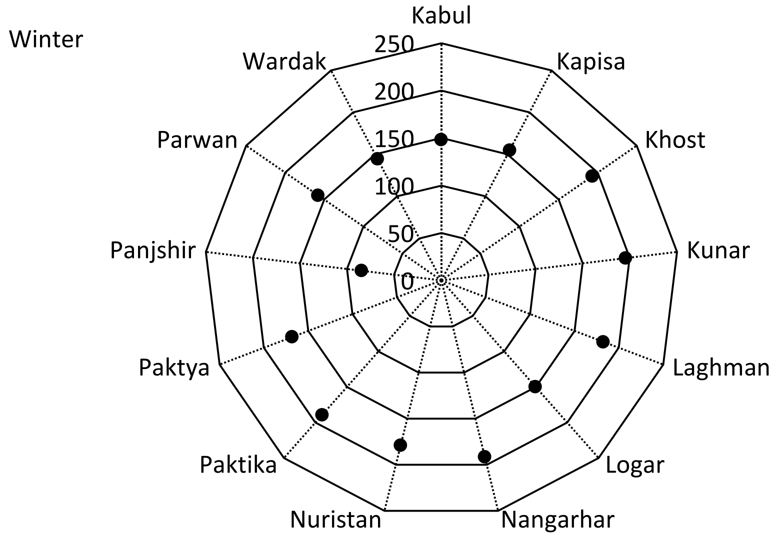


Figure 4.10: Mean seasonal annual 2003-2013 variation of actual evapotranspiration (mm) during October-April (winter) across the provinces of the Kabul River Basin

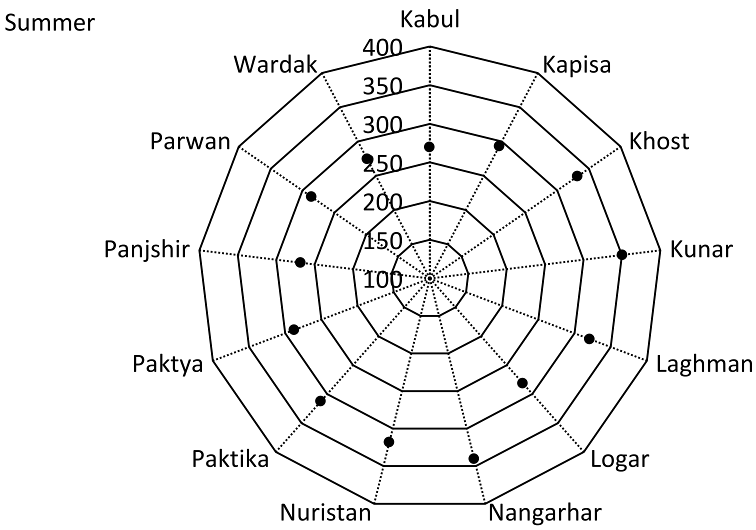


Figure 4.11: Mean seasonal annual (2003-2013) variation of actual evapotranspiration (mm) during May-September (summer) across the provinces of the Kabul River Basin

Another study (Senay et al., 2007) estimated 570 mm as the seasonal ET_a (May-September) as an average of 3 years (2003-2005) for the Kabul province. This is in distinct contrast to estimates of the current study amounting to only 259 mm for a 2003-2013. High level of ET_a estimations in the Kabul province by Senay et al. (2007)

may be due to tendency of SSEB to overestimate ET_a both at local and regional scales probably due to rainfall contributions and abundant soil moisture that naturally supplement crop water needs (Maupin et al., 2012).

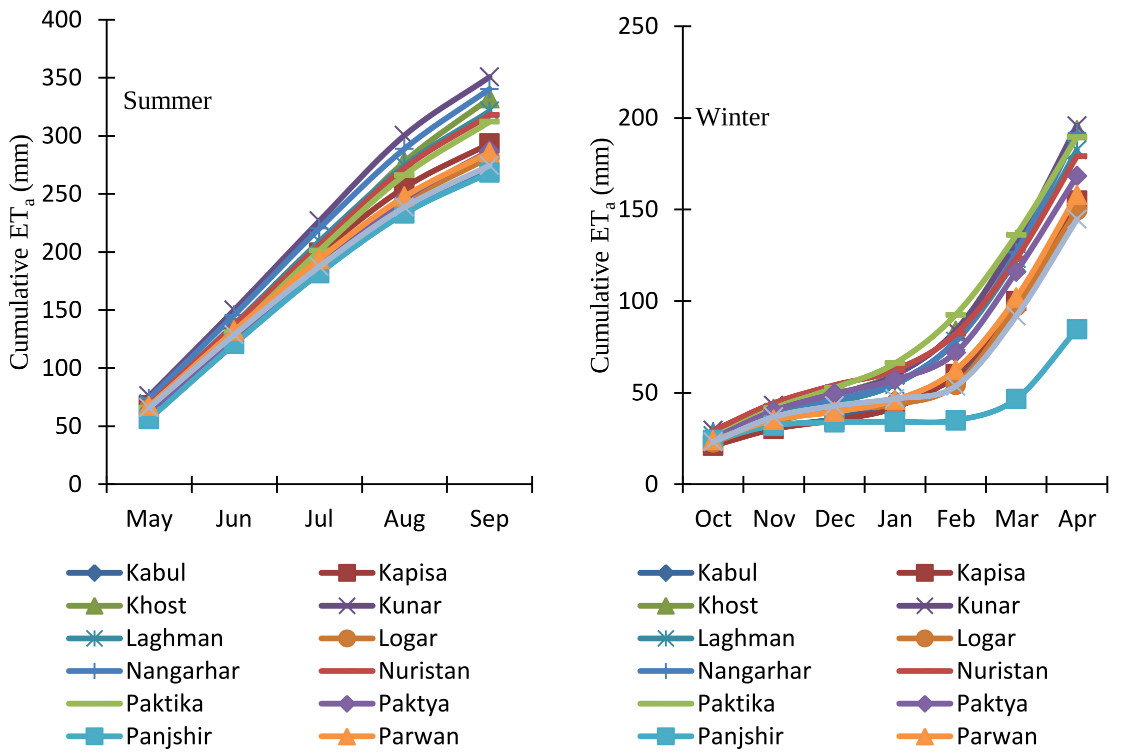


Figure 4.12: Cumulative behavior of mean season-annual (2003-2013) actual evapotranspiration (mm) in different provinces of the KRB during summer and winter seasons

The cumulative behavior of the ET_a shows that the mean annual (2003-2013) values for the summer and winter seasons were 303±28 mm and 165±30 mm respectively (Figure 4.12). The steep curve for cumulative ET_a of Panjshir province shows the sudden rise of temperature from the month of March as a result of which snowmelt which then contributes to the irrigation regime along different irrigated zones of the KRB.

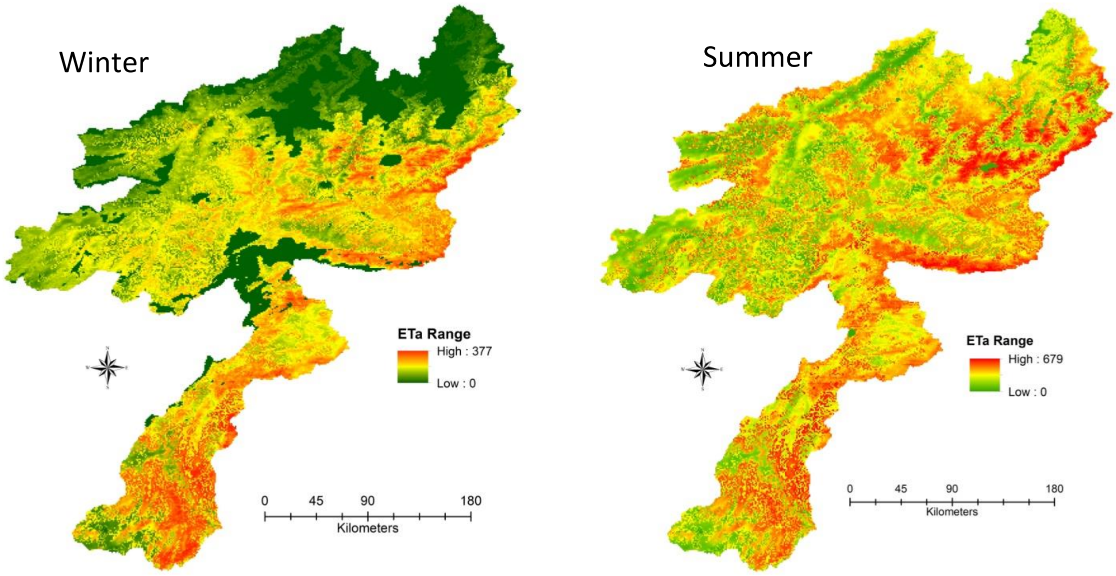


Figure 4.13: Distribution of actual evapotranspiration (mm) during winter (October-April) and summer (May-September) 2012-2013

There was a uniform trend in the summer season (May-September) while in the winter season (October-April) due to the lower temperatures, as one of the main drivers of evapotranspiration, ET_a values are lowest (Sobrino et al., 2007). An inter-seasonal comparison of ET_a in summer and winter (Figure 4.13) reveals a higher range of ET_a in summer 2013 compared to that in winter 2012-2013. The reason is the diversity and abundance of crops, vegetables and fruit orchards mostly in the summer season while winter is limited to fewer crops and is mostly dominated by wheat and barley.

4.3.4 Land cover based variation of ET_a across the Kabul River Basin (KRB) from 2003-2013

Throughout the KRB individual land cover based ET_a was estimated using the LULC map of the basin developed in this study. The results show a high ET_a in the areas with maximum precipitation that usually falls in the months of November-March which has been used in the peak irrigation period with various frequencies (Figure 4.14).

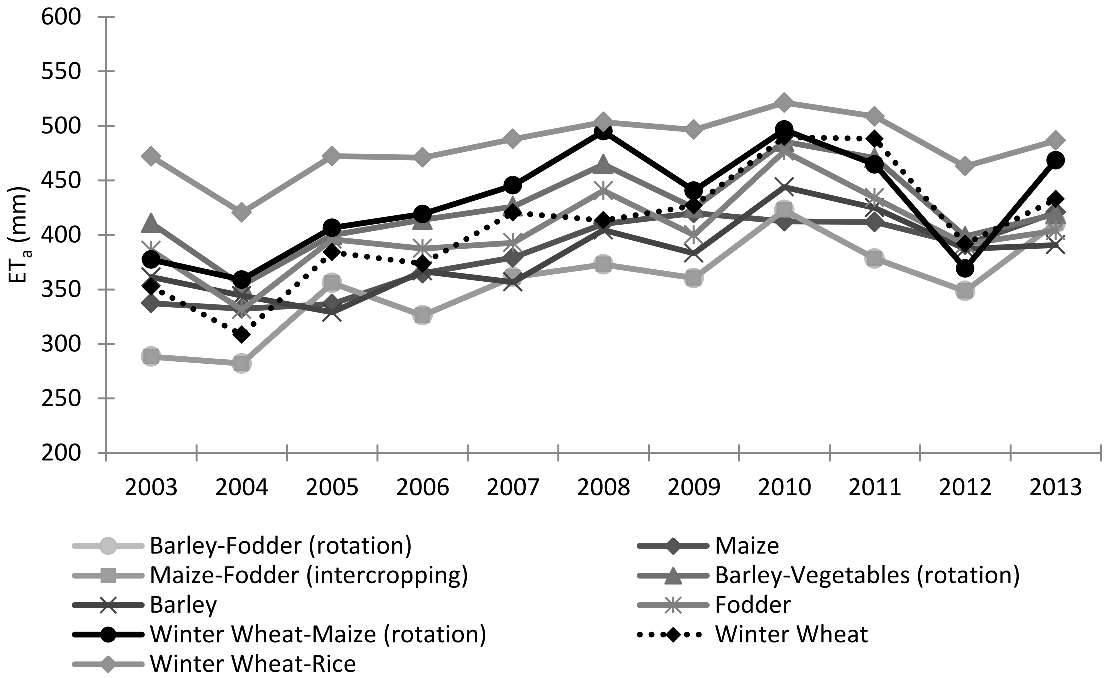


Figure 4.14: Land cover based distribution of actual evapotranspiration (ET_a) of main cereals across the Kabul River Basin 2003-2013

Among crops, wheat is the most highly consumed and cultivated crop in the whole country especially in the KRB (CSO-IRoA, 2014). Wheat is normally cultivated in rotation with maize and rice mostly in downstream of the KRB while in the central KRB. It is cultivated solely alongside fruit orchards in contrast to the downstream regions. Therefore, from 2003-2013 the average annual ET_a of wheat-maize, wheat-rice and wheat alone across the KRB was 468, 486 and 433 mm, respectively during 2003-2013.

For wheat, results from the neighboring Uzbekistan show ET_c values for wheat (Awan et al., 2014) and maize (Akhtar, 2011) of 397 and 317 mm respectively. The ET_a from maize, the second major crop grown in the KRB in rotation with corn production as well as for fodder intercropped with other fodder crops, was 421 mm (maize) and 411 mm (maize intercropped with fodder). The ET_a from poppy production was estimated to be 533 mm (poppy alone) and 463 mm (poppy in rotation with vegetables). Wheat, maize, poppy and vegetables are commonly grown in the eastern provinces where irrigated lands are more widespread.

4.3.5 Correlation and evaluation of the ET_a estimated through SEBS and AA Model

As mentioned in the previous section, the KRB has typically been suffering from data scarcity and therefore dependency on the remote sensing data during this study stands to reason. Yet, in order to build any opinion upon the results of the ET_a estimated through SEBS model, it is important to assess its accuracy through another method or otherwise physically observed data from the field. For this reason, ET_a estimated through SEBS and that of AA model were correlated (Figure 4.15). There has been a sound fitness between the ET_a estimated through SEBS and ET_a estimated through AA at Kunar and Nangarhar provinces; the coefficients of determination thus obtained were R^2=0.81 and R^2=0.77 respectively. The slight deviation in ET_a from the 1:1 line could be attributed to the spatial variability and resolution of the GLDAS data (25 km^2) used for SEBS model while the input data used for AA model has been very much location-specific and therefore deviation to some extent is observed. It is shown below that the cool months around the year, the ET_a values of AA model are lower than those of SEBS. The reason behind is that the AA model, uses a form of the Penman equation which does not work fine for those periods for which the available energy (R_n) is negative or otherwise very close to zero. A similar result has been obtained from the study of Xu and Singh (2005) whereby they estimated ET_a through Complementary Relationship Areal Evapotranspiration (CRAE) and AA models which resulted into lower values by using AA model against those of CRAE in the cool months of winter. The study of Liaqat et al., (2014) in the Indus Basin also shows that the ET_a calculated through AA was lower in the cool months of winter (October to March) compared to ET_a estimates through SEBS for the same period. According to Yang et al., (2016), AA model yields lower value of ET_a under high precipitation conditions which goes in line with the result of this study

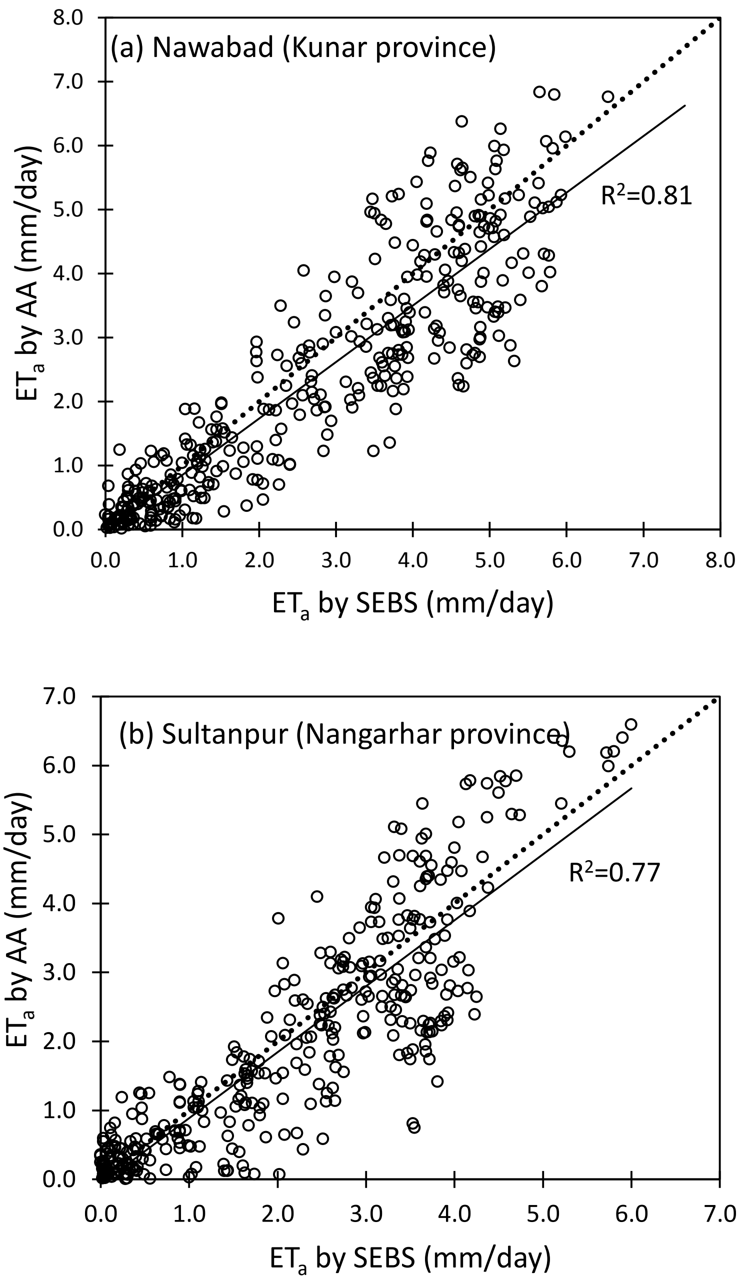


Figure 4.15: Comparison of the ET_a estimated through SEBS algorithm and AA model in Kunar (a) and Nangarhar (b) provinces of the KRB

4.3.6 Defining the actual evapotranspiration-NDVI relationship of major land cover classes

There is strong correlation between the physiological status of plants and NDVI. NDVI values extracted from the remotely sensed data can be utilized to define different crop development stages as described in the adopted crop calendar (Groten, 1993) providing there is no restriction from water availability to the crops (Seevers and Ottmann, 1994). Vegetation water content being an important parameter in agricultural application and is of paramount importance for assessing drought risks (Peñuelas 1994). According to Tucker (1979), NDVI can also be employed for the estimation of water content in plants and grasses. According to Ceccato (2001) the NDVI provides information about leaf chlorophyll content which is assumed to be in direct relation to leaf water content. There is least change in NDVI values until the soil water content deficit becomes severe (Seevers and Ottmann, 1994). Ritchie et al. (1976) report that evapotranspiration of grassland becomes limited when 75 % of available soil moisture content has been depleted (allowable depletion) which supports the argument that unless there is a severe shortage of soil moisture there is no major shift in the NDVI behavior. In other words, there is a direct relationship between a healthy crop’s NDVI and evapotranspiration (Figure 4.16). The crop development stage is usually defined by the phenology-driven crop’s NDVI curve and so is the case of evapotranspiration under normal conditions.

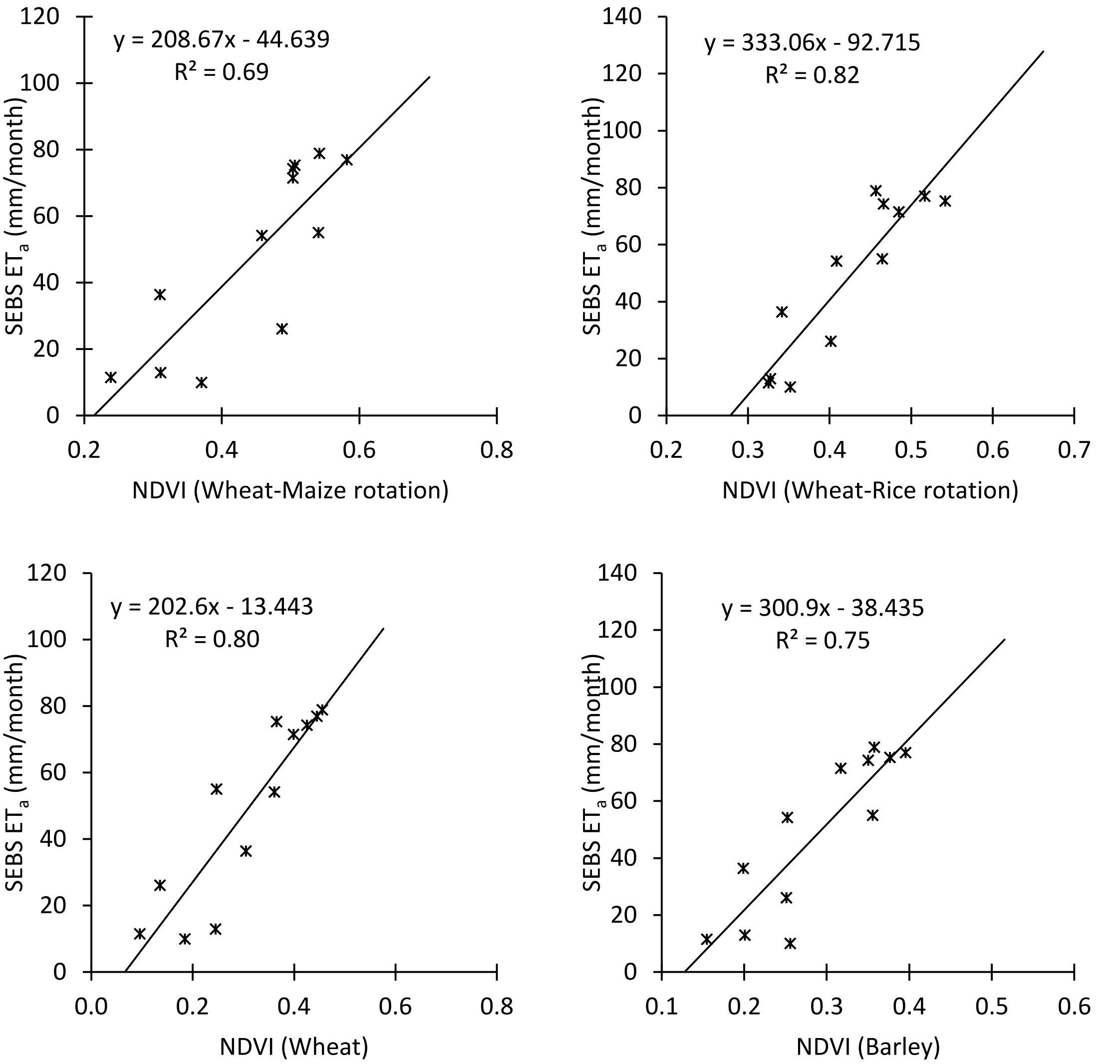


Figure 4.16: Relationship of SEBS actual evapotranspiration (ET_a) with NDVI of major crops in the Kabul River Basin

In the KRB, the major crops, wheat, maize, rice and barley often cultivated in rotation in most areas show a strong correlation between their respective ET_a and NDVI (Figure 4.16). The coefficient of determination (R^2) of the relation between NDVI and ET_a of wheat-maize rotation, wheat-rice rotation, wheat and barley was 0.69, 0.82, 0.80 and 0.75 respectively. This clearly highlights the coherence of NDVI and actual evapotranspiration. Among above-mentioned cropping pattern, R^2 value for wheat-rice rotation and wheat alone (irrigated) are 0.82 and 0.80, respectively, which reveals that the evapotranspiration and NDVI relationship is stronger in case of irrigated crops.

4.3.7 Effect of climatic variables on actual evapotranspiration

Relationship of rainfall and actual evapotranspiration

Analysis of precipitation in relation to evapotranspiration is essential for water balance estimation and in turn on water resources management. Precipitation is one of the key drivers for the evapotranspiration amount leaving the soil and plant canopy surface. Rainfall is sometimes used as proxy for evapotranspiration predictions (Collischonn and Collischonn, 2016). Rainfall is the primary source of water for agricultural production for large parts of the world; it is being characterized by its amount, distribution and intensity. The effective rainfall/precipitation is one of the main inputs to the soil that is being up-taken by plant for transpiration through its canopy as well as evaporation from the soil surface. Beside rainfall, the soil storage characteristics also play a key role in influencing the rate of evapotranspiration due to the fact that the crops' ET response follows directly the soil moisture and indirectly the precipitation.

In the KRB most of the precipitation occurs in winter with occasional monsoon showers in the east (downstream) of the country. The available precipitation (mostly in the form of snow in case of upstream heights) occurs in the month of November onwards which is stored over the mountainous peaks and melts down to runoff from April-August which coincides advantageously with the peak irrigation season and contributes therefore appropriately to provide the base for local food production. In order to show the relationship between rainfall and actual evapotranspiration, data from the year 2013 from downstream province (Sultanpur-Nangarhar) is presented below (Figure 4.17):

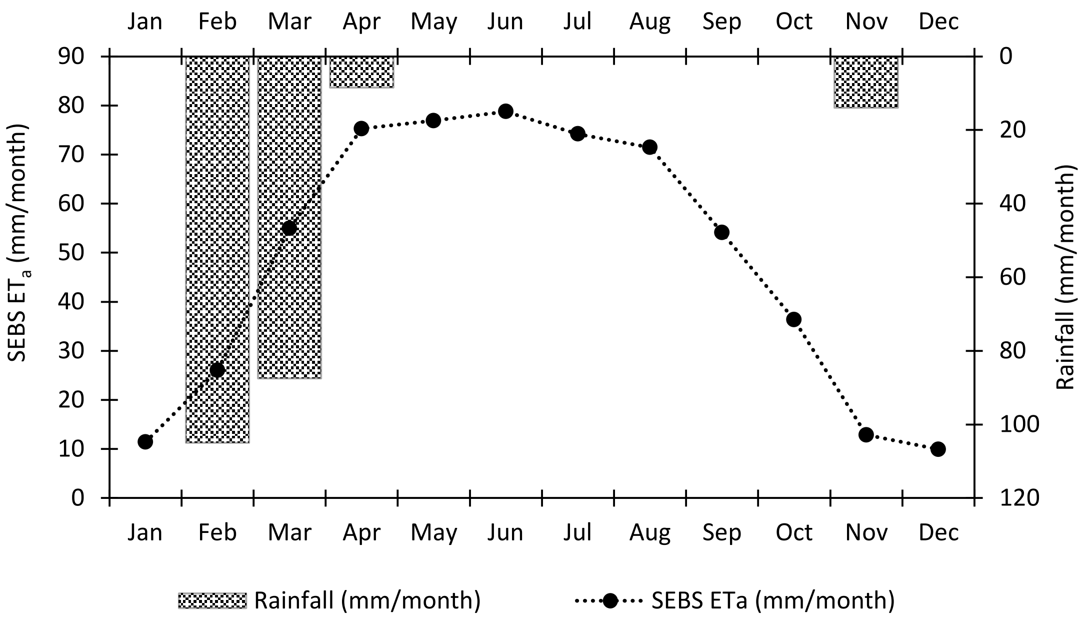


Figure 4.17: Effect of rainfall on actual evapotranspiration (ET_a)-an example from Nangarhar province (downstream KRB) in Afghanistan (data from 2013)

In February, the KRB received an average 105 mm of precipitation to which ET_a responded with 26 mm, while 87.5 mm received in March where the ET_a was almost double (55mm) mainly as a consequence of higher temperatures.

Relationship of temperature and actual evapotranspiration

The ET_a in the KRB is highest typically in April-August where most of the irrigation takes place from the river and canal network supplies thereby contributing to the evapotranspiration amount. The highest temperature recorded in 2013 was in June ($32C^0$) and July ($34C^0$) triggering 78 and 74mm ET_a respectively (Figure 4.18).

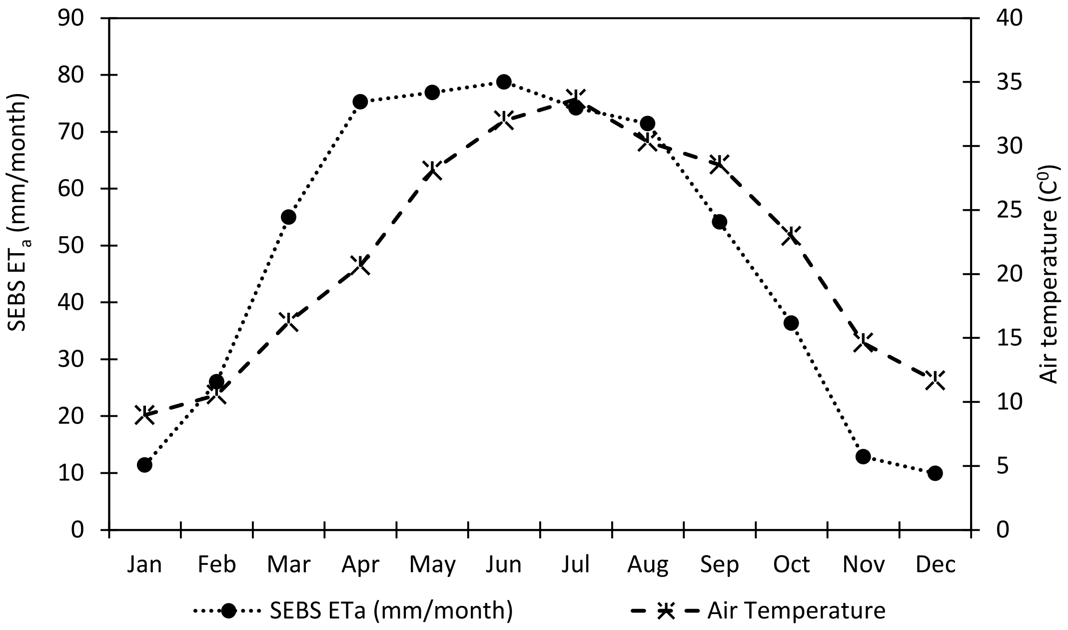


Figure 4.18: Effect of temperature (C^0) on actual evapotranspiration (ET_a)- an example from Nangarhar province (downstream KRB) of Afghanistan (2013)

Relationship of wind speed and actual evapotranspiration

The mean wind speed, being central to the evaporative demand, throughout 2013 was 2m/s while the maximum wind speed (2.5m/s) was recorded in December and January. Although higher wind speed tends to raised ET, the ET_a was least in these months owing to the highest wind speed. This can be explained firstly by a rather small increase in wind speed in the December-January period, and secondly by the fact that the lowest temperatures in these months influence ET_a with bigger magnitude and reverse tendency (towards lowering) (Figure 4.19).

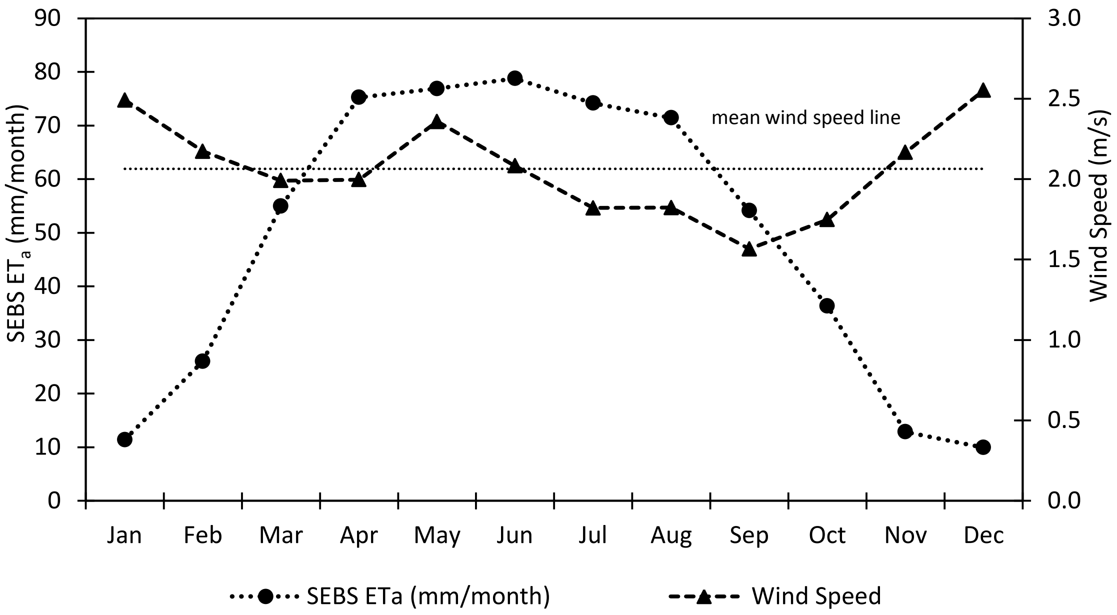


Figure 4.19: Effect of wind speed (m/s) on actual evapotranspiration (ET_a) - an example from Nangarhar province (downstream KRB) in Afghanistan (2013)

Relationship of relative humidity and actual evapotranspiration

Solar radiation is the main energy source and is capable of changing large quantities of liquid water into vapor state. The radiation amount that can reach the surface is determined by the geographic location of the surface and time of the year (Allen et al., 1998). In the KRB, the higher evapotranspiration in the months of April-August is mainly the result of lower relative humidity in these months. The sudden rise in relative humidity from August onwards shows the relative dependency of humidity on air temperature. If the water vapor content stays the same and the temperature drops, the relative humidity increases. It is evident from Figure 4.20 considering that there is steady drop in temperature from the months of August till January of the following year. If the water vapor content stays the same and the temperature rises, consequently the evapotranspiration rate increases while the relative humidity decreases and is the minimum in June-July whereby these are the hottest months of the year in Afghanistan.

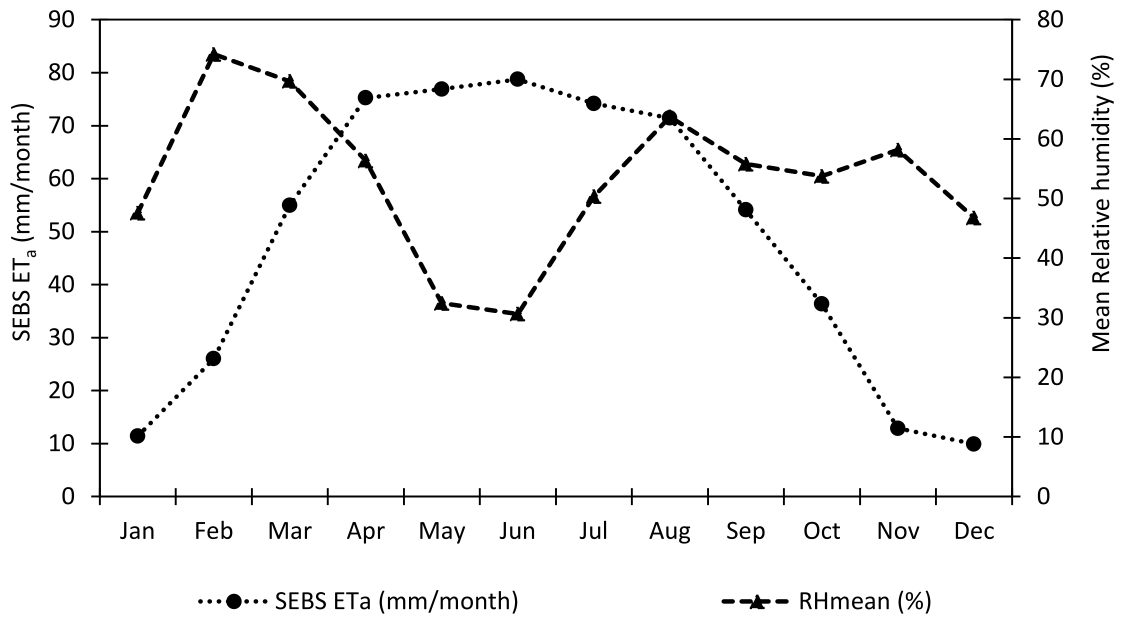


Figure 4.20: Effect of mean relative humidity (%) on actual evapotranspiration (ET_a)-an example from Nangarhar province (downstream KRB) in Afghanistan (2013)

5 ESTIMATION OF STREAMFLOW BY USING SWAT MODEL FOR ASSESSING WATER AVAIBILITY

5.1 Introduction

Afghanistan has an arid to semi-arid climate receiving inconsistent precipitation over the years. Precipitation varies from a low values in the west (Farah province) to highest magnitude in the south Salang pass in Hindu Kush Mountains. It fells mostly in the winter months especially in the February-April period. The wet season is associated with winter having frequent snowfalls while spring experiences dominant rainfalls at times when the vegetative cover is very low. The overall precipitation (in addition: its temporal distribution and intensity) is crucial for streamflow, groundwater recharge and irrigation water availability for summer cropping. At elevations above 2,000 m, winter precipitation generally represents around 80% of the country's water resources (without fossil groundwater). The amount of precipitation (water) received at these elevations is approximately 150 km^3. The rest of the country gets only 30 km^3 through rainfall, resulting in a total of 180 km^3 for the whole country (FAO, 1996; Aini, 2007). Due to above-mentioned spatio-temporal rainfall distribution, natural hydrographs in Afghanistan reach their maximum peaks in the spring and early summer seasons while a minimum flow is observed is in late summer to winter over large areas of the country. During this time many rivers dry up along sections of their course or are reduced to isolated pools during the minimum-flow period which is generally not sufficient to fulfill the crop water requirements (Petr 1999). This natural condition highlights the influence and significance of the coverage and thickness of the snow cap for crop production.

The total cultivable area in Afghanistan is around 12 % of its total land area out of which around 46% is irrigated while the remaining 54% is rainfed (World Bank 2016). Major arable lands for permanent crops are located in the North and South parts of the Country. The coverage of both irrigated and rain-fed cultivation varies depending on the extent of the snowfall in winter and rainfall during the cropping season. At present, around 99% of the current water use in the country has been solely accounted for irrigated agriculture which produces up to 85% of total agricultural outputs (Qureshi, 2002). It is therefore evident that the lack of irrigation water, diverted, is the primary constraint to agricultural productivity especially in countries like Afghanistan where the major water infrastructure has been destroyed by war in the past decades (FAO, 2015c).

At present, the Overall scheme efficiency (including field water application efficiency and network efficiency) is approximately 25% (Kelly, 2003) across the country which highlights major losses in the surface water supplies diverted from the rivers and canal network. The demand for water has grown tremendously amid a growing population and inter-sectoral competition and is expected to rise in the years ahead (Kelly, 2003) due to forecast continuation of these trends and – in addition – impacts by climate change enhancing water demand. Meanwhile, it is concurrently assumed that most likely Afghanistan will be water scarce country by 2030 having renewable water resources below the threshold (1500 m^3/capita/year) (Yang et al., 2003); (World Bank, 2013). Irrigated agriculture with enhanced water use efficiency is therefore vital for sustainable food production to feed the growing population with diversified nutrients' demands. Currently, in Afghanistan more than 7 million people are hit by food insecurity out of which 2.1 million suffer from severe food insecurity (UCDAVIS, 2013). Developing water resources and enhancing the productivity of irrigated agriculture are thus paramount to sustaining economic growth and addressing rural poverty. The major corridors for enhancing water use efficiency in irrigated agriculture are to raise the output per unit of water consumed, reduce water losses and reallocate water to higher priority use sectors (Howell, 2001).

The Kabul River Basin, part of the wider Indus River system shared with Pakistan encompasses around 12 % of Afghanistan's territory and accounts for about 26 % of Afghanistan's total annual river flow (World Bank, 2010). Yet, data and information on Afghanistan's land and water resources are scarce or otherwise outdated (Mack et al., 2010a) and require extra care for use in extensive planning and management. The poor quality and quantity of the land and water resources data highlights the need of fundamental research at different river basins in the country in order to quantify land and water resources and perform technical analyses for the management and development of these tremendous and valuable natural assets. Therefore, within the scope of this study, the water availability in the KRB, except the groundwater aquifer holding, was quantified through the rainfall-runoff model which is an integral part of the SWAT model (Soil Water Assessment Tool).

There are several models available for streamflow simulations. SWAT model is selected in this study because of its applicability, performance and reliability proven under a huge number of applications under different climatic settings globally. The SWAT model has been used in the quantification and estimation of various ecosystem functions and services (Francesconi et al., 2016) which contribute to different categories of ecosystem services in terms of regulating, cultural and provisioning etc. For example, SWAT model was used for the quantification of sediment yield (Arias et al., 2011), assessment of the water quality (Baker et al., 2015 and Bekele et al., 2005) and water quantity (Jujnovsky et al., 2012) etc. Moreover, SWAT model has been proven to be very effective in case of data-scarce river basins (Nyeko, 2014), which could be very well compared to KRB. Ndomba et al. (2008) suggests the suitability of the SWAT model for identifying hydrological controlling factors/parameters in ungauged catchments. The results thus add value to the reliable application of SWAT model at data-scarce complex river basins. Another motivation behind the use of SWAT model was its capability to capture monthly flow trends a wide range of catchment characteristics and locations (Mutenyo et al., 2015).

The surface water availability quantified, validated and calibrated under this study at hydrological stations will provide a base for the future investment plans aimed at agricultural area expansion, increasing land and water productivity as well as inter-sectoral water distribution across the KRB.

5.2 Materials and methods

5.2.1 Study area

The KRB administratively consists of seven subbasins. Among these subbasins, two subbasins namely, Gomal and Shamal are not located within the hydrological watershed of the KRB but are part of the KRB in large due to administrative and accessibility reasons. The KRB (without Gomal and Shamal subbasins) stretches out from the central highlands of the country to the eastern valleys of Kunar, Nangarhar and Nuristan provinces covering a land area of 52,888 km^2 (Figure 5.1, see also Chapter 2).

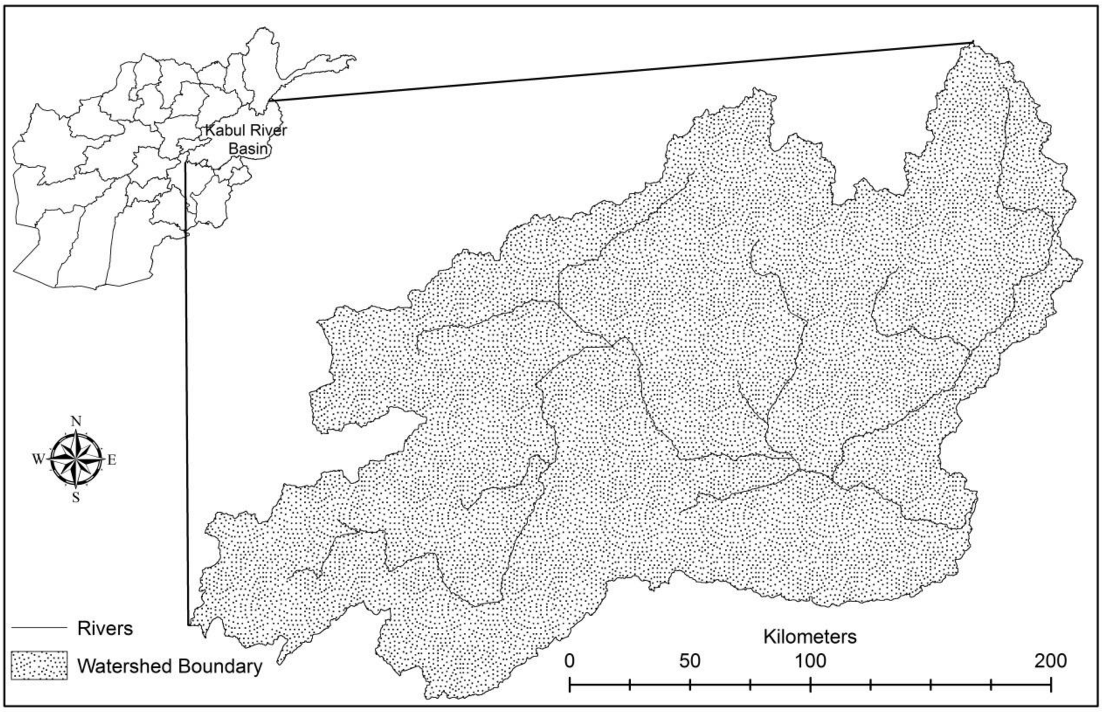


Figure 5.1: Study area map with its major rivers' network

The KRB discharges west to east into the larger Indus basin in the Khyber Pakthukhwa province across the Durand-line. The main rivers' web which constitute the Kabul River Basin are the rivers Kunar, Landai Sind and Pech originating in Kunar province, the rivers Laghman and Alingar rivers in Laghman province, the rivers Panjshir and Shatul in Panjshir province, the rivers Ghorband and Salang rivers in Parwan, river Paghman in Kabul, river Logar in Logar province and river Surkhrud in Nangarhar province. There are several other seasonal streams and small rivers in the KRB but during the automatic delineation in SWAT, these rivers were not delineated due to the limitation of the coarse resolution (90m) of the digital elevation model (DEM) (Rahman et al., 2010).

5.2.2 Conceptual Framework

A conceptual framework (Figure 5.2) has been established to simulate the rainfall-runoff on monthly basis at the targeted monitoring points for the entire KRB. The main processing engine used for this purpose was SWAT model (Arnold et al., 1998). The model parameterization setup involves major six steps that have to be carried out for required variables' simulation including the preparation of input data, discretize the subbasins, definition of the hydrological response units (HRUs), sensitivity analysis of the parameters, calibration and uncertainty analysis and –in a last step - validation of the simulated data.

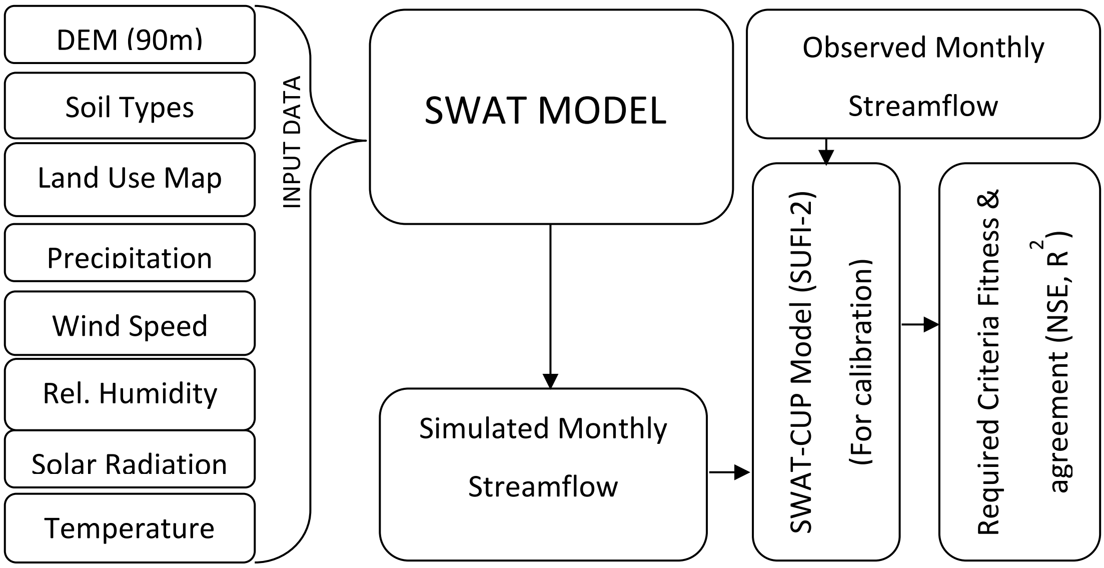


Figure 5.2: Conceptual framework for the streamflow quantification at Kabul River Basin

Description of the SWAT model

The Soil and Water Assessment Tool (SWAT) is a sophisticated and widely used continuous-time simulation model for simulation of water, sediment, pesticides and nutrient transport at basin level. The model has been used for diverse analyses ranging from the effect of climate (Awan and Ismaeel, 2014; Uniyal et al., 2015; Awan et al., 2016; Carvalho-Santos et al., 2016) and land use change (Lamparter et al., 2015; Lin et al., 2015), and impacts of land management practices in complex and large watersheds (Arnold et al., 1998; Setegn et al., 2008; Abbaspour et al., 2015). It has also been used for other different management scenarios on streamflow, nutrient and sediment transport (Verma et al., 2015) and soil erosion (Schiffer et al., 2015). In addition to these themes, SWAT model also incorporates runoff estimation and water demand analyses (Tibebe et al., 2016).

Water balance is the basic approach used for quantifying any process studied with the SWAT model irrespective of the nature of the problem. The SWAT model simulations are based on the water balance equation of the soil water content. The mathematical expression is given as (Neitsch et al., 2005):

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right) \qquad \text{Equation (5.1)}$$

where:

SW_t is the final soil water content (mm)

SW_0 is the initial soil water content on day *i* (mm)

t is the time (days)

R_{day} is the amount of precipitation on day *i* (mm)

Q_{surf} is the amount of surface run off on day *i* (mm)

E_a is the amount of evapotranspiration on day *i* (mm)

w_{seep} is the amount of water entering the vadose zone from the soil profile on day *i* (mm); The “vadose zone” is the unsaturated part of earth between the land surface and the top of the phreatic zone (zone of saturation) The vadose zone extends from the top of the ground surface to the water table and

Q_{gw} is the amount of return flow on day *i* (mm)

For estimation of the surface runoff (Q_{surf}), the SWAT model considers the following Soil Conservations Service (SCS) curve number equation (USA-SCS, 1972):

$$Q_{surf} = \frac{(P_e)^2}{(P_e + S)} \qquad \text{Equation (5.2)}$$

where P_e *(mm)* is the depth of effective precipitation and is calculated as $P_e = (R_{day} - I_a)$,
R_{day} is the rainfall depth for the day (mm),
I_a is the initial abstraction which includes surface storage, interception and infiltration prior to runoff (mm), and
S is the retention parameter or depth of effective available storage in the watershed when runoff begins (mm).

Due to the changes in soils, land use, management and slope, there are spatial variations in retention parameters while temporal variation in retention parameters is due to the changes in soil water content. The retention parameter is included in the above equation is defined as:

$$S = 25.4\left[\frac{1000}{CN} - 10\right] \qquad \text{Equation (5.3)}$$

where CN is the curve number for the day and a function of the land use, soil permeability and antecedent soil water conditions.

The initial abstractions, I_a, is commonly approximated as 0.2S. Thus equation (5.2) becomes:

$$Q_{surf} = \frac{(\mathrm{R}_{day} - 0.2\mathrm{S})^2}{(\mathrm{R}_{day} + 0.8\mathrm{S})} \qquad \text{Equation (5.4)}$$

In this situation, runoff only occurs when $R_{day} > I_a$.

Model Inputs

Watershed delineation

One of the initial processes involved in the model set up is the delineation of the rivers, river basin and its subbasins. The SWAT model, being deterministic in nature and a mainly physically-based model, uses the ArcGIS interface which derives topography, contour and slope from a digital elevation model which enables to divide the entire watershed into several subbasins. These subbasins are then further subdivided into hydrological response units (HRUs) which consist of homogeneous land-use, management and soil characteristics leading to same hydrological behavior per HRU. For the HRUs definition, the SWAT model uses data on land use, soil type and slope prepared by the user. The watershed slope is derived from the digital elevation model (DEM) using the Slope Spatial Analysis tool in ARC Map 10.2. Employing the DEM as the input raster, the SWAT model translates the elevation into a slope projection using percent slope. Through the automatic delineation of the entire watershed, 32 subbasins and 1065 HRUs were created in the KRB.

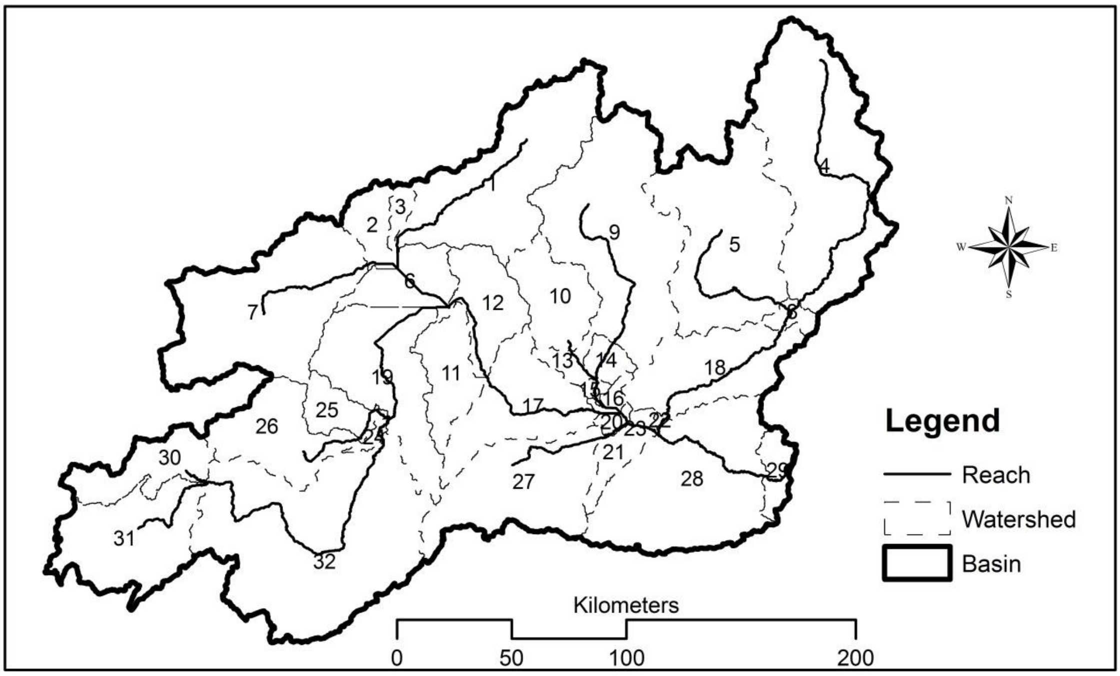


Figure 5.3: Automatically delineated subbasins (watersheds)

Digital Elevation Model

The Digital Elevation Model (DEM) is one of the main input requirements for running SWAT model. A DEM is a 3-dimensional digital model of a terrain's surface which is created from terrain elevation data. It is a quantitative representation of terrain and is important for Earth relevant sciences as well as hydrological studies and applications. In this study, the shuttle radar topography mission (SRTM)'s DEM with a spatial resolution of (90 m x 90 m) was obtained from the United States Geological Survey website: http://afghanistan.cr.usgs.gov which has been pre-processed for voids and can be readily used.

The quality of any DEM is based on the accuracy of elevation at each individual pixel (absolute accuracy) while its precision depends on the method to measure elevation, spatial density of measurements and variability of topography. The DEM was used in SWAT model for streams definition, slope, area and flow direction and accumulation across the KRB. During the automatic delineation in SWAT some small rivers and streams were not delineated due to the limitation of the rather coarse resolution (90 m) of the DEM (Chapter 3, Figure 16) (Rahman et al., 2010) especially in the case of larger basins (Buakhao and Kangrang, 2016).

In previous studies (Buakhao and Kangrang, 2016) over different terrains and areas it has been concluded that there has been no significant benefit of using a finer resolution for the delineation of the watershed. A coarser resolution DEM can be used to shorten the processing time of the model as the time required for delineation of a watershed is a function of the grid (DEM) size. Therefore in case of the KRB, using 90 m resolution DEM avoided producing extra stream networks, HRUs and subbasins for which ground physical data has been absent or otherwise the streams had been temporarily experiencing streamflow along the year.

Soil Data

The soil types of the KRB were clipped from the FAO-Soil database (FAO 1995). Seven dominant soil types covered the entire study region of 32 subbasins with a spatial distribution as visualized in Figure 5.4. The required spatial data package was projected to UTM zone 42N through ArcGIS which is the transverse Mercator projection parameter for Afghanistan.

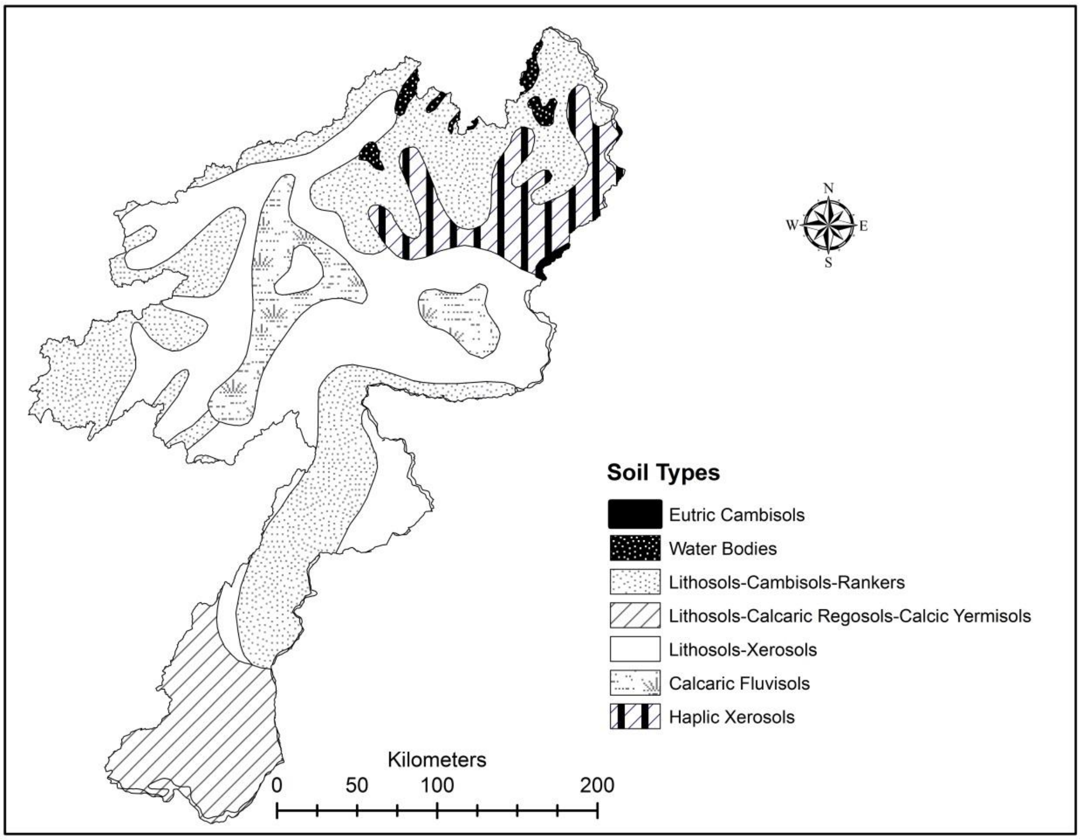


Figure 5.4: Spatial distribution of different soil types across the Kabul River Basin

Land use and land cover data

Another main input of the SWAT model is the LULC map of the KRB; SWAT requires topographic information, LULC data and soil data for determination of relevant hydrological parameters (Di Luzio et al., 2002). The LULC map used in this study was prepared for the year 2013 (Chapter 3) with 17 classes. There are not major changes in the LULC maps of 2013 compared to the preceding years, therefore it was considered to be a representative LULC map for the entire study period. The spatial resolution of the LULC maps was 250 m prepared from the NDVI time series (MOD13Q1 and MYD13Q1) filtered and smoothed by the University of Natural Resources and Life Sciences, Vienna (BOKU) (Vuolo et al., 2012).

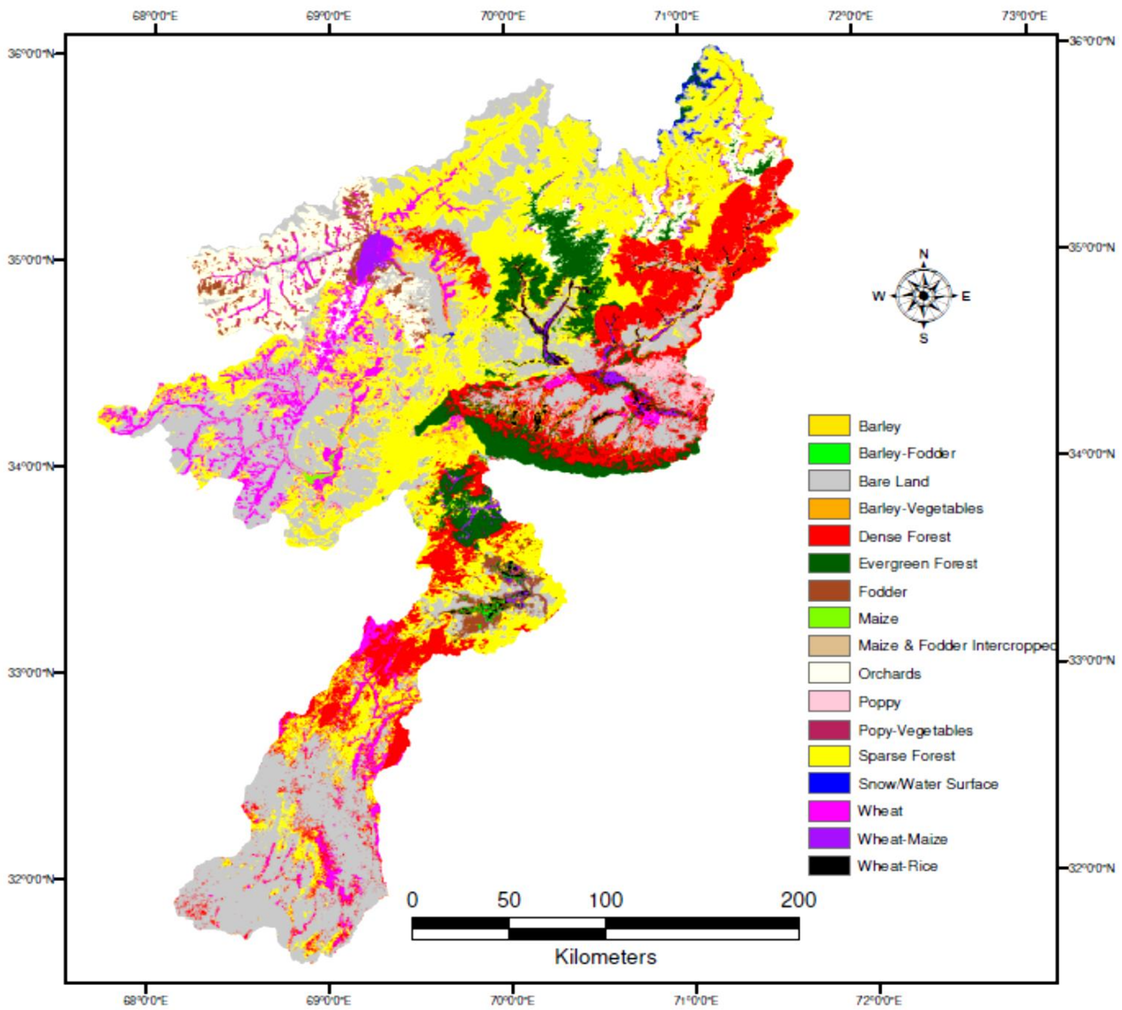


Figure 5.5: Land use and land cover map of the Kabul River Basin

Climate data

Among the climate data, daily rainfall data covering the period of 2008-2013 was collated from 25 meteorological stations across the KRB. The remaining weather parameters i.e. wind speed, temperature, relative humidity and solar radiation, were taken from the Climate Forecast System Reanalysis (CFSR) global meteorological dataset (Fuka et al., 2013; Dile and Srinivasan, 2014).

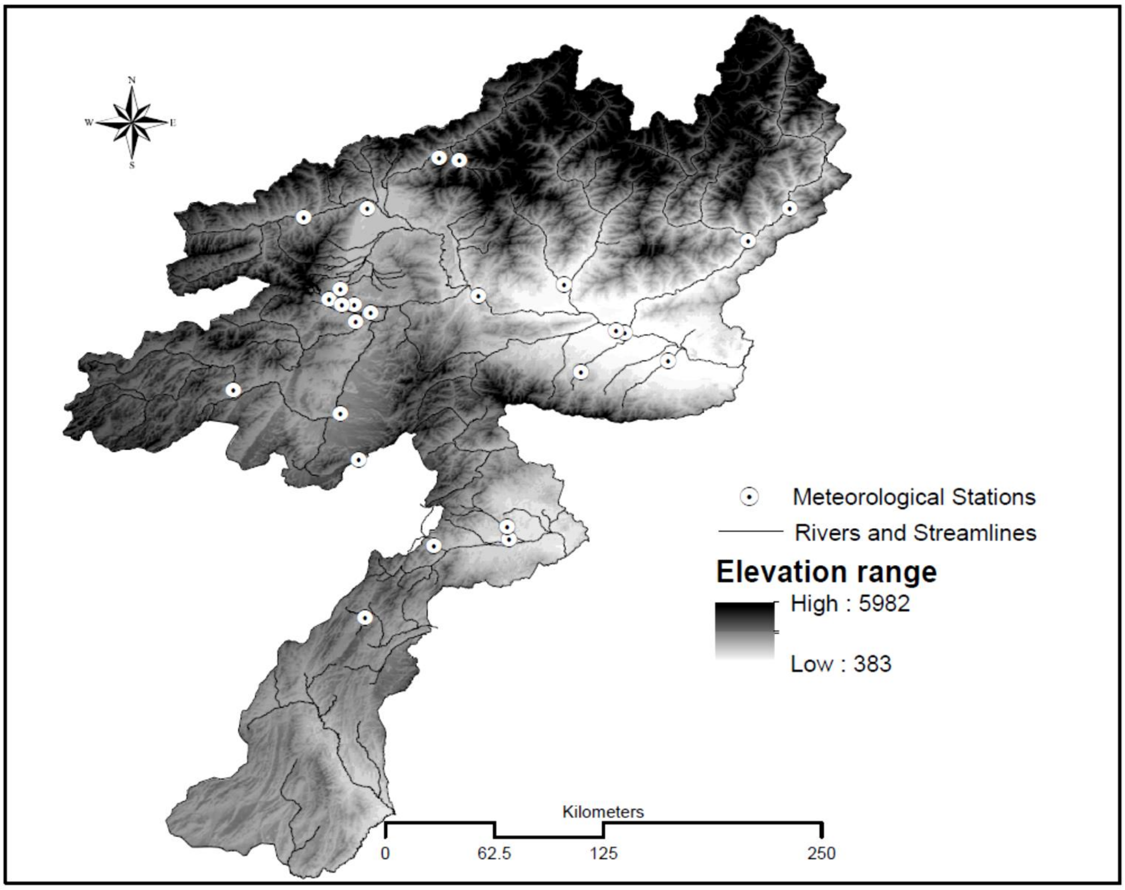


Figure 5.6: Location of the meteorological stations across the KRB

Streamflow data

The monthly streamflow data were collected from 6 stations installed on different rivers of the KRB. The choice of these stations was done in a way to make sure that there were no storage areas or reservoirs or any major diversions that could possibly influence the discharge at the monitoring points.

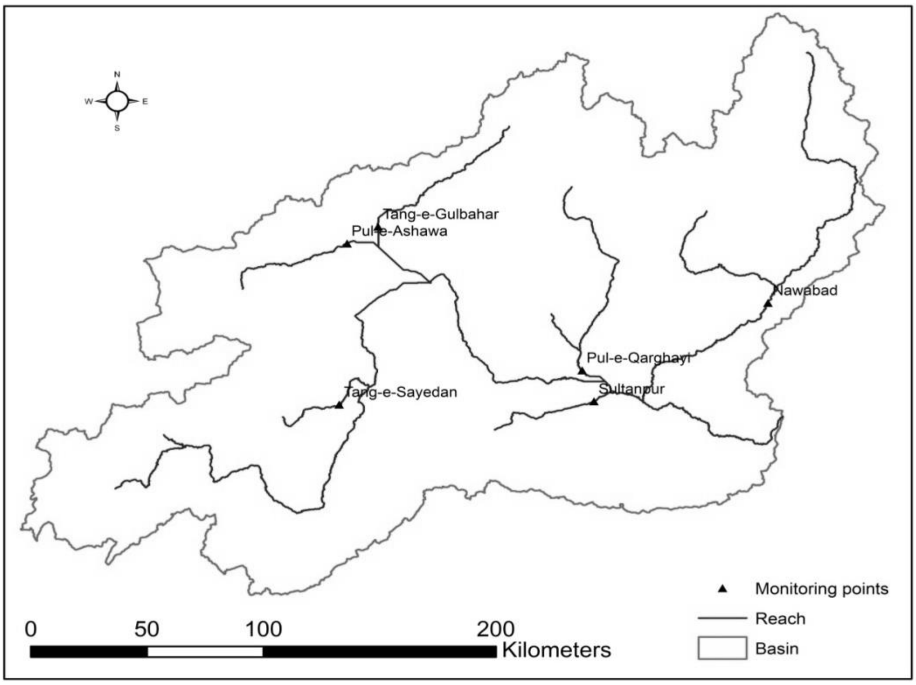


Figure 5.7: Selected monitoring points across the watershed

The calibration and validation period of the selected stations from which the data was collected are listed in Table 5-1:

Table 5-1: Calibration and validation period of the monitoring points

S. No.	Station	River	Calibration Period	Validation Period
1	Nawabad	Kunar	2008-2010	2011-2013
2	Pul-e-Qarghayi	Laghman	2008-2010	2011-2013
3	Pul-e-Ashawa	Ghorband	2008-2010	2011-2013
4	Tangi-e-Gulbahar	Panjshir	2008-2010	2011-2013
5	Tangi-e-Saidan	Kabul	2008-2010	2011-2013
6	Sultanpur	Surkhrod	2009-2011	2012-2013

Model performance evaluation

Hydrological models are the most effective means for simulating water fluxes and balances and therefore provide the base for estimation, analysis, management and planning of available water resources and are vital for the investment plans aiming at multi-sectoral and multi-disciplinary projects. For the verification of the robustness of the model, it is very important to evaluate its simulation results against some known ground data using accepted methods.

This study is applying the Nash-Sutcliffe efficiency (NSE) which is a normalized statistic which is computed as the ratio of residual variance to measured data variances (Nash and Sutcliffe 1970). NSE usually recommended for correlating the simulated and observed streamflows that are embedded in the SWAT Calibration and Uncertainty Programs (SWAT-CUP) (Ritter and Muñoz-Carpena 2013; Moriasi et al., 2007). The NSE calculates the best fitness based on the following equation:

$$\text{NSE} = 1 + \frac{\sum_{i=0}^{n}(Q_{obs}-Q_{sim})_i^2}{\sum_{i=0}^{n}(Q_{obs}-Q^{mean})_i^2} \qquad \text{Equation (5.5)}$$

where Q_{obs} and Q_{sim} represent observed and simulated streamflow, respectively, and Q^{mean} is the mean of observed data.

The NSE values range between -∞ and 1.0; in optimal conditions the value of NSE is 1.0. Depending upon the nature of studies, the acceptance level of NSE values vary between 0 and 1.0, whereas values <0.0 indicates that the mean observed values are better predictor than the simulated values and is therefore considered to be unacceptable performance.

In addition to NSE, the coefficient of determination (R^2) was also used to assess the linear collinearity between the simulated and observed data. The R^2 range is from -1 to 1. When the value of R^2 is equal to 0, it shows that there is no linear relation but R2 is equal to 1, it shows the ideal fitness or indicates the 100% fitness/ positive correlation between simulated and observed values. In case R^2>0.5 then it is considered to be acceptable (Santhi et al., 2001; Bonuma et al., 2013).

SWAT Calibration and Uncertainty Programs (SWAT-CUP)

As the KRB, is the most highly populated, topographically diversified region with distinct cropping patterns at the upstream and downstream parts of the basin, it is very challenging to determine the most sensitive parameters (e.g. hydrological, soil, meteorological, groundwater etc.) and their relevant uncertainty in simulating the streamflow with such complex hydrogeology in order to achieve a final agreement with the observed discharges. In this study, the relative sensitivity values of the parameters that were deemed to be affecting the parameter estimation process were evaluated.

The streamflow relevant parameters were estimated in this study by using the Sequential Uncertainty Fitting (SUFI-2) algorithm (Abbaspour, 2007) embedded into SWAT-CUP. In this algorithm, the discrepancy between measured and simulated variables denotes the uncertainty. SUFI-2 joins the calibration and uncertainty analysis for finding the parameter uncertainties that result in prediction uncertainties bracketing most of the observed data collected at the streamflow gauges, while producing the smallest possible prediction uncertainty band. In addition to this, in SUFI-2, uncertainty of input parameters is depicted as a homogeneous distribution all over, while modeled output uncertainty is quantified at the 95% prediction uncertainty (95PPU).

The cumulative distribution of any output variable is achieved through Latin hypercube sampling (Iman et al., 1980) which is already embedded into the SWAT-CUP. During calibration in SWAT-CUP, in each iteration, the ranges of previous parameters were reorganized by calculating the sensitivity matrix, and the equivalent of a Hessian matrix (Neudecker and Magnus, 1988) followed by the calculation of a covariance matrix, 95% confidence intervals of the parameters, and a correlation matrix. Parameters were then updated such that the new ranges were smaller than the previous ranges, and were centered on the best simulation.

The final results were then evaluated using the criteria set up for model evaluation guidelines for systematic quantification of watershed simulations (Moriasi et al., 2007). Based on these guidelines three quantitative statistics are advised by

Moriasi et al. (2007), i.e. the Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR). According to these acceptability ranges, the modeled simulation can be justified as satisfactory if NSE > 0.50.

5.3 Results and discussion

5.3.1 Calibration of the simulated monthly streamflow

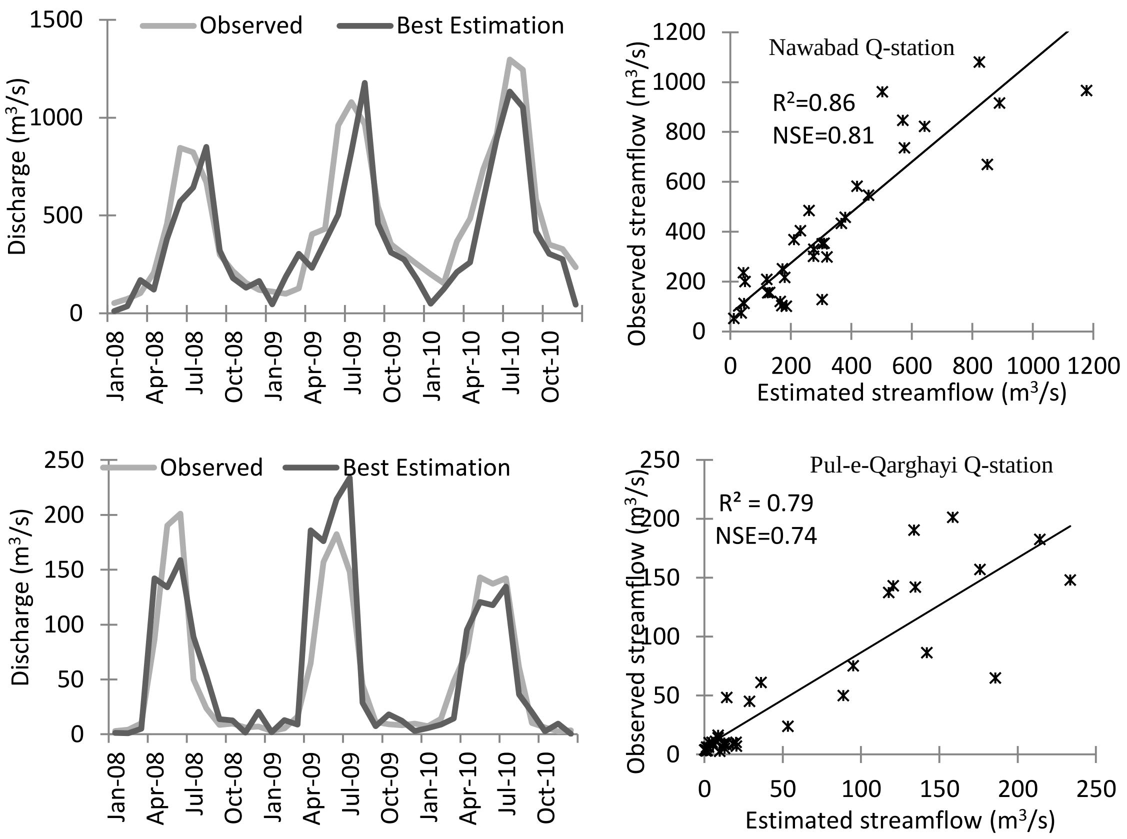
Calibration of the streamflow at the KRB with its non-uniform topography and diverse climate conditions at the upstream and downstream of the basin, is quite complex, because of difficulties to come up with a common set of parameters that are sensitive for the entire basin. Therefore, the SWAT model under was calibrated at several sites in the KRB at the major river monitoring points across various reaches. A single site calibration usually leads to a relatively higher Nash-Sutcliffe efficiency than when multi-sites are used (Shrestha et al., 2016). The SWAT model calibration and validation statistics are graphically presented in Figures 3 and 4. For the Nawabad monitoring point, downstream of the KRB, that receives streamflow from Asmar and Chaghasrai rivers, the model simulated the mean monthly streamflow to be satisfactory with NSE=0.81 and r^2=0.86 for the period of 2008-2010.

The peak hydrograph in June-August is due to an interplay between (i) the snowmelt at the source (in the early months) and (ii) the Monsoon rains over the Chitral region of the Hindukush mountainous series (in later months). Similarly, there was a good fitness between simulated and observed mean monthly streamflows for Pul-e-Qarghayi monitoring point i.e. NSE=0.74, r^2=0.79 throughout the calibration period (2008-2013). At the Pul-e-Ashawa and Tangi-e-Gulbahar monitoring stations, the hydrograph peak is in May-July with delayed snowmelt response especially when the temperature rises in these months.

The correlation between observed and simulated flow at the Pul-e-Ashawa monitoring point was satisfactory with NSE=0.70, and R^2=0.87. There was also good correlation between the observed and simulated monthly streamflow at the Tangi-e-

Gulbahar station. Similarly, the streamflows at the Tangi-e-Saidan and Sultanpur stream gauges located on Kabul and Surkhrud rivers respectively, are seasonal and these rivers are rarely full throughout the twelve months of the year. Therefore the NSE value for Tangi-e-Saidan and Sultanpur stream gauges were relatively lower, i.e. 0.62 and 0.64 respectively while the coefficient of determination, R^2 for the aforementioned monitoring points were 0.81 and 0.75.

Throughout the calibration period, the year 2008 was the driest year while 2009 was the wettest with peak hydrographs in the main part of the KRB testifying the considerable amount of water available for crop water use and power generation. The correlation of the observed and estimated streamflow is given in Figure 5.8:



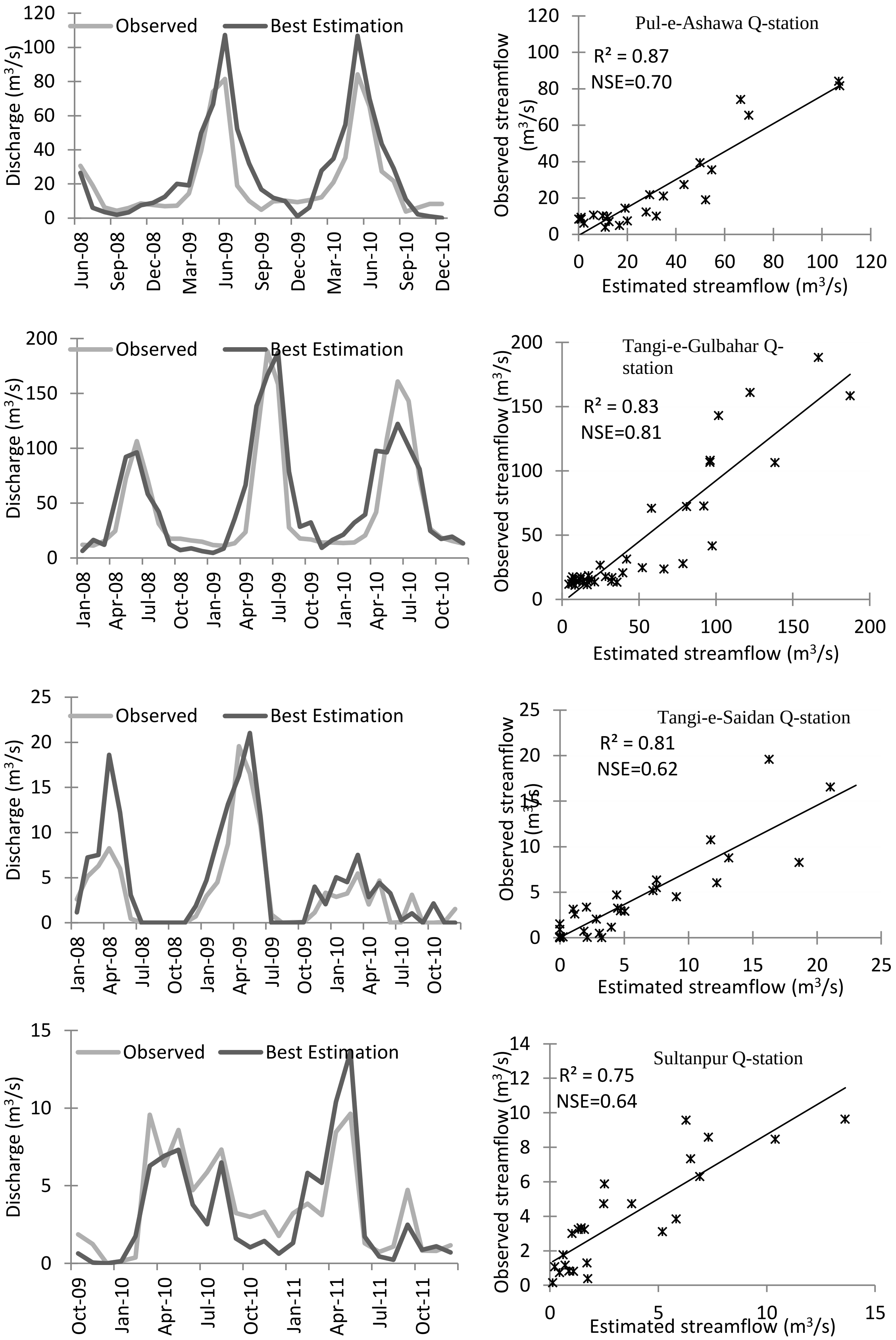


Figure 5.8 Calibration of the main discharge measurement stations in Kabul River Basin

5.3.2 Uncertainty analysis

Out of all the parameters tested during the calibration process, 14 parameters were found to be most sensitive in the KRB simulations with regard to the specific soil, meteorological, geographical and topographical conditions. The 4 most sensitive parameters were found to be SCS runoff curve number (CN2), soil bulk density (SOL_BD), Baseflow alpha factor (Alpha_BF) (days), groundwater delays (GW_Delay) (days) with sensitivity ranking of 1, 2, 3 and 4 respectively. The sensitive parameters considered for the validation of the SWAT model are listed in Table 5-2. The remaining parameters had no considerable effect in the streamflow simulations and therefore these parameters were omitted from the iterations been carried out to reach the proposed objective function.

Table 5-2: Sensitive parameters used for calibration of the streamflow at the Kabul River Basin (KRB)

S. No.	Parameter	Sensitivity Ranking	Fitted Value	Parametric range	
				Min value	Max value
1	*r__CN2.mgt	1	-0.49	-0.49	-0.48
2	r__SOL_BD(..).sol	2	-0.02	-0.02	-0.01
3	**v__ALPHA_BF.gw	3	0.19	0.18	0.22
4	v__GW_DELAY.gw	4	160.64	160.34	166.11
5	v__REVAPMN.gw	5	19.89	19.51	19.93
6	v__GWQMN.gw	6	43.49	43.43	44.24
7	v__EPCO.bsn	7	0.28	0.27	0.28
8	v__ESCO.bsn	8	0.49	0.44	0.50
9	v__CH_N2.rte	9	0.19	0.18	0.19
10	v__SMTMP.bsn	10	-3.61	-3.70	-3.55
11	v__SMFMX.bsn	11	13.41	12.55	13.60
12	v__SMFMN.bsn	12	8.90	8.55	9.25
13	v__TIMP.bsn	13	0.15	0.15	0.16
14	v__SURLAG.bsn	14	1.76	1.52	1.97

** r_: an existing parameter value is multiplied by (1+ a given value)*
*** v_:an existing parameter value is to be replaced by a given value*

5.3.3 Validation of the simulated monthly streamflow

After achieving the targeted objective function (NSR>0.5) (Moriasi et al., 2007), the sensitive parameters (Table 5-2) were used for validation of the monthly streamflow covering a period of 2011-2013 throughout the major monitoring points across the KRB. During validation, a decrease in the NSE and R^2 values between the observed and estimated streamflow was noticed almost at all discharge monitoring stations (Figure 5.9). Hence the resultant NSE values for Nawabad, Pul-e-Qarghayi, Pul-e-Ashawa and, Tangi-e-Gulbahar were 0.73, 0.62, 0.61, 0.71 and the R^2 values were 0.77, 0.86, 0.72 and 0.79 respectively. Meanwhile the NSE values for the seasonal and relatively smaller capacity rivers' monitoring points at Tangi-e-Saidan and Sultanpur were 0.52 and 0.59 while R^2 were 0.74 and 0.65 respectively. The range of NSE and R^2 in this study were in-line and better agreement with similar studies carried out at other large basin levels during calibration and validation of multi sites at basin level (Srinivasan et al., 1998 and Cao et al., 2006).

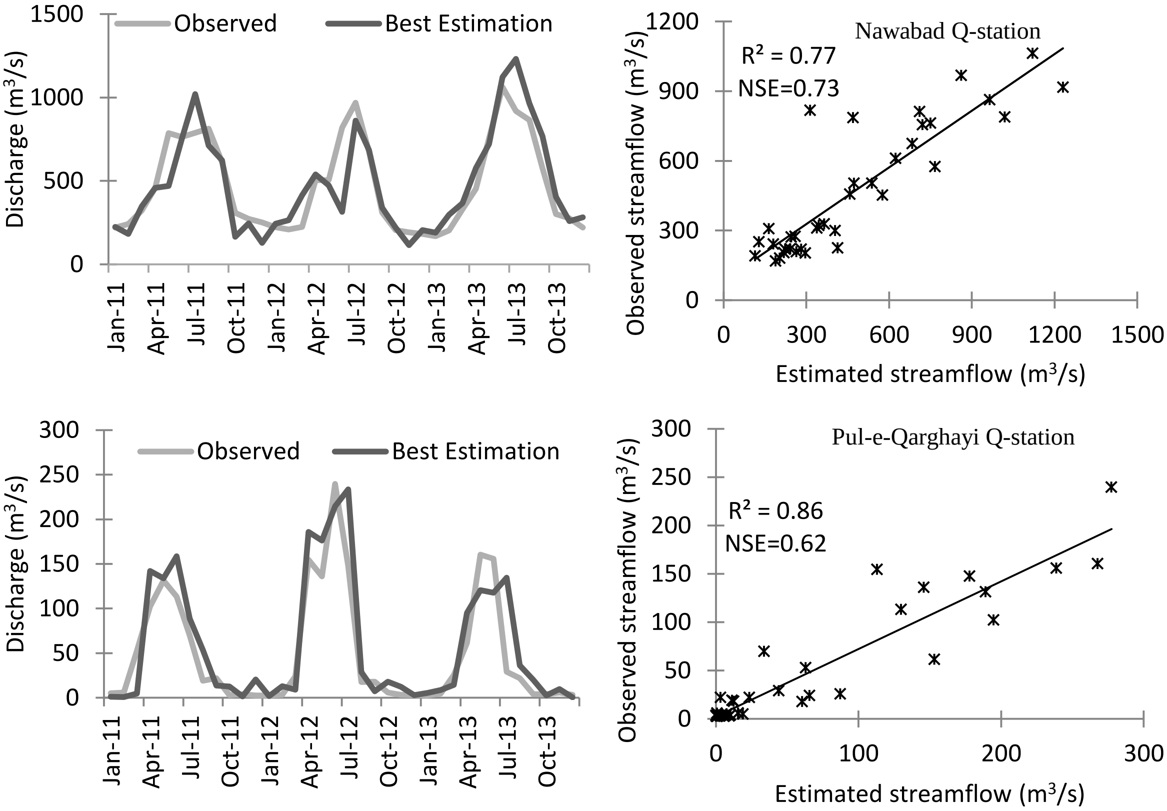


Figure 5.9: Validation of the main discharge measurement stations in Kabul River Basin

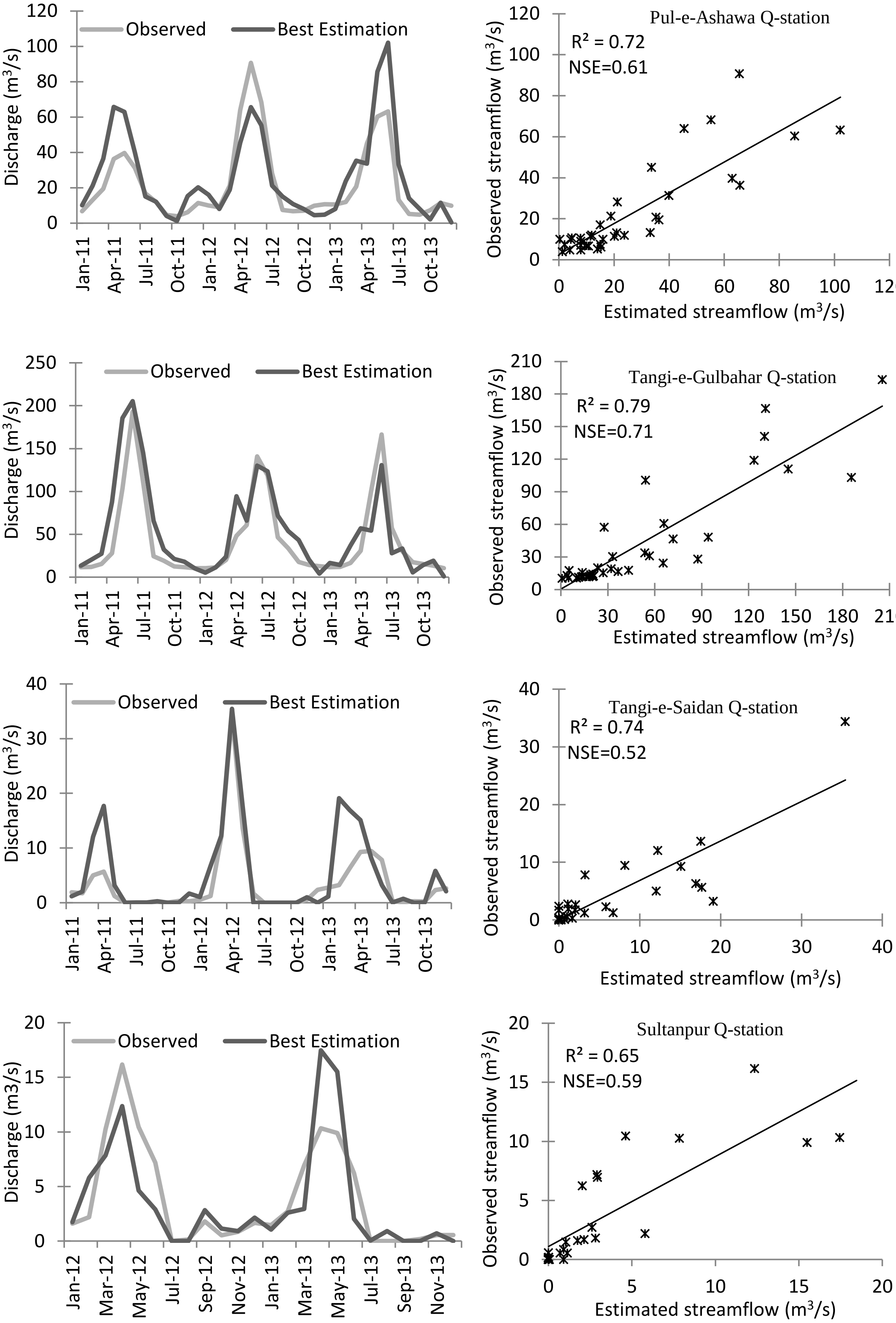


Figure 5.9: Continued

During the calibration and validation periods, the model shows maximum uncertainties at the peak flow periods except at the Tangi-e-Gulbahar and Pul-e-Ashawa streamflow measurement stations. The uncertainties are relatively evident at those streamflow monitoring points with seasonal streamflow occurrence and that dry up during June-December. During the validation period, the year 2011 was the driest while 2013 was the wettest year with peak hydrographs throughout the KRB.

The relatively lower NSE and R^2 in calibration and validation is due to the fact that the streamflow gauges are spread out and usually one or fewer gauges represent an entire sub-watershed which causes errors and uncertainties in runoff simulation (Arnold et al., 1998). Based on the study of Fontaine et al. (2002), one of the limitations of the SWAT model in large watersheds with dominating snowmelts and heterogeneous topography is the earlier starting of the rising and recession hydrograph limb. Furthermore, the recorded precipitation might not be representative for the entire (sub)watershed due to the pre-described highly heterogenic nature of the river basin, and therefore discrepancies might occur between the observed and simulated streamflow.

Most of the alluvial-fan regions across the country have water channels that are partly natural, and partly diversions made by local inhabitants for the purpose of diverting seasonal flows for irrigation (Shroder and Ahmadzai, 2016). Furthermore, despite the installation and establishment of flow measurement network across the river network of Afghanistan (FAO, 2015c), there were no proper calibration and validation plans in hand which caused consistent delays in the publishing of the hydrological year book by the Ministry of Energy and Water. Different from conventional stations, the newly installed stations have the capability to measure several parameters at the same time (i.e. rainfall, relative humidity, water level, water quality, temperature and sunshine) (FAO, 2015c), but it has taken years to equip the local staff with knowledge on handling, maintenance and troubleshooting in case of technical problems with these devices. Their use and monitoring requires careful handling while dealing with the water resources management and relevant investment plans. The local infrastructure and hardware gain attention at the planning and policy level, but the data relevant issues especially during operation (and maintenance) are considered with comparatively low attention.

6 SUMMARY AND CONCLUSIONS

Kabul River Basin is the key watershed hosting around the 1/3rd of the total population of Afghanistan. By generating and providing water for drinking water supply, irrigation and groundwater recharge, the KRB creates the base for livelihood of millions of inhabitants; due to providing water for fulfilling the local industrial water demand as well as generating hydropower for local consumption. The KRB is essential for the economic development of Afghanistan especially given the fact of increasing population and migration into the KRB. As a transboundary river basin, it contributes to feed the Indus river basin being the backbone of irrigated agriculture in Pakistan and KRB is therefore strategically and politically very important for the region. Yet, unfortunately in the last couple of decades, KRB faces the multiplicity of governance, management and development relevant challenges.

In the post-war recovery efforts, Afghanistan, being at the upstream, has been implementing plans for utilizing the water resources of the KRB for the different evolving sectors, e.g. agriculture, municipal, industrial, hydropower etc. There have been potential tensions between Afghanistan and Pakistan due to the absence of a bilateral understanding over the share of each contributing country, an issue which needs to be addressed while considering the international laws on transboundary river basins. For any bilateral agreement on shared water resources, it is therefore of utmost importance to estimate the land cover and water demand (for different sectors and with appropriate spatio-temporal resolution) as well as the available water resources. Besides these transboundary questions – and embedded in that regional context – the above mentioned information is also needed to guide the water management within the KRB and its internal development. These aspects are addressed in this study with detailed analysis in terms of focusing on relevant parameters (ET_a dominated by land use/land cover tackling the demand-side; discharge representing water supply-side) at different spatial and temporal scales.

The spatial segregation of the KRB into smaller administrative units aiming at a LULC analysis proved to be a sound approach especially in regions where physical ground data is scarce and the physiographic differences vary greatly among upstream and downstream of the river basin which is known rugged terrain and huge elevation differences. The segregated spatial analysis of the LULC enabled to achieve an output in terms of detailed land use/land cover classification and in turn via site-specific and rather high-resolution ET_a. This output of the study has a high value towards utilization and was not available by any previous study referring to KRB. It provides a good basis for assessing the status-quo regarding land use, understanding driver for changes in the past, get an understanding on future trends and identifying options for further expansion . This can guide to the establishment of sound investment plans and their implementation in the field of agriculture and in context with integrated water resources management at the subbasins' administrative levels of the KRB.

The segregated spatial analyses of the LULC of the KRB with reference to the base year of the study 2003 show that there was an increase in the ground cover of wheat, barley, barley and rice by 31%, 7% and 32%, respectively, in 2013. Although no change was observed in the areal extent of maize in 2013 compared to the base year, yet there was an increase in 2006 by 7% while decrease in 2009 by around 3%. Similarly, in 2003 the ground share of wheat, maize barley and rice was around 48%, 23%, 18% and 11% respectively, while in 2013, these values shifted to 52%, 21%, 15% and 12% respectively. Based on the evaluation of the above results, from 2003 to 2013, the increase in wheat ground coverage was compensated by the decline in barley cultivation. Both crops, in general, follow the same cropping calendar. The maize and rice share was almost consistent among the dominant cereals produced in the KRB. Based on the analyses of the LULC map of the KRB in 2013, the total cultivated area was about 669,169 ha which accounts for around 9% of the total area of the KRB against 539,913 ha in 2003 which accounted for around 7% of the total area.

The use of the moderate resolution 250 m phenologically tuned NDVI product for the estimation of the spatial extent of the land cover provided reliable results which are sufficient to match the required up-to-date LULC information of the KRB. Using remote sensing techniques for an LULC analysis is an appropriate option to cope with the data-scarcity issues as well as to contribute newest information to the pool of agriculture and water resources sector development in Afghanistan.

The novelty of this study is the crop phenology based spatial segregation of the physiographically diversified large river basin and the use of NDVI as the identification marker for individual land covers at various spatial and temporal scales. The use of phenology (crop calendar) based spatial segregation of the KRB was helpful in attaining the higher accuracy during land use and land cover analysis. The phenology based analysis at such heterogenic and large river basins will also help in identifying the irrigated and rainfed land covers which is one of the key necessities while dealing with irrigation quota or allocation among different spatial units. Keeping in view the predicted rise in industrial and domestic water demand, the detailed LULC maps of the KRB will further help in the planning and reservation of a known water quota each year for fulfilling the crop water requirements across the basin. It will also support the relevant ministries to diagnose the potential areas for irrigation expansion as well as intensification and establishment of reservoirs to ensure the sustainable water resources availability especially in the peak demand season and to counterbalance disadvantageous impacts by climate change in terms of a more quick hydrological reaction of the basins on precipitation (altering of the currently coinciding peak supply and demand periods; increasing risk of floods). The outcomes of this study will be valuable in the trans-boundary water issues of the KRB with regard to the local and international stakeholders.

Like other river basins in the neighborhood especially in conflicted regions, KRB is also suffering from the scarcity of physical data which is essential for strategic and operational planning of the land and water resources. Furthermore, the lack of technical skills within the institutions relevant to the field of water resource management further limits the prospects of sustainable planning and management of natural resources. For a holistic, basin-wide management of water resources, it is imperative to estimate actual evapotranspiration, especially in a country such as Afghanistan where some 99% of its water is withdrawn solely for irrigation purposes.

This study analyzed the actual evapotranspiration (ET_a) at basin, subbasin and provincial scales of the KRB. The gained spatial information is of great value for the strategically important trans-boundary KRB. Moreover, information on ET_a in these spatial units is also available on time steps relevant for water management i.e., monthly, seasonal and annual from 2003-2013. Such detailed information, both in space and time, will enable the policy makers in the region not only to strategically and operationally plan their water resources but also to monitor the water allocation in strategic time steps. During the ET_a analysis at the basin level the mean ET_a, throughout the study period (2003-2013), was estimated to be 539±29 mm. The mean ET_a throughout the study period (2003-2013), across the subbasins Alingar, Chak aw Logar, Ghorband aw Panjshir, Gomal, Kabul, Kunar and Shamal was 491 mm, 421 mm, 447 mm, 465 mm, 503 mm, 521 mm and 551 mm respectively. The highest ET_a values were estimated for the Shamal, Kunar and Kabul subbasins which host relatively large irrigated areas with high temperatures and other favorable climatic and geographic factors. Among the provincial administrative units, the highest mean ET_a for the winter season was estimated for Kunar, Khost and Nangarhar provinces, which was 196 mm, 193 mm and 192 mm respectively while Panjshir province had the lowest mean ET_a of around 85 mm as it is located at an altitude of around 2000 m with mountainous terrain. In the summer season, the ET_a values were highest for the lowland provinces of the KRB, i.e. Kunar (351 mm), Nangarhar (340 mm) and Khost (332 mm) and lowest in Panjshir province (268 mm). Similarly, the total ET_a (both in summer and winter) throughout the study period was the highest in the lowland provinces of Kunar (546 mm), Nangarhar (532 mm), Khost (526 mm), Laghman (504 mm) and Paktika (502 mm). These are the provinces where crop rotation is common with relatively large irrigated areas compared to rest of the provinces of the KRB.

The detailed estimation of ET_a at high spatial and temporal scales effectively can support region specific water management and planning. The estimated ET_a can be used as an indicator to assess the performance of irrigation and water allocation and management in general. It is crucial for the authorities to strategically invest in the capacity development of the local manpower at the Ministries of Agriculture, Irrigation and Livestock as well as Ministry of Energy and Water to safeguard the irrigation quota for the dominant crops especially in the peak irrigation demand period. The ET_a derived under this research could be used in comparisons to future studies over the effects/impacts of climate change on ET_a.

The SWAT model was used to simulate the rainfall-runoff at the KRB known for its distinct geographical and land use differences between up-and downstream parts. As a wide and geographically diverse river basin, it is rather complicated to come up with a joint set of parameters for sensitivity analysis as well as the correlation of the observed and simulated streamflow. This is so when one considers that there is only one cropping season per year at the upstream but crop rotation at the downstream of the KRB. Hence, the parameterization of SWAT model for these two conditions requires extra time and calculations. It is vital to estimate the available streamflow in any watershed/river basin for the production of streamflow management plans, drought response plans as well as to ensure fair allocation among different water users and the environment. The resultant simulations could be improved if hydrological modelling could be used at the spatially disaggregated level. The existing data requires careful handling if used for water resources management and investment plans keeping in view the issues with improvement of the hydro-meteorological network as well as its maintenance and management. Since the Government of Afghanistan intends to build more dams and storage structures to create a regional system of water trade and water conservation (Ghani, 2016). But without taking key measures for the accurate estimation and measurement of water resources, Afghanistan can’t manage the most important transboundary basins’ water treasure. Beside this, a heightened attention may be required aiming at the rehabilitation and development of irrigation infrastructure in order to raise farm application and conveyance efficiencies thereby minimizing the water losses along canal networks and achieve the targeted cereal production demand for ensured food security across the basin.

This study provides an approach appropriate for ground setting for river basin management plans and supports the design of an engineering response to water scarcity driven by future climate change recommending water storage infrastructure to be utilized in extreme conditions of drought and floods etc. The discrepancy between simulated and observed streamflow witnessed and verified by visual inspection highlights the need to upgrade the existing streamflow and precipitation measurement stations.

Improved capacity building of the local technical staff required to be able to respond technically and on time to the growing food and water demand in this agrarian country. Another most important aspect of the overall mismanagement of water resources is the insufficient consideration by the policy- and decision-makers referring to hydrological issues and the need to produce high-quality and reliable databases which are pre-requisite for any sustainable planning. Beside this, the governing bodies at the key water management departments need immediately to pay attention to inactive hydro-meteorological stations as well as build up the capacity of the local staff dealing with these stations on regular basis. Moreover, decentralization of the data collection, processing and management has to be encouraged; this will not only enhance the dependency on the central office but may rather train and build up the local capacity at the subbasin levels and will further save time what is needed to react appropriately on increasingly variable water supply and demand situations. It will also support the capacity building on local governance and institutional development which is very important for conceiving planning, implementation and administration of water management interventions. The globally projected climate change scenarios warn Afghanistan’s snow cover to be at stake meaning that sustainable strategies are required to be implemented in order to cope with drought conditions in the years ahead. A catalyzed support should be extended to the subbasin level on priority basis and the inactive stations have to be reactivated and data calibrated without the long awaited foreign helpers and investment agencies, which are rather cautious with respect to investing in the transboundary river basins.

The calibrated and validated SWAT model in combination with approaches for data provision by remote sensing techniques as worked out in this study, can be used for further-going purposes: (i) supporting an adaptive water management by updating the data input and refining interpretation of findings in the light of future changes in the KRB; (ii) identifying most suitable sites for expanding/intensifying irrigation schemes; (iii) detecting locations appropriate for raising storage capacity of basins/sub-basins (reservoirs, aquifers) to counterbalance disadvantageous impacts of climate and land use change; (iv) carrying out studies on matter flow based on the water balance quantification in this study in order to enhance water quality management; (v) using SWAT model as discussion tool while dealing with water allocation within and among different consumers as well as across sub-basins, (vi) guiding methodological refinements in terms of selecting sites paying-off detailed irrigation scheduling and requiring hydrological modeling with closer time-steps and application of more sophisticated models (provided that the data base is improved and allows application and effective utilization of these tools).

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