Wetland Model in an Earth Systems Modeling Framework for Regional Environmental Policy Analysis

By

Sirein Salah Awadalla

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Signature of Author ....
Engineering Systems Division
May 6, 2011

Certified by ....
Kenneth Strzepek
Research Scientist at the Center for Global Change Science, MIT
Thesis Supervisor

Certified by ....
Ruben Juanes
Professor of Hydrology
Internal Advisor

Accepted by ....
Heidi M. Nepf
Chair, Departmental Committee for Graduate Students

Accepted by ....
Dava Newman
Director of Technology and Policy

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Abstract

The objective of this research is to investigate incorporating a wetland component into a land energy and water fluxes model, the Community Land Model (CLM). CLM is the land fluxes component of the Integrated Global Systems Model (IGSM), a framework that simulates the relationship of physical systems to climate variations. Wetlands play an important role in the storage and regulation of the global water budget so including them in a land water cycle model is found to be necessary in balancing the regional water budgets of simulated river basins. This research focuses on modeling broad hydrological characteristics of wetlands (and lakes) into CLM. CLM's wetland component is reconstructed to reflect a more realistic wetland water budget; it allows for the exchange of water with CLM's river routing component; it allows for varying the storage of wetlands; it allows for calculating discharge from wetlands based on the physics of these ecosystems; and allows the surface water extent of wetlands to vary, a characteristic important to ecological behavior of wetlands and management of wetland ecosystems. The research then implements the modified version of the model for the Sudd wetland, in South Sudan, as it relates to its larger river system, the White Nile. Projects designed to better manage this wetland, such as diverting its inflow to reduce the amount of water consumed by evaporation, are currently under review by its various stakeholders. This diversion stands to change the area of the Sudd, which has direct implications on the ecological and social services derived from the wetland locally. The modified CLM is thus used to provide a better understanding of the science of this management option, and furthers the discussion on the benefits or drawbacks to diversion. Thus, *using area as a proxy for environmental impact, what are the environmental, economic and social risks associated with diverting water from inflow into the Sudd?* The new wetland component's performance is evaluated against existing observed and modeled data on Sudd hydrology and compared to existing models of the Sudd. The research finds that the potential benefits of diversion cannot be said to unequivocally better the larger system of the White Nile.

Thesis Supervisor: Kenneth Strzepek
Title: Research Scientist at the Center for Global Change Science, MIT

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And I would like to dedicate this work to the memory of John Garang de Mabior, who saw so much potential in Sudan and inspired us all to do the same!

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1.0 Introduction and Motivation

Wetlands are important ecosystems vis a vis the global climate system, both from a scientific perspective and as case studies for management under climate variability. Serving multiple functions, wetlands: 1) act as sources or sinks for greenhouse gases (GHG) such as methane gas and CO_2, which research shows to be the cause of anthropogenic climate change; (IPCC, 2007; Mitsch, 2000) and 2) wetlands play an active role in regional hydrologic cycles that, depending on the type of wetland in question, connect several or all of the parameters in the water budget such as precipitation, tides, groundwater recharge and streamflow, making them part of the physical system that controls climate, and sensitive to perturbations in this climate system (Mitsch, 2000). Their connectedness to the hydrologic cycle, however, often makes wetland hydrology complex. Wetlands present much functionality at the ecosystem level as well: their semi-aquatic state provides habitat to a wide range of biodiversity, including migratory birds and protected animal species, and makes possible farming, fishing and grazing land for local populations (Frasier and Keddy, 2005; Dugan, 2005). These functionalities are highly correlated to the temporal variability of a wetland’s hydrology or its hydroperiod. In cases where wetlands are part of larger hydrologic systems such as a river basin or coastal area, wetlands act as buffers to extreme weather conditions such as droughts and floods, regulating flows between aquatic and surrounding terrestrial areas, as well as providing reservoirs for water. Wetlands have also been referred to as the “kidneys of nature,” acting as natural water treatment systems (Mitsch, 2000).

As such, in the last three decades, wetlands have become a subject of management policy that highlights their functionality and advocates for their conservation, mostly to inverse previous policies that greatly reduced their numbers. Although exact numbers of how much wetland area has been lost are not available, it is estimated that as much as 50% of original wetland area has been lost due to agriculture, draining and filling (Dugal, 1993). Therefore, managing wetlands becomes an interesting point of research that requires a better understanding of 1) wetland systems, their hydrology and how it interacts with other factors in the ecosystem such as biogeochemistry; 2) the effect of global climate variations on different wetlands; 3) the environmental and economic functions that wetlands provide; and 4) the prioritization of these needs and functions. Given the complex factors that impact the study of wetlands, this research investigates incorporating a wetland component into a land systems model, and using it to analyze management options for one wetland. The land model under question is the Community Land Model (CLM); assigning the landscape into different land units, of which wetlands is one, CLM is set up to simulate the appropriate biogeophysical and hydrological processes associated with each land type, and thus calculates the global land water and energy exchange with the atmosphere and oceans (Oleson, 2004). The wetland component of CLM is found to lack certain characteristics deemed important to the functions played by wetlands in their respective catchments. The lake component also possesses some of these same characteristics and stands for improvement, so are incorporated into this research as well.

The modified CLM is then implemented the White Nile in east Africa with a focus on the freshwater wetland, the Sudd, where the modified CLM is used to inform management options for the Sudd. The Sudd receives inflow from the African Equatorial Lakes, which flow northward from Kenya, Tanzania and Uganda. Outflow from the Sudd, along with discharge from two other neighboring wetlands – Bahr El. Ghazal and the Machar marshes in the Sobat River basin – forms the White Nile (Sutcliffe and Park, 1999), which then makes its way northward into northern Sudan, connecting with the Blue Nile and Atbara River. The main Nile then flows to Egypt before dispersing into the Mediterranean Sea. Several projects have been proposed for the management of the White Nile River system, most significant among them is building a canal that diverts water from the Sudd's inflow, to be deposited downstream. This process is said to increase the amount of water flowing downstream into northern Sudan and Egypt. The diversion is also intended to reduce the area of the Sudd, so that there is less evaporation from the flooded water (Howell, 1988). A reduction in the area, however, impacts the wetland's ability to meet the needs of the local population, such as fishing, grazing and agriculture, as well as reduces its environmental services. In summary, the research presents wetlands as part of the physical earth system, and that is impacted by global hydro-climatology variability. On the other hand, wetlands have distinct hydrology, the main features of which are developed for CLM. In addition, the research shows how the new component can then be used to make policy recommendations for the Sudd.

1.1 Problem Statement

The figure below describes the approach applied in this research; broad features of wetland hydrology - and lakes, which were found to have similar characteristics to wetlands –

are modeled into CLM. Then using this new model, established management options are simulated and policy recommendations are made based on results from these simulations:

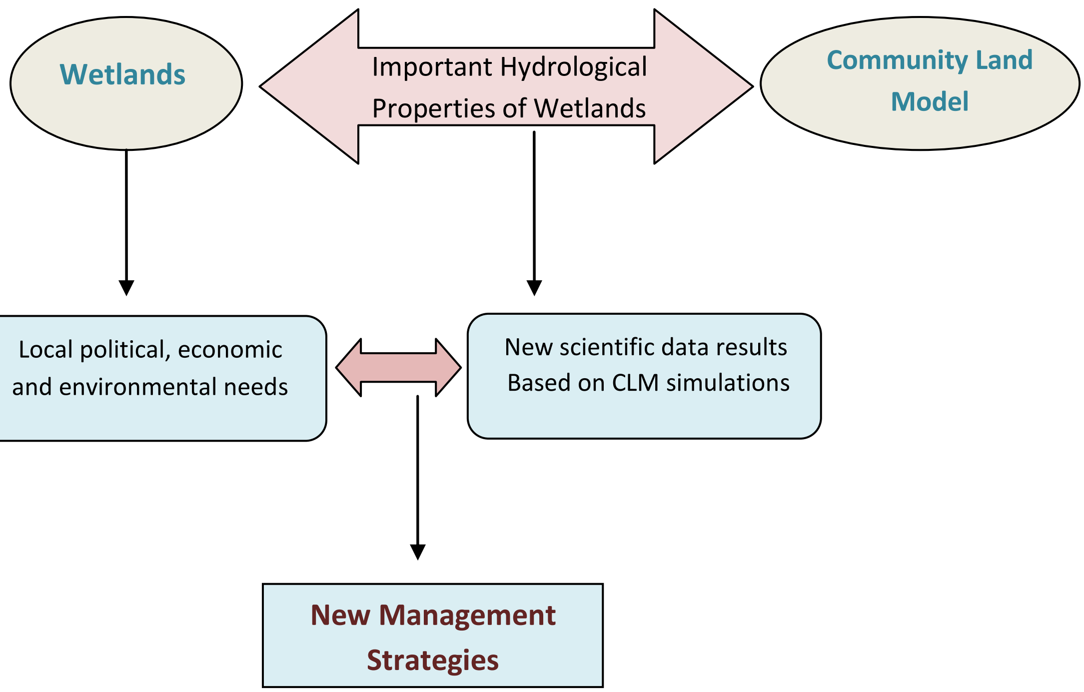


Figure 1-1Schematic of research approach

The research asks:

Using area as a proxy for environmental impact, what are the environmental, economic and social risks associated with diverting water from inflow into the Sudd?

In other words, how can the environmental dynamics of diverting inflow from the Sudd be used to contribute to the ongoing discussion on management policies? This question can be deconstructed into the following steps:

- How can CLM be modified to include a wetland (and lake) component?
- What is the impact to area of diverting water from the Sudd?

- What are the competing models of the Sudd, and what do they say about the relationship of its area to its inflow?
- Can a wetland and river model built into an earth systems model be used to recreate historical outflows that respond to inflow diversion?
- What are quantitative and qualitative tools that capture the environmental impact of diversion on the Sudd?

This research is a contribution to ongoing discussions on how to formulate wetland management econometrics and policies in general. It does so primarily by exploring the political dynamics of South Sudan, with its downstream neighbors, in choosing whether to divert inflow, and how this political space is influenced when using CLM.

1.2 Scope

In incorporating a more sophisticated wetland component to CLM, the scope of the research is limited to the hydrology of wetlands, and does not include other ways that wetlands interact with the climate or land system, such as their regulation of greenhouse gases. It also does not get into how the biogeochemistry of the wetland is specifically impacted by climate. Instead, wetland area is treated as a proxy for environmental impacts, and unless otherwise stated, area *embodies* factors like land for grazing, fishing, animal habitat, vegetation and other wetland services. A breakdown of area into these different components will provide a more detailed understanding of the policies involved, but it does not significantly vary the wetland's hydrology and is therefore outside the scope of this research. Delineating a wetland's area is often controversial as this area is sometimes taken to mean the size of flooded open water region, submerged vegetation, or the catchment based on a topographical demarcation.

The research will start with providing a literature review of the science, ecological functions and services of wetlands. Concerning science, the literature review also examines how wetlands relate to climate variability. Climate change science and research is seen as an opportunity to build this understanding since it directly looks at how wetlands interact with climate. Specifically, it outlines wetland parameters investigated, how environmental impact is measured, and how these impacts are related to policy measures. The following chapter looks directly at CLM, describing its general water balance mechanisms as well as how wetlands and lakes are specifically addressed. This is followed by the methodology employed in developing unique lake and wetland components to CLM. As was mentioned, lakes were found to possess similar hydrologic characteristics so are also incorporated into the modified CLM. Once this methodology is presented, the modified model is then implemented for the White Nile and the Sudd wetland, specifically. The hydrology of this river system is described, and following details on how the model is specifically applied for the White Nile, the several management options of the Sudd are presented, and one of them, diversion of inflow, is simulated using the new modified CLM. Results from this simulation are then juxtaposed to the various stakeholder positions regarding diversion policy, and recommendations are made based on these results and understanding of the stakeholder positions. Effectively, CLM is used to simulate the science and hydrology of the Sudd wetland, and to make policy recommendations on one management option for the Sudd.

2.0 OVERVIEW OF WETLAND HYDROLOGY

The following is a literature review of the relevant fields whose nexus informs this research. It reviews the definition of wetlands, and their ecological services. The literature review, in explaining how wetlands interact with global climate, presents studies on how wetlands are affected by climate change, as this angle directs the discussion to the intersection of wetlands and climate. The following chapter, also part of the literature review, explains CLM and an assessment of its performance to show the importance of including a wetland (and lake) component to its set of tools.

2.1 Wetland Ecosystems

Wetlands are ecosystems found at the boundary of terrestrial and aquatic bodies, and often times, have characteristics of both types of land covers. Although there are many definitions of wetlands, some functional for scientific research, others more appropriate for management or legal purposes, most definitions include wetlands as being "distinguished by the presence of water, either at the surface or within the root zone," having hydric soils and supporting hydrophytic vegetation, or vegetation "adapted to wet conditions" (Mitsch, 2000). The Center for Environmental Systems Research has assembled a Global Lakes and Wetlands Database, and estimates the total wetland area to be 8-10 million km^2 or 6.2 to 7.6% of total land surface (Lehner and Doll, 2004).

Wetlands perform many services at the global, population (biodiversity) and ecosystem levels. At the global level, wetlands are "ideal environments" for balancing the global nitrogen cycle; while salt marshes contribute 25% of natural sources of sulfur and its reduction in the atmosphere; also, wetlands have an estimated total "primary productivity" of 4 to 9 PgC/yr (10^{15} grams of carbon per year), out of a total of 1,400 Pg C in the earth's soil (Gorham, 1991), while other studies state that wetlands contain about 30% of the total organic carbon storage in the planet; and wetlands release up to 0.03-0.12 PgC/yr in methane, compared to 5.6 PgC/yr of methane released by burning of fossil fuels (Asselmann and Crutszen, 1989). Reducing the size of wetlands or offsetting their balance at a global scale may result in the release of these greenhouse gases.

Services provided by wetlands to biodiversity are also numerous and include being a habitat for animals harvested for pelts, migratory ground for waterfowl and other birds, and habitat for fish and shellfish. Over 95% of fish and shellfish species in the United States, for instance, are "wetland dependent", while wetlands accommodate a wide range of animal and vegetation species; in fact, wetlands are home to 20 and 75% of endangered or threatened animal and vegetation species, respectively, in the United States (Mitsch, 2000).

At the ecosystem level, wetlands have value for flood mitigation, by intercepting runoff and storm waters. Wetlands partake in storm abatement, recharging the aquifer, and improving the water quality (Mitsch, 2000; Fraser and Keddy, 2005). A study in Boston, Massachusetts estimates that if the wetlands surrounding the Charles River were drained, damages from river floods would cost about $17 million per year (US Army Corps of Engineers, 1972). The following section looks at several studies conducted to assess the impact of climate change on wetland hydrology. Climate change research introduces an opportunity for understanding exactly how wetlands are impacted by global climate variations. This is seen as relevant to the research since the new wetland and lake components are part of global earth system models, where climate parameters have localized effects.

2.1.1 Wetlands under a Changing Climate

The Intergovernmental Panel on Climate Change (IPCC) reports that "[w]arming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level" (IPCC, 2007). The main impacts of climate change on water systems are in trends in stream flow volume, and peaks; trends in freshwater demands and quality; quantity of groundwater and its recharge; reduction or disappearance of glaciers; increases in extreme weather occurrences, such as storm events, with longer dry periods in between; and the uneven distribution of response to these changing trends, reflecting an uneven distribution of "adaptive capacity" (IPCC, 2007) between different regions of the world. The report goes on to mention some of the likely hydrologic impacts of climate change on specific ecosystems such as freshwater wetlands, lakes and streams, coastlines and estuaries, forests, savannahs and grasslands, and mountain ecosystems. In the case of wetlands, climate change is said to "have its most pronounced effects on inland freshwater wetlands through altered precipitation and more frequent or intense disturbance events (droughts, storms, floods). Relatively small increases in precipitation variability can significantly affect wetland plants and animals at different stages of their life cycle […]. Generally, climatic warming is expected to start a drying trend in wetland ecosystems" (IPCC, 2007). Climate change research affords an important angle for studying how these global variations affect wetlands, and a better understanding of the nexus of climate and wetland hydrology. As such, the following studies are presented to show how global climate variability impacts wetlands, a central concept leading this research as the new wetland component is built into CLM, a model essentially built to investigate global land energy and water fluxes.

Winter (2000) classified vulnerability of wetlands to climate change along two general categories: wetlands dependent primarily on precipitation for their water supply are the most vulnerable to climate change; and wetlands dependent primarily on recharge from regional groundwater are the least vulnerable due to aquifers' "buffering capacity" to climate change. This conclusion is formed by introducing the concept of "hydrologic landscapes, [which] are defined by the flow characteristics of ground water and surface water and by the interaction of atmospheric water, surface water, and ground water for any given locality or region" (Winter, 2000). The paper goes on to say that "sources of water to and losses of water from wetlands in the context of their position within hydrologic landscapes is fundamental to evaluating the effect of climate change on these ecosystems" (Winter, 2000), meaning that understanding how climate change affects wetlands requires an understanding of how the different flows into the wetland (inflow, recharge, precipitation, evaporation) interact with the geomorphology of the wetland. Others postulate that not just the dominant dependence of wetlands on these parameters, but how they interact with each other determines the impact of climate change on the wetlands (Burkett and Kusler, 2000).

Building on Winter's concepts, Johnson et al (2005) investigated the impacts of climate change on Northern Prairie wetlands, in North America. They use WETSIM, a wetland model that inputs daily values of temperature and precipitation to "estimate wetland water balance, wetland stage and vegetation dynamics." The model's temperature was then increased by 3^{o}C, and its precipitation was allowed to vary by +20% and -20% and the resultant vegetation changes were documented.

Burkett and Kusler's (2000) study was a catalog of the types of wetlands in the United States and how they could change in the coming decades due to climate change. The study relies on two GCMs that predict increased temperature and precipitation over most of the US by the year 2099. The study showed that coastal and estuarine wetlands are threatened by sea-level rise, and partially attributes wetland losses in the Gulf of Mexico to currently rising sea levels. Sea level rise compromises the productivity of freshwater vegetation in these wetlands due to the intrusion of salt water, and alters the productivity of seagrass and vegetation that's submerged in brackish water. As is also documented in the IPCC (2007), Burkett and Kusler found that permafrost in high latitudes (Alaska) is predicted to undergo melting and its quality degraded by rising sea levels. Although wetlands that are dependent on groundwater have a hydrology less vulnerable to climate change, reducing the soil moisture in the vadose zone coupled with increased summer droughts could lead to higher numbers in wildfires, which would lead to peats releasing previously sequestered carbon. Alpine wetlands, prairie potholes, and other "depressional, slope, flats, river, and lake fringe wetlands" stand to change in area and services provided as a result of increasing temperatures and altered precipitation and soil moisture regimes.

Environment Canada conducted a country-wide study (1998) on the impacts of climate change and adaptation measures, with a section focusing on the wetlands of Canada, which cover 14% of the country. Different scenarios were used in these studies; they all projected that Canada will experience increased temperatures resulting in increased evapotranspiration, while scenarios allowed precipitation to either increase or decrease. Results of the model simulations suggested that most semi-permanent wetlands stand to change from open water to fully vegetated surfaces. Another simulation, where precipitation was allowed to decrease, showed that wetland salinity increased, reducing water quantity and quality. The results also showed that increasing temperature reduced the total area of wetlands; the study concluded that if climate change increased the amount of precipitation that would balance effects of temperature while decreasing precipitation exacerbates temperatures effects. These reductions in water quantity and increase in vegetation are then said to lessen the habitat quality of waterfowl and create an inviting environment to invasive plants. As in the case of Alaskan wetlands, the study found that climate change will reduce peat land area, and melt larger areas of permafrost, which will become wetlands.

Wetlands are highly sensitive to climate trends, as is shown by the above studies. Changes to climate impacting factors occurring in one part of the globe stand to reach wetlands in other parts of the world. As such, incorporating wetlands into a global land model like CLM, has valuable benefits to understanding the full picture of wetland hydrology; in other words, using CLM can show how increases in temperature or tides as a result of global change, for instance, changes wetlands in Alaska, east Africa, or in other parts of the globe. The following section explains CLM, how its original design addressed wetlands (and lakes), and what was seen as the relevant changes needed to be made for a better representation of wetlands (and lakes).

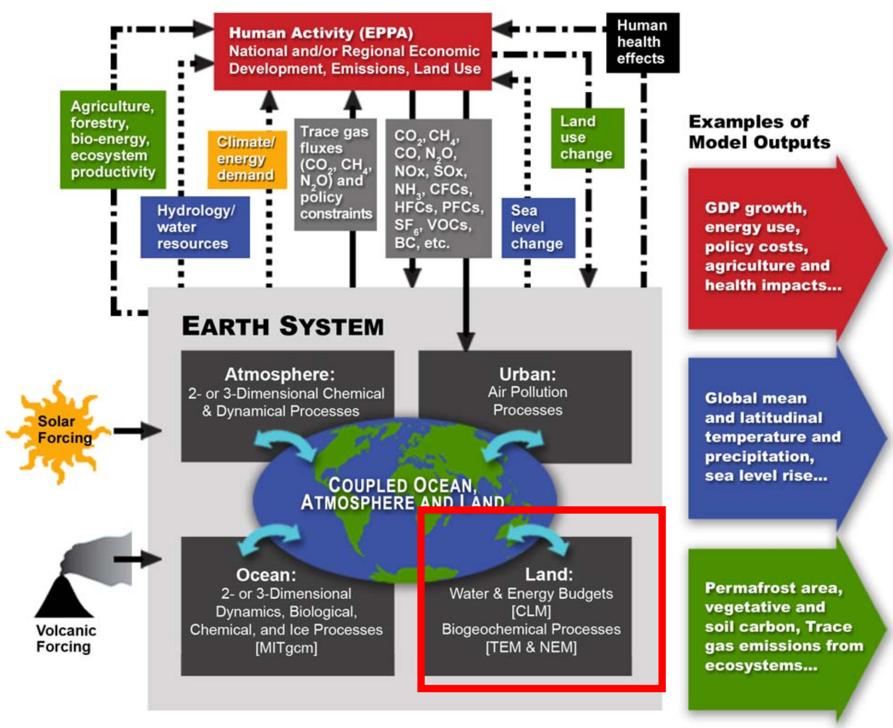
3.0 MODEL BACKGROUND

This section describes where the enhanced wetland and lake model components were implemented within the riverine and land system component of the Integrated Global Systems Model (IGSM). Described below, the IGSM framework includes an earth system component and a human activities component, combined to investigate how emissions, population, land use change and other human influences impact and are impacted by the climate system. Specifically, details are also provide that describe how and where the wetland and lake model enhancements were implemented.

As stated previously, the IPCC synthesizes results of general circulation models (GCMs) when creating the assessment reports. These GCMs are designed to model future climate trends – with a focus on anthropogenic influences on climate. They are designed to capture the processes that contribute to a changing climate. Some have become more complex and are part of "earth system models", simulating "atmospheric general circulation, ocean general circulation, sea-ice dynamics and thermodynamics, and […] land processes" relevant to how climate projections are determined (Donner and Large, 2008). The IGSM is such a model, developed at the Joint Program for the Science and Policy of Global Change, at the Massachusetts Institute of Technology. In addition to the earth system model components, it is linked to a human activities model, as an attempt "to include each of the major areas in the natural and social sciences that are relevant to the issue of climate change. Furthermore, it is designed to illuminate key issues linking science to policy," (Prinn, et al, 1999). Some of the policy issues that IGSM is used to research include the effects of urban air pollution, sea level change, and human health impacts. It also investigates policy issues around fresh water owing to the fact that water plays such a central role in many climate-related sectors such as energy, food production, industry, health and environmental systems (Strzepek et al, 2010).

The IGSM Version 2 (Sokolov et al., 2005) is made up of a general economic equilibrium model for simulating human activities and emissions; an atmospheric dynamics component that includes urban and atmospheric chemistry; a 2D and 3D ocean circulation model; and an systems model known as the Global Land System (Schlosser et al., 2007). The wetland hydrology component developed for this research is built within GLS.

The Global Land System is itself made up of three components that together describe the biogeochemical and biogeophysical processes that determine land-atmosphere fluxes of water, energy, carbon, nitrogen and methane. The combined efforts of the three components determine how living organisms play a role in the land storage of these elements and their fluxes. One component is the Terrestrial Ecosystem Model (TEM), which estimates "changes in terrestrial carbon storage and the net flux of carbon dioxide between land and the atmosphere as a result of ecosystem metabolism" (Schlosser, 2007); the second scheme is the Natural Emissions Model (NEM) and it estimates emissions of nitrous oxide and methane gas from natural land cover types such as wetlands and tundra. Finally, CLM computes energy and water fluxes between land and the atmosphere, the land water and energy budgets, as well as provides the biogeophysical properties that determine how gas emissions are computed by the other two components. Some of these properties are, for example, soil moisture, surface albedo, and vegetation types. CLM is also where wetland and lake hydrology equations are situated and where they were modified for the purpose of this research. The figure below, similar to that from Sokolov et al. (2005), shows the IGSM components and processes, and highlights where CLM fits.

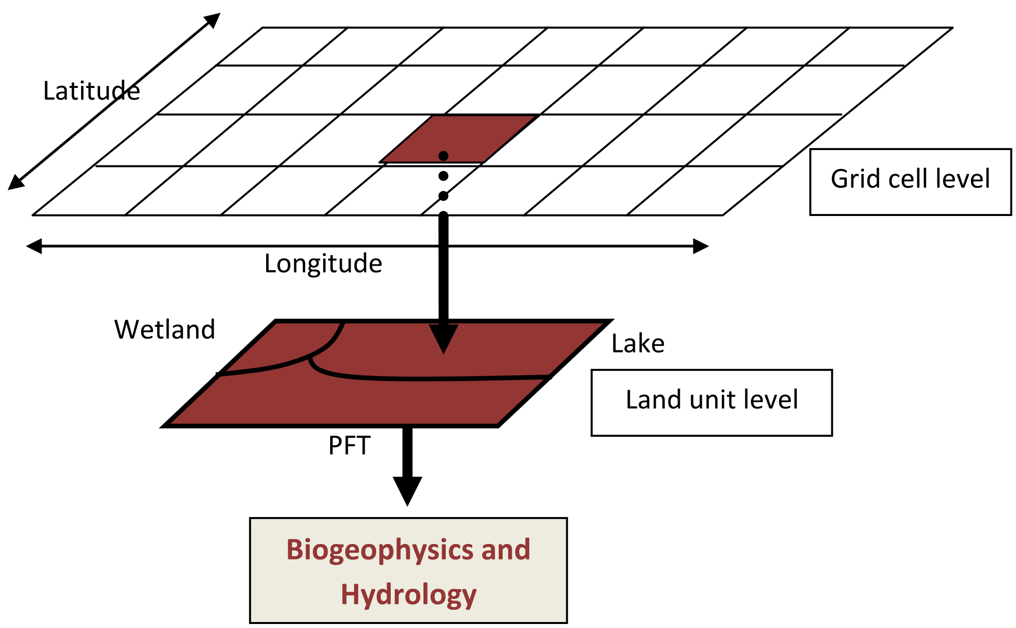


3-1showing IGSM components, with CLM boxed in red, from Sokolov et al (2005)

3.1 The Community Land Model

Based on a heritage of land-process modeling by the scientific community and coordinated by the National Center for Atmospheric Research (NCAR), CLM was formally introduced as a community-built model in 2002, as the culmination of several models. Since then, the model has further been developed to simulate such functions as “carbon cycling, ecological modeling, groundwater hydrology, and river routing” (Oleson, 2004). CLM3.5, the version of CLM used in this research (onwards referred to as CLM) evolved to performing the following functions, taken from Oleson (2004): vegetation composition; how solar and long wave radiation are absorbed, reflected, or transmitted; surface albedo; momentum, sensible heat and latent heat fluxes; phase change in soils and snow; canopy, soil and snow hydrology (evaporation, throughfall, interception, infiltration and subsurface drainage, snow melt, soil moisture, runoff and river routing); photosynthesis; and volatile organic compounds.

CLM is designed as a nested subgrid hierarchy (Figure 3-2) where the landscape is divided into grid cells (the highest level). Grid cells receive inputs of temperature, precipitation, solar radiation and other atmospheric forcing data; runoff, water, momentum and energy fluxes are computed for lower levels and then aggregated to the grid cell level before fluxing to the atmosphere or routed in river systems. The second spatial level is that of the land unit. CLM supports 5 types of land units: vegetated, urban, lake (shallow and deep), glaciers and wetlands; these different types have diverse properties for computing water/energy demands.



3-2 CLM nested subgrid hierarchy for the landscape, showing the grid cell and land unit levels, where biogeophysical and hydrologic processes are performed

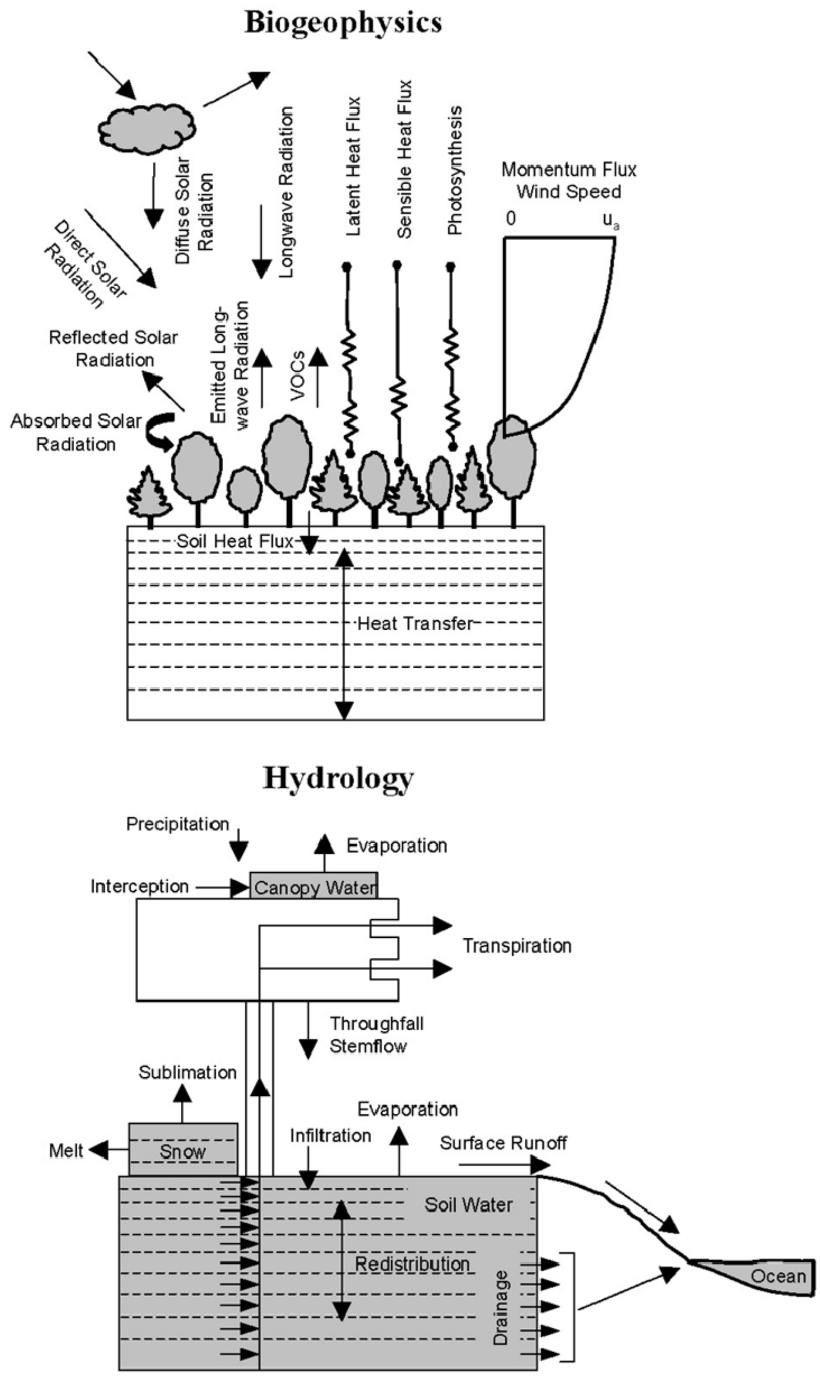


Figure 3-3 Biogeophysical and hydrology processes performed by CLM (adapted from Bonan, 2002)

The four latter types are referred to as "non-vegetated" types, and they share common processes for computing hydrological parameters such as evaporation. The land units are then divided into columns. This is where the "state variables for water and energy in the soil and snow are defined, as well as the fluxes of these components within the soil and snow." Only under the vegetated land unit, the third level is introduced as the plant functional level, and includes bare soil as a functional type. This is where plant physiology is defined and different PTFs share water and energy values defined at the column level. The above figure shows the biogeophysical and hydrological processes performed by CLM; the latter are precipitation, interception and throughfall, snow sublimation and melt, infiltration into the subsurface and groundwater, evaporation from the different land cover types, leaf surfaces and canopy transpiration, soil moisture, and surface and subsurface runoff.

3.1.1 CLM Lake and Wetland Water Balance

CLM hydrology is constrained by a water balance equation computed at the column level. It should be noted that lake and wetland land units have a 1:1 ratio to columns, so that processes implemented at the column level are effectively implemented at the lake/wetland land unit level. In any case, the water balance equation is calculated as:

$$\Delta W_{can} + \Delta W_{sno} + \sum_{i}^{N}\left(\Delta W_{liq,i} + \Delta W_{ice,i}\right) = \left(q_{rain} + q_{sno} - E_v - E_g - q_{over} - q_{drai} - q_{rgwl}\right)\Delta t$$

where ΔW_{can} is the change in total column canopy water, ΔW_{sno} is the change in total canopy snow; the summation calculates the total change in soil water and ice, for layers i to N. These changes in water storage are set to equal water fluxes in the form of rain, q_{rain}, snow, q_{sno}, vegetaion evapotranspiration, E_v, ground evaporation, E_g, and three runoff values: overland; q_{over}, subsurface drainage (which includes runoff from the lower layers of soil in the unsaturated zone) q_{drai}, and a runoff term created specifically for lakes, wetlands and glaciers, q_{rgwl}. Depending on the type of landunit, the above water balance will have some of these terms. For instance, q_{rgwl} is zero for vegetated landunits.

On the other hand, lakes and wetlands are implicitly viewed as non-vegetated surfaces and therefore exclude explicit calculation of all terms relating to plant hydrology. Other terms not specifically calculated in lake/wetland hydrology are infiltration, subsurface flow, percolation and aquifer recharge so that the water balance equation for these ecosystems reduces to:

$$\Delta W_{sno} + \sum_{i}^{N}\left(\Delta W_{liq,i} + \Delta W_{ice,i}\right) = \left(q_{rain} + q_{sno} - E_g - q_{rgwl}\right)\Delta t$$

Furthermore, CLM does not consider storage changes for lakes and wetlands and therefore *constant depth values* and *constant areas* are assumed; the areal extent of wetlands and lakes, taken from Cogley's (1991) 1^ox1^o dataset, are read in at the beginning of the run. What this results in is *non-varying* water volumes for these ecosystems. This feature is among those that will be enhanced for this study (and is described below in Section 4). Before expounding further on the implications of CLM's lake and wetland hydrology, the following sections describe how CLM computes evaporation and runoff for these ecosystems. It is followed by a description of CLM runoff, which is sent to the river routing component of CLM (River Transport Model), which creates streamflow.

Evaporation

Evaporation of water molecules into the atmosphere increases with their saturation gradient, and is limited by a resistance term, due to aerodynamic or canopy properties (Shuttleworth, 1979). In CLM, evaporation from non-vegetated surfaces is calculated by the following equation:

$$E_g = -\frac{\rho_{atm}\left(q_{atm} - q_g\right)}{r_{aw}}$$

The equation states that evaporation, E_g is calculated as atmospheric air density, ρ_{atm}, multiplied by the difference in ground saturation specific humidity and atmospheric specific humidity, - (q_g – q_{atm}) , divided by the aerodynamic roughness length. CLM assumes a first guess for reference-height wind speed and the Monin-Obukhov length. Using these first guesses, the friction velocity, potential temperature, specific humidity scales, roughness length for latent heat, and reference-height wind speed are then obtained iteratively. These parameters are then used to calculate the aerodynamic resistance, and water vapor flux. These values are combined to calculate latent heat (Oleson, 2004). Evaporation from lakes and wetlands is computed as open water evaporation, assuming an unlimited supply of water from which to evaporate, as opposed to vegetated surfaces, where evaporation is constrained by the amount of water available (among other physiological resistance factors).

It is important to note that wetlands, as was shown in previous sections, are defined by the presence of hydrophytic vegetation, which potentially changes their calculated evaporation rate. For this study, CLM's convention of calculating open water evaporation is maintained.

3.1.2 CLM Runoff

Depending on the land unit CLM calculates a specific type of runoff, which is then aggregated to the grid cell level before being sent to the River Transport Model (RTM) and used to generate streamflow. These runoff types are surface runoff and subsurface drainage, calculated for vegetated surfaces, and runoff from glaciers, wetlands and lakes. All three types are important for the development of CLM since the first two determine the amount of water generated in a catchment where a lake or wetland sits, i.e. the amount of water that drains into a lake and wetland; and the latter is a direct calculation of runoff from these ecosystems.

Surface Runoff

Following the concepts developed by Beven and Kirkby (1979) and used in TOPMODEL for calculating runoff, CLM surface runoff is proportional to the calculated saturated surface area. CLM determines the water table depth of a given location, and using a topographical index of grid cells, CLM then calculates the fractional saturated area for the same place. These two parameters are then used to calculate Dunne overland runoff (Dunne, 1970), which is proportional to the fractional area of land surface that has saturated due to a rise in the water table. In CLM, this is given by:

$$q_{over} = f_{sat} q_{liq,0} + (1 - f_{sat}) \overline{w}_s^4 qliq, 0$$

where q_{over} is the surface runoff. It is equal to the percent of land surface that's saturated by the water table, f_{sat}, multiplied by the $q_{liq,0}$, precipitation or snow melt at the top soil layer. Surface runoff also includes flow from the unsaturated top three layers of soil (based on their degree of permeability), given by the soil layer thickness weighted wetness in the first three layers, w_s, and multiplied by precipitation and snow melt in the first soil layer.

In the cases of both surface and subsurface runoff, soil water conditions are an important factor. CLM soil water conditions are calculated at each time step by dividing the subsurface into 10 layers. For each layer 1) vertical flow (infiltration, surface/subsurface runoff, gradient diffusion, canopy transpiration) are calculated based on the Z-L Yang (1998, unpublished manuscript) equation. In this equation, water is conserved by calculating one-dimensional vertical flow, given boundary and initial conditions, as:

$$\frac{d\theta}{dt} = -\frac{dq}{dz} - e$$

where θ is the volumetric soil water content, t is time, q is soil water flux, z is height, and e is a soil moisture sink. 2) The soil water flux, q, is calculated using Darcy's Law, which relies on the soil's hydraulic conductivity and pressure drop or "soil matric potential". These parameters are derived from their relationship to soil texture conditions and volumetric soil water, based on the work of Clapp and Hornberger (1978) and Cosby et al (1984). 3) Darcy's Law and mass conservation are combined to become the Richard's Equation (Oleson, 2004). Through these processes, vertical soil-water flow between soil layers is calculated and used to obtain surface or subsurface runoff.

Subsurface Drainage

Following the above outlined process for determining soil miosture content, how it's partitioned to canopy transpiration, aquifer recharge, and others terms, subsurface runoff or base flow is calculated from the last 4 soil layers, and is computed as "drainage out of the bottom of the soil column plus any adjustments required to keep the liquid water content of each layer between maximum and minimum values" (Oleson, 2004). It is given by the equation:

$$q_{drai} = q_{drai,wet} + q_{drai,dry} + \frac{w_{liq}^{excess}}{\Delta t} - \frac{w_{liq}^{deficit}}{\Delta t} + k\left[z_{h,10}\right] + \frac{\partial k[z_{h,10}]}{\partial \theta_{liq,10}} \Delta\theta_{liq,10}$$

In the equation above, base flow is q_{drai}. It is the sum of lateral drainage from saurated and unsaturated soil layers, $q_{drai,wet}$ and $q_{drai,dry,}$ respectively, in addition to the water content in excess of what's needed to fully saturate soil columns, w^{excess}, minus their minimum soil water content, $w^{deficit}$. The last two terms in the question calculate drainage from the bottom soil layer (layer 10), which is based on its hydraulic conductivity and how the conductivity changes with respect to its water content, θ.

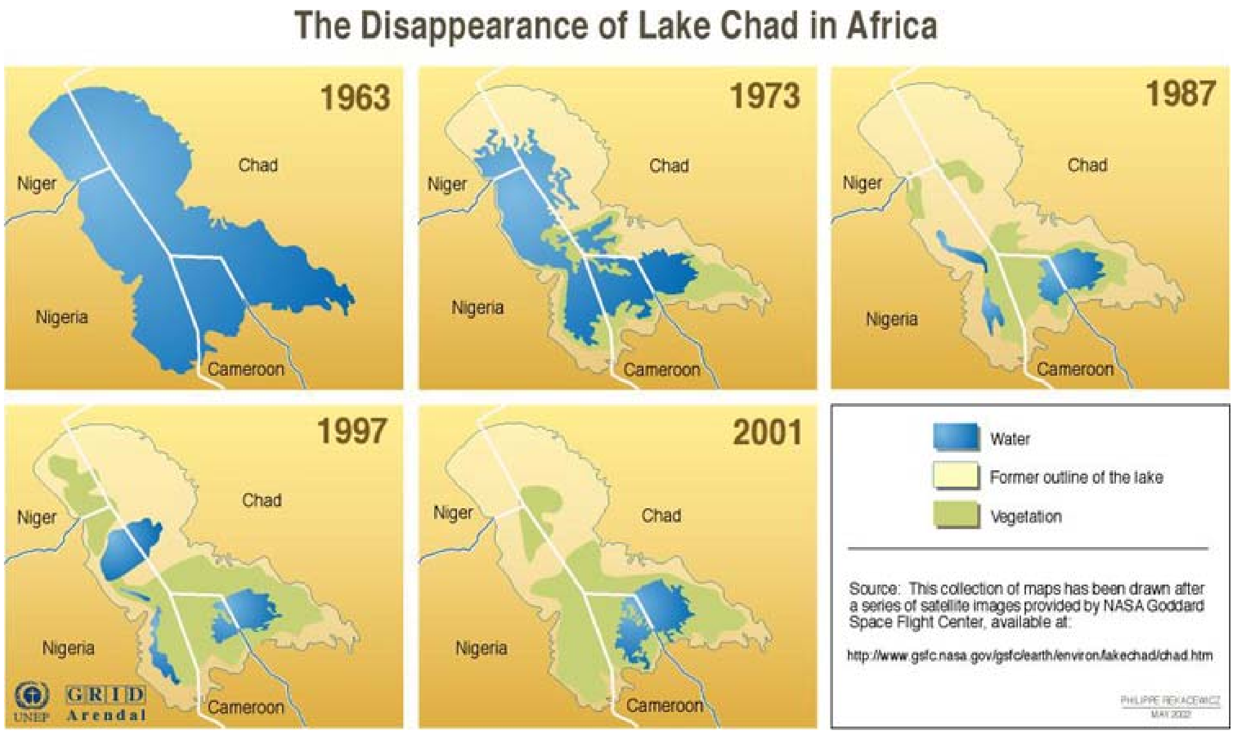
Runoff from Glaciers, Wetlands and Lakes

The final variable contributing to runoff at the grid cell level is runoff generated from lakes, wetlands and glaciers, q_{rgwl}. Rearranging the water balance equation for lakes/wetlands, runoff is calculated in accordance with the following equation:

$$q_{rgwl} = q_{grnd,ice} + q_{grnd,liq} - E_g - E_v - \frac{(W_b^{n+1} - W_b^n)}{\Delta t}$$

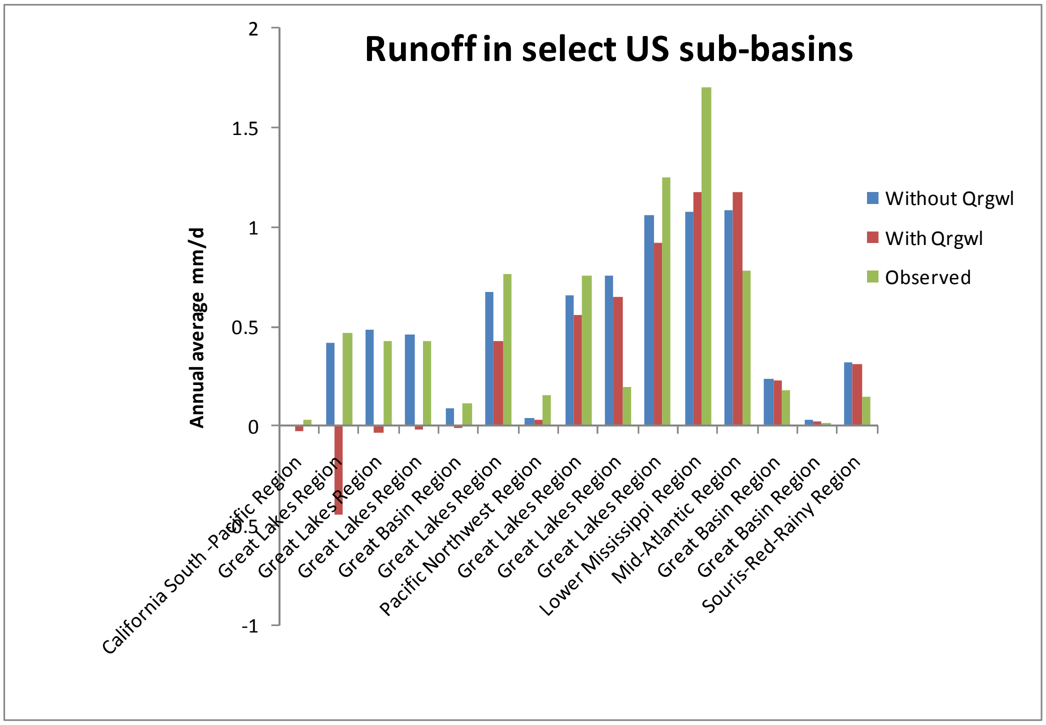
Runoff from glaciers, lakes and wetlands is thus given by liquid and solid forms of precipitation falling to the surface, minus the change in the land unit's water balance, $W_{b,}$ at times n and n+1, and ground and vegetation evaporation, E_g and E_v, respectively. Since lakes, wetlands and glaciers are considered non-vegetated surfaces, E_v is set to zero. The water balance term includes snow, ice and liquid content within the lake and wetland depth layers. A river routing model, the River Transport Model (RTM), then collects runoff from each cell and routes it to its adjacent downstream cell.

As was stated earlier, CLM lake and wetland volumes do not change. What this means is that the last term on the right hand side of the equation (change in water balance) goes to zero for all time steps, and runoff is the exchange between precipitation and open water evaporation. The immediate implication of not varying lake and wetland water storage is that one of the main environmental services performed by wetlands and lakes, namely modulating flow in their basins, is missing. What CLM calculates as runoff is simply the difference of precipitation and evaporation, and does not consider how wetland and lake storage changes with these variables. Indeed, the main contribution of this study is correcting this conceptual error. To demonstrate the importance of changing lake storage, Figure 3-4, (taken from the United Nations Environment Program website) shows how Lake Chad in Africa has changed in the past few decades. In CLM, this observed trend in volume (area and depth) of Lake Chad would be absent, given its inability to explicitly track changes in the lake's storage.



3-4 Lake Chad over the last 5 decades (taken from http://www.grida.no/publications/vg/africa/page/3115.aspx)

In addition, the above equation means that in cases when evaporation exceeds precipitation, CLM will generate *negative* runoff values to preserve the simplified water balance condition (i.e. no storage change). The following graph looks at annual average runoff generated for selected sub-basins in the United States. Total runoff for each catchment was calculated using surface and subsurface runoff, on the one hand, and all three runoff variables on the other. The two datasets were compared to observed streamflow data for the same locations. The annual averages are expressed in mm/day, for the period of 1949-1976. The graph in Figure 3-5 looks at sub-basins within the named larger basins.



3-5 Comparison of CLM runoff (surface and subsurface only) to all three runoff variables and observed streamflow for all select US sub-basins

In parts of the Great Lakes basin, for instance, the annual average runoff is negative, according to CLM, while for the Great Basin region, total CLM runoff is set to zero. The above graph demonstrates the importance of land storage units in the water balance of a river basin.

3.1.3 River Transport Model

One variable that may be a good measure of the robustness of a land fluxes model is streamflow. This is due to the availability of many datasets, observed or modeled, which can be used to validate the model's performance. Further, when land models are used to inform water policy, streamflow is an important link between the "natural and managed hydrologic systems" (Strzepek et al, 2010). According to Oleson (2004) RTM was developed to close the hydrologic cycle of CLM; to model ocean convection and circulation, which are affected by freshwater inputs; and to provide another diagnostic tool for assessing the performance of CLM's hydrology. The RTM uses a "linear transport scheme" based on the topographical relationship of adjacent cells, at 0.5^{o} x 0.5^{o} spatial resolution. Using topographical data, a river direction matrix is input into RTM, telling it the downstream relationship between contiguous cells. The downstream relationship is defined as one of eight compass points; each cell is labeled a value between 0 and 8, where 1-8 are each of the 8 compass points (north, northeast, east, southeast, south, southwest, west and northwest), and 0 means the cell is an ocean cell. At each cell, RTM calculates the change in water storage, $\frac{dS}{dt}$, as equal to the sum of all upstream flows draining into the cell, F_{in}, in addition to the runoff (surface, subsurface and wetland/lake/glacier runoff), R, generated at that cell, minus its outflow, F_{out}, according to the following equation:

$$\frac{dS}{dt} = \sum F_{in} + R - F_{out.}$$

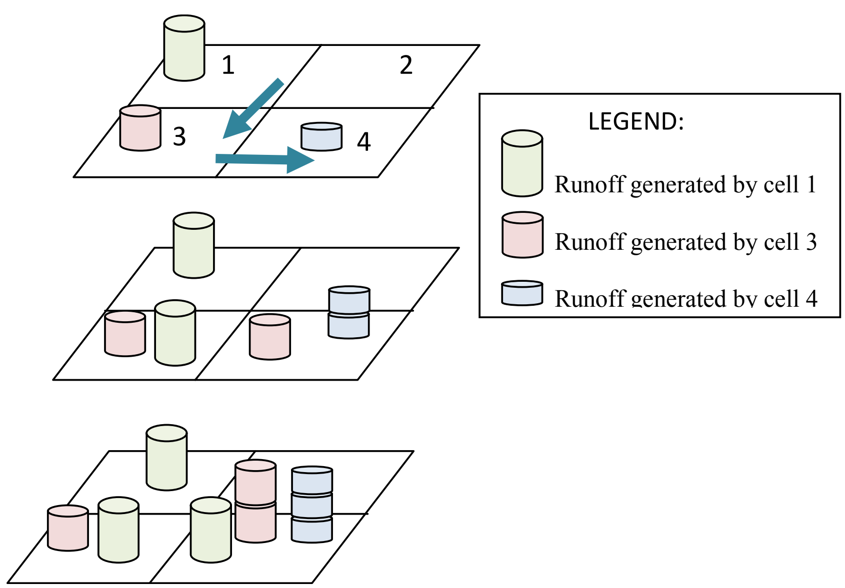
RTM's procedure for calculating outflow F_{out} follows Miller (1994) in that it is based on continuous streamflow, as well as its use of a single effective velocity to derive outflow. Miller shows that for larger basins, there is little difference between the use of an effective velocity and a variable one (that is determined by topography and other local properties). This effective velocity in RTM is 0.35 m/s. Also following Miller (1994), outflow is based on the distance between cells, d, and the cell's storage at a given time step, S:

$$F_{out} = \frac{v}{d} S$$

RTM conserves water globally, as

$$\sum_{i,j} \left[\frac{dS}{dt}\right]_{i,j} = \sum_{i,j} R_{i,j}$$

where i and j are cell indexes, $\frac{dS}{dt}$ is the change in storage, and R is total runoff generated at each cell. Figure 3-6 is a visual representation of what RTM does:



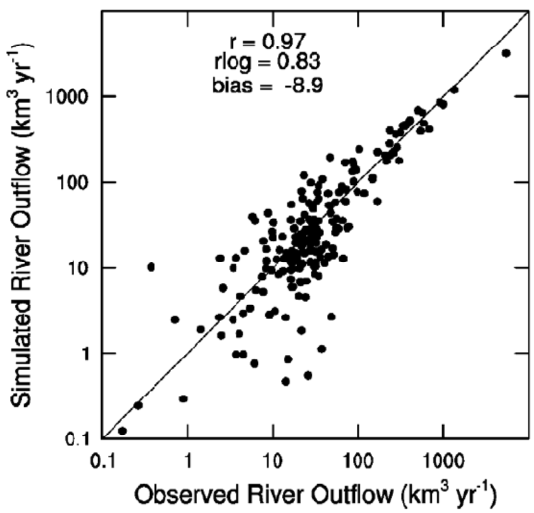
3-6 A simple schematic that shows how RTM generates streamflow from grid cell runoff

The figure above is a simplified schematic of what RTM does, where the three layers of grid cells represent time steps (the top layer is time step 1). In the first time step, runoff is generated in 3 of the 4 cells. In the second time step, following the river direction given by the arrows, runoff from cell 1 becomes streamflow and is transported to cell 3; what was previously runoff in cell 3 flows to cell 4. In addition, each of these cells generates its own runoff at this time step as well. In the third time step, cell 1 first send its previous storage of runoff to cell 3, while it produces runoff for the current time step; cell 3 sends its previous storage to cell 4, while simultaneously generating its own runoff and accepting flow from its upstream neighbor, cell 1. And cell 4 receives flow from cell 3, while it also generates its own runoff. Note that in this example, cell 4 is the final discharge cell (in reality, RTM's final discharge cells are usually ocean cells).

The main implication of this process is that the process for generating streamflow is the same, regardless of the land unit found in a given cell. In other words, the equations for calculating streamflow are the same for lakes, wetlands, forests, grasslands, mountainous or flat terrain. In addition to how streamflow is generated for different environments, cases where one type of land surface spreads across many cells means that these cells need to interact with each other in ways more direct (and very particular to the type of environment) than what is done here in RTM.

3.1.4 General Assessment of CLM Hydrology

This section highlights several studies that convey how CLM hydrological processes perform in comparison to observed data and other models. There is focus on the parameters that are important to the modified wetland model, mainly CLM runoff, river discharge and evapotranspiration. Qian et al (2005) conducted a general assessment of CLM's (version 3; CLM3) streamflow, continental freshwater discharge, surface runoff and soil moisture for the period 1948-2000 and found CLM3 to compute these parameters well as compared to their observed long term means. In order to conduct the assessment, CLM3 was run using NCEP/NCAR reanalysis data of precipitation, temperature, pressure, solar radiation, wind speed and specific humidity, which is available at sub-daily increments, for a spatial resolution of T62 (~1.875^{o}). The CLM3 hydrologic parameters were then compared to available observations. The authors comment on the reliability of both the forcing data as well as the validation data, stating that errors in results are attributable to either as well as to the model itself. When possible, the authors intercepted and corrected these sources of error. For instance, they bias corrected the temperature, solar radiation and precipitation using available monthly observations. Comparing CLM's annual streamflow to observations from Dai and Trenberth (2002) for the 200 largest rivers produced the figure below of long term mean stream flows, displayed on a logarithmic scale.



3-7 CLM streamflow compared to observed streamflow (from Dai and Trenberth, 2002) for the 200 largest rivers. (Taken from Qian, 2005)

Results show a correlation of r=0.97 between CLM3 and observed data, although there's a mean CLM3 bias of -8.9 km^3/yr. The paper finds that CLM3 was able to capture the seasonal variations for the 10 largest rivers. The study also compared continental fresh water discharge against observations at each latitudinal degree. CLM3's discharge captures peak outflows from the world's largest rivers, but was found to underestimate the discharge for the 8^oS-22^oN zonal region. The third parameter was CLM3 runoff, which was compared to "long-term mean stream flow data from 663 gauge stations to calibrate the global runoff fields calculated from a water balance model, resulting in a monthly climatology (mostly for the 1950-1990 period) of runoff at 0.5° resolution" (Qian, 2005). Although it is acknowledged that this is not observed data, the paper states that it is the most complete available dataset. CLM3 showed large positive biases in northern mid and high latitudes (100-200% more than observed) and negative summer biases (-50% to -100%). The authors contribute CLM3's large bias to, among other reasons, the model's land-storage capacity (e.g. lakes and wetlands). Observations on soil moisture were found to be very limited, but CLM3's results were found to be comparable to available observations (Qian, 2005).

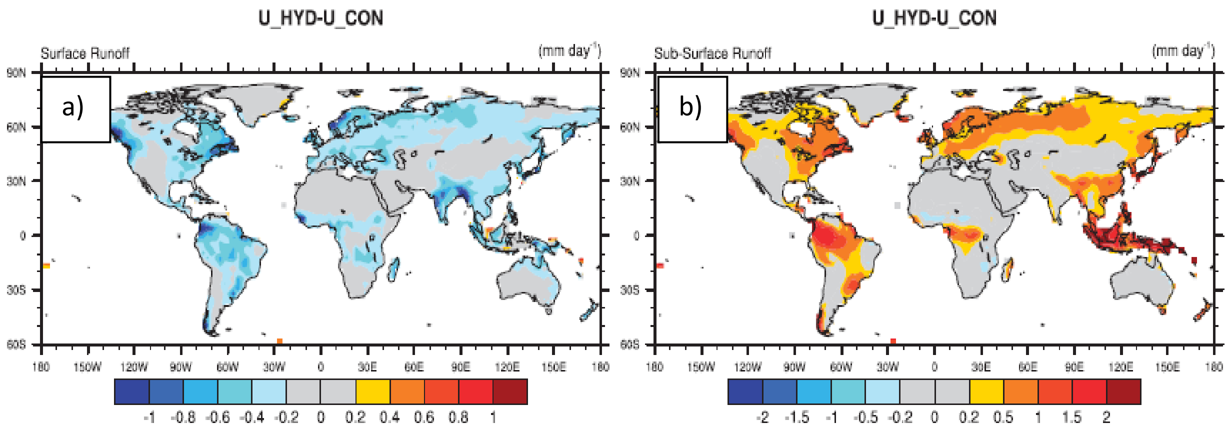
Lawrence and Chase (2009) evaluated CLM3's evapotranspiration (ET), and found that the partitioning of ET into bare soil evaporation, evaporation from intercepted precipitation and canopy transpiration differed from results obtained by other biogeophysical models. CLM3 attributed 15% of total ET to canopy transpiration, 47% to bare soils, and 38% to intercepted rainfall, while other models partitioned ET into 47%, 36%, and 17%, of each of the three parameters, respectively. Changing CLM3's parameterization of "1) soil hydrological properties; 2) soil evaporation; 3) soil infiltration and runoff; 4) deep soil drainage; 5) photosynthesis and transpiration; 6) soil moisture root stress; 7) root zone soil moisture representation; and 8) canopy interception and evaporation" improved the partitioning significantly and brought it closer to results from other models. Each of these parameterizations was systematically added into CLM3, and evaluated for its impact on global hydrology, against results of multi-model averages provided by Dirmeyer et al (2005). CLM version 3.5 (CLM3.5), which includes similar new parameterization schemes, also improves ET values. Table 3-1 shows results of CLM3, the work by Lawrence and Chase (2009) (CLMSib), CLM3.5 and Dirmeyer (2005) multi-model averages. All values refer to global averages in mm/day, where P is precipitation, ET is evapotranspiration, T is canopy transpiration, CE is evaporation from canopy intercepted precipitation, SE is soil evaporation, SR is surface runoff and D is drainage.

Table 3-18Results from Lawrence, 2009, showing precipitation, evapotranspiration, partitioning of ET, surface runoff and drainage, for CLM3, CLMSib, CLM3.5 and results from Dirmeyer, 2005

	P	Total ET	T (%ET)	CE (%ET)	SE (%ET)	SR	D
CLM3	2.46	1.52	0.23 (15)	0.58 (39)	0.7 (46)	0.47	0.41
CLMSib	2.44	1.55	0.65 (42)	0.34 (22)	0.56 (36)	0.32	0.51
Dirmeyer	2.29	1.34	0.64 (47)	0.22 (17)	0.48 (36)	0.32	0.63
CLM3.5	2.18	1.39	0.57 (41)	0.28 (20)	0.54 (39)	0.14	0.64

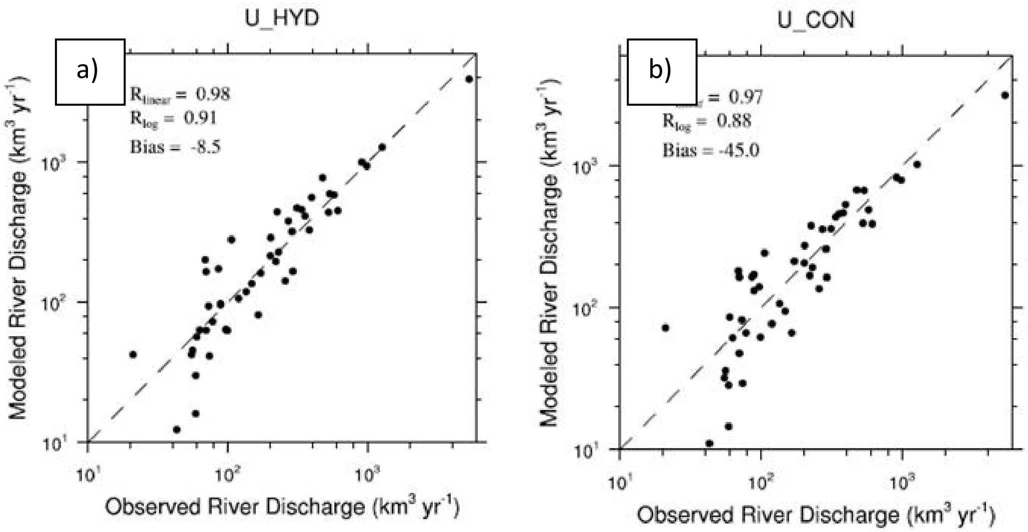
The results show improvements in ET partitioning from CLM3 to CLMSib and CLM3.5 as they're compared to Dirmeyer (2005), although CLM3.5's surface runoff is 43% that of the model mean of Dirmeyer (2005).

Modifications were made to CLM3's hydrology and incorporated into CLM3.5. As reported in Oleson et al (2008), these were: incorporating new datasets of PFT, leaf index area and glacier and wetland maps that are based on multi-year values as opposed to one-year values in CLM3; improvements to how canopy intercepted radiation is divided between the shaded and sunlit fractions of the leaf; lowering canopy interception; better mechanisms for calculating overland runoff from saturated surfaces, which lowers the surface runoff to total runoff ratio; a more explicit representation of groundwater; increasing soil permeability in cold regions, which also lowers their surface runoff ratio; improving mechanism that determines how much soil moisture is available to plant roots; and improving mechanism for calculating soil evaporation, results of which are shown in the table above. Aside from the ET partitioning results, modeling improvements were also reflected in runoff results, and the following diagram shows runoff difference between CLM3.5 (U_Hyd) and CLM3 (U_CON). Figure 3-8 shows less surface runoff in humid areas, with a resulting increase in subsurface runoff for the same regions.



3-8 CLM3.5 (U_HYD) - CLM3 (U_CON) a) surface and b) subsurface runoff values in mm/day.

Also, CLM3.5 stream flow was compared to data from the University of New Hampshire – Global Runoff Data Center (UNH-GRDC). UNH_GRDC combines observed river discharge information with output from a climate-driven water balance model. "[C]omparisons [to CLM3.5] were made for grid cells where UNH_GRDC had valid observed runoff". The following two diagrams show how CLM3.5 (U_HYD) and CLM3 (U_CON) compare to this data. The correlation between CLM3.5 and UNH_GRDC is 0.98, only slightly improving CLM3 (0.97). However, CLM3.5 has a bias of -8.5 km^3/yr, compared to CLM3's bias of - 45 km^3/yr.



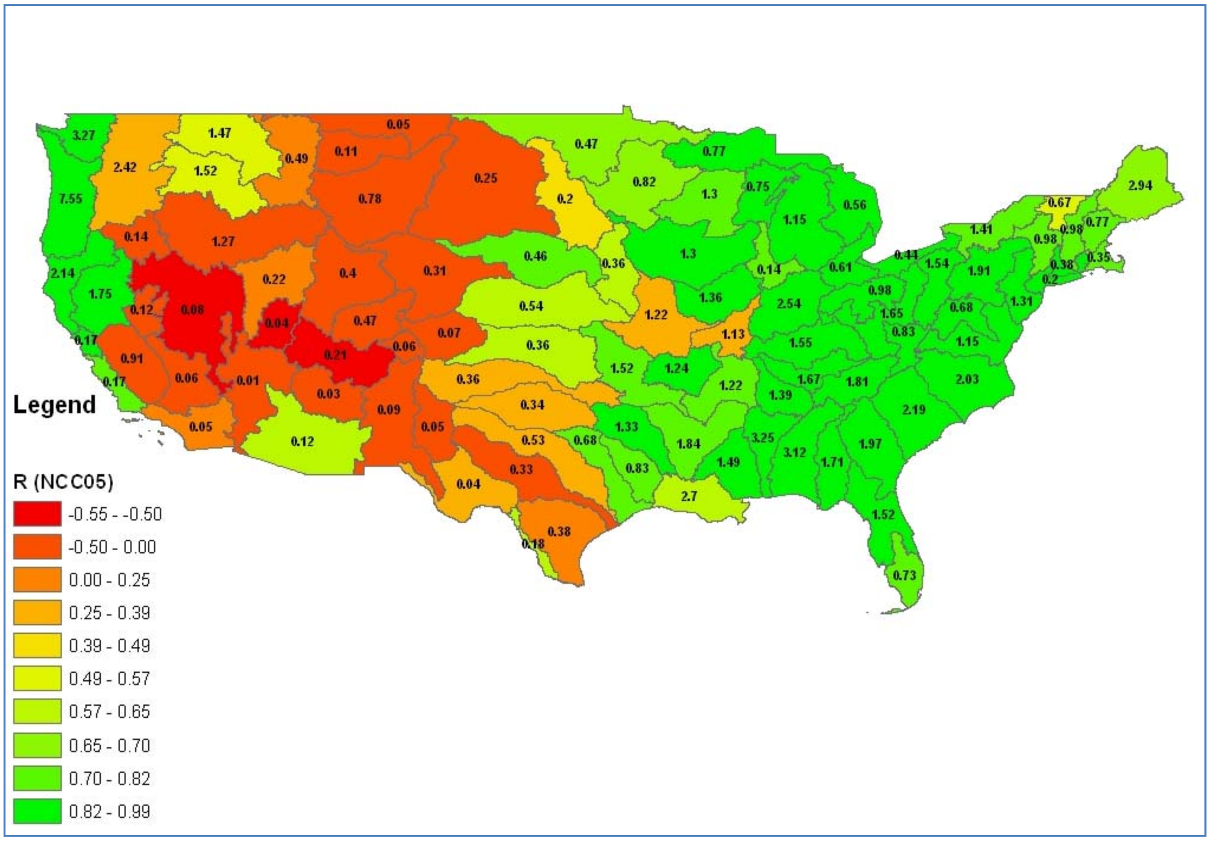
3-9 a) CLM3.5 streamflow compared to UNH_GRDC streamflow; b) CLM3 compared to UNH_GRDC. Both on logarithmic scale. The diagram also shows correlation and log correlation values and biases. (Taken from Oleson, 2009)

The above studies focused on assessing the large spatial scale, long-term means of CLM variables, finding that, for instance, long-term means of CLM streamflow in general agreed with observations. Strzepek et al (2010), on the other hand, conducted an assessment of CLM3.5 runoff for the 99 sub-basins within the United States. The study choose 3 forcing datasets to run CLM: "NCEP Corrected by CRU (NCC, Ngo-Duc et al., 2005), Climate Analysis Section (CAS), (Qian et al., 2006), and the Global Offline Land Data (GOLD), (Dirmeyer and Tan, 2001)" (Strzepek et al, 2010), at 3 spatial resolutions each, 0.5° x0.5° , 1°x1° and 2°x2.5°, resulting in 9 CLM runoff outputs. Taking only *surface runoff and subsurface drainage,* CLM's was then compared to observed monthly streamflow data for the years 1948-1976. Calculating unweighted average correlation coefficients for the 9 flow results showed that NCC 0.5x0.5 forcing dataset resulted in values which compared most favorably to observed data. The study also shows that CLM runoff compared better when correlation coefficients were weighted by the runoff to area ratio of the basin. The following results show unweighted and weighted correlation coefficients from the 9 forcing datasets:

Table 3-2 Unweighted, Ru and weighted Rw correlation coefficcents for streamflow produced from CLM via the 9 forcing datasets, NCC, CAS and GOLD at 3 spatial resolutions each. (From Strzepek et al, 2010)

	CAS05	CAS1	CAS2	GOLD05	GOLD1	GOLD2	NCC05	NCC1	NCC2
R_u	0.47	0.46	0.46	0.42	0.41	0.41	0.52	0.51	0.49
R_w	0.77	0.77	0.77	0.74	0.75	0.75	0.79	0.79	0.76

Based on the above results, runoff results based on NCC 0.5x0.5 compared best to observed streamflow values for the 99 sub-basins within the US. Figure 3-10 shows correlation coefficients for the different sub-basins, where basins in darker green shades showed coefficients at around 0.90:



3-10 Correlation coefficients for 99 sub-basins in US. Map also displays the percent streamflow to total for the US (from Strzepek, 2010)

Again, the above analysis only looked at *surface* and *subsurface drainage* and did not include the term that describes runoff from lakes, wetlands and glaciers. Following a description of the lake and wetlands equations used in this model, is a closer look at the different parameters used to compute runoff and how they were modified using these equations in the new wetland and lakes component.

4.0 METHODOLOGY: THE MODIFIED CLM-LW

This section describes how CLM was modified to include components that explicitly calculate lake and wetland hydrology, which allow for a variable storage, area and depth in these ecosystems, and recalculate outflow as a function of volume, area, depth, inflow, land-atmosphere fluxes, and geometry. The new CLM lake and wetland components will be collectively referred to as CLM-LW.

4.1 Lake/Wetland Components in RTM

The following describes the new changes applied to CLM3.5 so as to obtain CLM-LW, where most of CLM-LW code was written within RTM. The main changes to lakes and wetlands in CLM-RTM can be summarized in the following steps:

1) The CLM hierarchical structure for partitioning grid cells into land units of lakes and wetlands is maintained
    a. CLM uses these definitions to determine the correct biogeophysical processes associated with each land unit, a feature that is preserved
    b. However, changes were made to the total wetland areas recorded in CLM
2) Evaporation for lakes and wetlands
    a. Lakes are allowed to use CLM calculated evaporation, while new code was written for wetland evaporation
3) Runoff at the land unit level is calculated in CLM and sent to RTM
    a. What CLM sends to RTM as lake/wetland runoff now refers to the difference between precipitation and evaporation; CLM-LW removes the water balance component from runoff calculation, and calculates each lake/wetland's water balance according to more sophisticated equations
4) Lake and wetland clusters
    a. Code is built into RTM so that where a single lake or wetland spans multiple cells, each set of cells making up that lake/wetland is treated as one entity.
    b. Re-routing was done so that lake and wetland clusters have a single discharge cell.

c. Inflow entering lakes and wetlands from multiple locations, either from their catchment or as river flow from upstream, is collected as one value.

5) Lake and wetland equations for outflow

a. Using inflow, precipitation and evaporation, equations that allow for a change in storage, and a variable depth or area for the wetland/lake are coded into RTM.

b. Outflow is calculated as a function of volume, inflow, precipitation and evaporation.

c. Equations were parameterized for a daily time step.

6) Downstream of lake and wetland clusters

a. Outflow is discharged according to the above-mentioned equations of flow, and allowed to follow the existing RTM code for routing river flow to downstream cells.

4.1.1 CLM Grid Cell and Land Unit Structure

As was mentioned above, CLM divides the landscape into a nested hierarchy of grid cells, land units, columns and PFTs. Lakes and wetlands are defined at the land unit level, contain one column each (no PFTs). The lake and wetland land unit areal extent is read in from a surface dataset as a percentage of the grid cell. The lake and wetland surface dataset used in CLM was developed in Cogley (1991), based on a 1^{o}x1^{o} spatial resolution. The Cogley database has 21 fields of land surface types which include intermittent freshwater lakes, glaciers, perennial rivers, bare land, and multiple types of wetlands. Although this database is relatively old (developed in the mid-80s), it is still widely used due to its being of “moderate size, [having] internal consistency and useful content” (Cogley, 2003). However, one of the setbacks to this database is that it consistently underestimates the areal extent of wetlands and lakes. Table 4-1 is from Lehner and Doll (2004), and shows their global wetland area estimates, compared to estimates from other studies and those of Cogley, with all values given in 1000 km^2. The columns boxed in blue are Cogley’s estimates for various wetlands around the globe, and GLWD-3 estimates. An example of how Cogley consistently underestimates wetland areas is demonstrated by values in the row boxed in red, which shows that it is documented that the Amazon wetlands span about 300 000 km^3, the Cogley database records these wetlands to be about 21 000 km^3.

Table 4-1 Wetland area estimates from different studies, highlighting Cogley, GLWD-3 and areas of Ramsar sites (From Lehner and Doll, 2004)

Global wetland distribution of GLWD as compared to different authors

Country/Region	Documented wetland extent	Matthews and Fung	Cogley	Stillwell-Soller et al.	GLCC	MODIS	Gross wetlands map[a]	GLWD-3
Niger Inland Delta[b]	15–17[c]; 20-30[d]	30	14	7	0	1	43	36
Zaire Swamps[b]	132–220[f]; 200[e]	100	69	30	0	0	139	184
Sudd Swamps[b]	16–31[d]; >30[e]	21	3	28	18	5	37	29
Okavango Delta[b]	10–18[c]; 16[e]	13	7	5	4	5	21	19
China, incl. Tibet	250[e,f]	93	378	27	5	76	495	311
Canada	1270[e]	681	757	1119	218	107	1814	1601
USA, lower 48	420[e]	197	80	173	8	25	373	733
Alaska	710[e]	197	13	243	0	8	328	456
Gran Pantanal[b]	140[e]	143	146	98	4	0	229	142
Amazon Wetlands[b]	300[e]	69	21	471	31	0	480	357
Ramsar sites	1059[g]	323	176	164	36	47	500	642
North America (1)	2400[e,h]; 2416[i,j]	1126	872	1542	248	153	2609	2866
South America	1208[k]	727	578	1365	80	58	2132	1594
Europe (2)		811	413	432	22	18	1195	260
Africa	1213–1247[i]	718	368	265	152	296	1431	1314
Asia		1688	2043	1183	587	659	3997	2856
Australia and Oceania (3)	>240[l]	188	67	8	1	108	342	275
Global (4)	8558[c]; 7000-9000[e]; 5600-9700[j,m]	5260	4340	4795	1093	1291	11,711	9167

Therefore, in order for CLM-LW to produce meaningful results, wetland areas should be well represented, and this is done for the case study as will be shown later.

4.1.2 Lake and Wetland Evaporation

The process by which CLM computes evaporation from lakes and wetlands was presented above. Changes were applied to evaporation calculated from wetlands, so that CLM-LW calculates evaporation using the Modified-Hargreaves process for calculating open water evaporation. The Penman-Montieth equation is considered to be the most physically sound method for calculating evaporation, as it captures both the physiological and aerodynamic properties for the area for which it's used (Allen et al, 1998). However, one major setback to this method is that many parameters are needed for which limited or no observational data exists. Motivated by this limitation in data, Hargreaves et al (1985) developed a method that estimates monthly reference evapotranspiration, $ET_{o,}$ using only extra-terrestrial radiation, and maximum as well as minimum temperatures. Doogers and Allen (2002) then found that monthly precipitation values were indicators of specific humidity, and that better estimates of ET_o (as compared to ET_o calculated using the Penman-Montieth) were obtained when monthly precipitation was factored into the equation; thus they developed the Modified Hargreaves (MH) method for calculating monthly ET_o.

CLM-LW uses the *daily* Modified Hargreaves developed in Farmer et al. (2011) for wetland evaporation. The method takes the following equation:

$$ET_o = 0.0019 \cdot 0.408RA \cdot \left(T_{avg} + 21.0584\right)(TD - 0.0874P)^{0.6278}$$

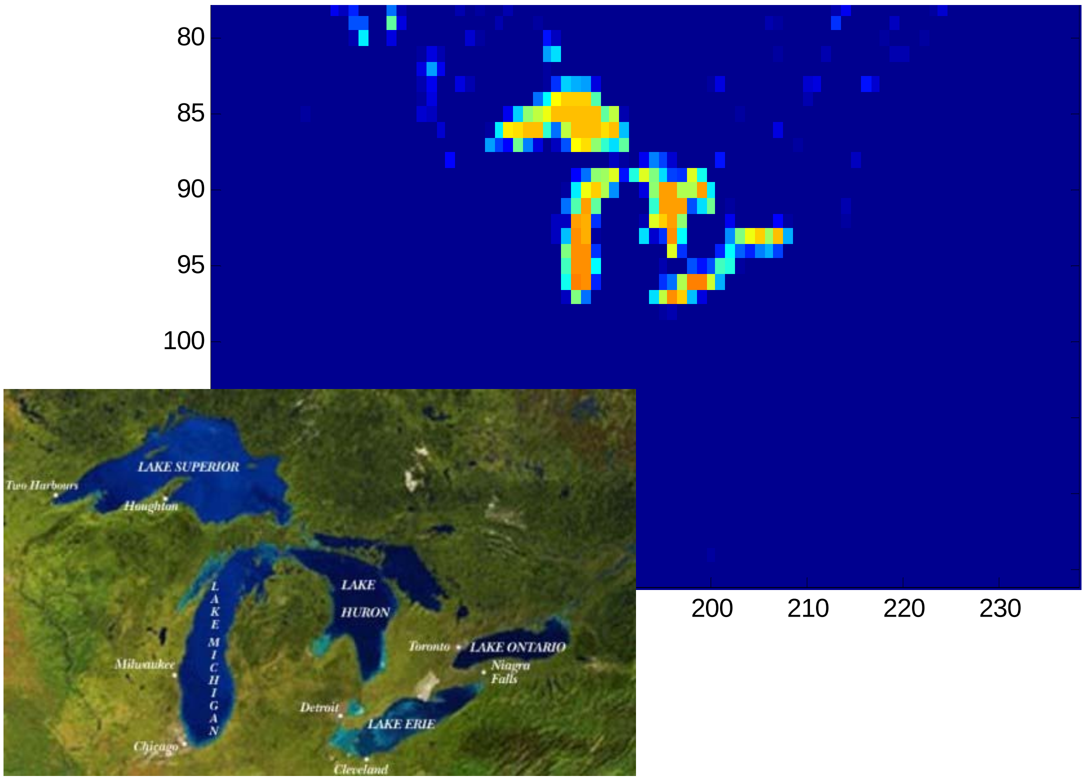
where, ET_o is the potential evapotranspiration, RA is daily extraterrestrial radiation, T_{avg} is the average daily temperature, TD is the daily temperature range, and P is precipitation.

4.1.3 Lake and Wetland Clusters

Another major modification made to CLM-LW is the creation of lake and wetland clusters. RTM, as was stated previously, is more akin to a river meta-model, such that flows entering one cell do not interact with the hydrological or biogeophysical processes of this cell. For instance, inflow does not contribute to how much evaporates from the cell it is entering; it does not contribute to soil moisture, infiltration, or other losses. Instead, inflow entering the cell accumulates with other inflows coming from the cell's other upstream cells, and in addition to runoff generated in that cell, is routed off to the next downstream cell, and so on. In reality, channel losses occur and could have a significant impact on a basin's water budget. For example, taking Sutcliffe and Park (1999) values, the main Nile River (White + Blue + Atbara) has an average annual inflow of 85.4 km^3, while what enters the Aswan Dam is 84 km^3. There are also annual channel losses of 3 km^3 between Malakal and Khartoum.

More importantly for the purpose of research is that in situations where a single lake/wetland spans several cells, it should be treated as a single unit; inflow coming into some of these cells should interact with all other parameters in all other cells of the lake/wetland unit. The same is true for precipitation, evaporation, depth, area, and so on. In the original CLM-RTM, this is not the case. And this was indeed among the major modifications that make up CLM-LW.

Figure 4-1 shows the grid cells that make up the Great Lakes of North America: Lake Superior, Erie, Huron, Michigan and Ontario, which each span many grid cells.



4-1 CLM cells that make up Great Lakes; inset picture from http://thelargest.net/lake-in-america/great-lakes

CLM-LW is developed such that the cells making up Lake Superior would interact with each other; that inflow entering the outer cells of Lake Michigan would be distributed among all of its cells according to the lake's geomorphology; that precipitation and evaporation rates for Lake Erie consider the value of these parameters for all of the lake's cells; that depth varies consistently for all the cells that make up Lake Huron; that the variable volume of a given lake refers to how volume changes in each of that lake's cells; and that all cells in a lake or wetland contribute to how outflow is calculated.

Therefore, CLM-LW was developed to recognize the cells that make up a lake or wetland unit, while distinguishing between nearby cells that are part of different units. The lake and wetland clusters were achieved through the use of structured arrays and manipulation of the river direction matrix, which determines upstream-downstream relationships between adjacent cells. The following steps were employed to create clusters:

1) Based on a literature review of the exact location of lakes and wetlands within the White Nile basin, it was determined which and how many cells make up each wetland or lake
2) The value of key cells in the river direction matrix, which correspond to cells within lake/wetland, was changed so that they point in another direction. This was done so that cells with the lake/wetland unit have localized flow, thus establishing a way for these cells to communicate
3) The above step also results in the lakes/wetlands having a single discharge cell rather than multiple ones, which was previously the case. The discharge cell is defined as the first non-lake/non-wetland cell outside the lake/wetland, to which flow from inside cells eventually reaches
4) Code was written so that, given the latitude/longitude parameters of a cell (or more accurately, its index number), the cell's "catchment", or all the upstream cells that drain to it, can be determined. The catchment of every lake/wetland discharge cell was then determined, using this code
    a. For the discharge cell of the Sudd, for instance, its catchment spans the entire White Nile above that cell
5) From this catchment, all other previously determined catchments, as well as all other non-lake/non-wetland cells were subtracted out, leaving only the wetland or lake that's directly adjacent to the discharge cell
6) Fortran 90's Structured Arrays allow for elements of an array to be defined by other arrays rather than a scalar value
    a. Structured arrays were then used to record the discharge cell location as well as the cells that make up that wetland or lake
    b. The advantage of using structured arrays is that other information about the lake or wetland can later be recorded, such as its initial volume, the coefficients used in its flow equations, and so on

In this way, what were previously disjointed cells, each independently calculating outflow, now become cells that are part of the same unit. Also, this procedure means that the following can be done:

1) Inflow entering the outermost cells of the cluster can be collected and singled out as one value;
2) Precipitation and evaporation difference, what CLM computes as the runoff for lakes and wetlands, can also be extracted and averaged out for all the cells in the cluster; and
3) Outflow can be computed as the inflow into the discharge cell, taking care to separate it from inflows into the discharge cell coming from other upstream cells (that are not part of the cluster) or the fractions of the cluster cells that are a land unit that is not lake or wetland.

4.1.4 Lake and Wetland Equations

The equations utilized in CLM-LW that describe lake and wetland hydrology were first developed by Sutcliffe and Park (1987) and later manifestations of them were developed by Yates and Strzepek (1998), Kashaigili et al (2006), and Block and Rajagopalan (2009). The equations use a mass balance approach; assumes lakes and wetlands have the same hydrologic response as that of reservoirs; considers head-area-volume curves and non-linear outflows for determining reservoir storage; and run at a monthly time step (Sutcliffe and Park, 1987). The following, from Yates and Strzepek, is the generic form of the lake hydrology equation:

$$\frac{dV}{dt} = I_t + I_u + \left(\left(P_{eff} - PET\right)\left(a_1V^3 + a_2V^2 + a_3V\right)\right) - \left(b_1V^2 + b_2V + b_3\right)$$

where I_t is tributary flow or runoff calculated at the catchment; I_u is upstream river flow; P_{eff} is the effective rainfall; PET is the potential evapotranspiration; V is volume; and a and b are coefficients to convert volume into area and discharge, respectively.

Swamps have the following flow equation:

$$\frac{dV}{dt} = I_t(1 - \tau) + I_u + \left(\left(P_{eff} - PET\right)(kV)\right) - r_c kV - \left(aV^2\right)$$

In this equation, τ is the percentage of tributary flow that bypasses the wetland and flows straight to the river; k is the non-varying depth of the wetland; r_c is the recharge rate for wetlands, and a is the discharge coefficient. These equations were manipulated so that CLM-LW can run at a daily time step, rather than monthly.

CLM-LW was implemented in a way that allows for its customization to different wetlands/lakes, as long as they can be assumed to behave like reservoirs. What are required are 1) an assessment of the structural and input parameters into the lake/wetland, and 2) a parameterization of the equations of flow for the specific ecosystem. The following section shows how CLM-LW was implemented for lakes and wetlands within the White Nile.

5.0 THE WHITE NILE AS A CASE STUDY

This chapter investigates how CLM-LW was implemented for the mainly the Sudd wetland, located in the White Nile, one of two major tributaries that make up the Nile basin in the eastern part of Africa. Following a brief description of the Nile basin, the chapter is divided into four parts: the first is a brief description of the sub-catchments of the White Nile and how they interact with the Sudd wetland. This is following by a detailed description of the Sudd wetland, based on a literature review. The third part is a description of how CLM-LW was customized to fit the lakes and wetlands in the White Nile. The last part is a description of the results obtained from CLM-LW for the White Nile and the Sudd. Note that CLM-LW was implemented to simulate flow patterns, volumes, and evapotranspiration, in six sub-basins – 3 wetlands and 3 lakes – which together, make up the White Nile River. Finally, *The Hydrology of the Nile Basin* by Sutcliffe and Parks (1999) serves as a major point of reference for much of the research on the White Nile, and is often referred to below.

5.1 Nile Basin

The Nile extends over 35 degrees of latitude (4^{o}S to 31^{o}N). Its more distant source is the upper catchment of Luvironza River in Burundi, a tributary of the river Kagera. The river flows into Lake Victoria, the second largest fresh water lake in the world. Victoria releases part of its waters into Lake Kyoga, which has been classified as either a swamp or lake. Kyoga discharges itself into Lake Albert, which also receives its waters through the Semiliki River from Lakes George and Edward. As the waters leave Lake Albert in its northerly descent, it becomes Bahr el Jebel, the beginning of the Sudd sub-basin. There, it connects with negligible flows from Bahr el Ghazal, and high, seasonally variable flows from the Sobat River (Howell et al, 1988).

The other major half of the Nile is the Blue Nile whose major tributaries are the Rahad and Dinder. These waters originate in Lake Tana in Ethiopia, and in the surrounding eastern and southern regions to the lake. After the confluence of the White and Blue Niles in Khartoum, Sudan, the main river is then joined by the Atbara, also originating in the Ethiopian plateaus, northeast of Lake Tana. The main Nile then makes its way northward through Egypt, and fans out in a delta before pouring into the Mediterranean Sea (Howell et al, 1988).

The Sobat, Blue Nile and Atbara (which all originate in Ethiopia) contribute about 86% of the Nile's total discharge at the Aswan dam in Egypt. The rivers originating at the Ethiopian highlands are marked by extreme seasonal variations, in contrast to the flow from the East African catchment, which are highly regulated and damped by the presence of lakes and wetlands. The flows from the Ethiopian highlands, at their seasonal highest, provide about 95% of the flow entering Egypt, while at their lowest, only about 60%. At peak flow, the velocity and quantity of the Blue Nile causes a ponding effect for the White Nile, and water is backed for more than 300 km. This natural reservoir is only released when the Blue Nile's flow drops in late September. Research shows that this natural feature has inspired most construction projects along the Nile (Howell et al, 1988).

The Nile basin's rainfall regime is mostly governed by the Inter-Tropical Convergence Zone (ITCZ), and is characterized by latitudinal variations across the stretch of the basin and resulting climatic classification (arid, tropical then equatorial, from north to south). This is also reflected in the seasonal variation of rainfall along the sub-basins. The average rainfall on the Nile basin is 630mm: over the Ethiopian highlands and Equatorial Lakes, annual rainfall can reach more than 2300mm, while above 18^{o}N, rainfall is negligible (Dumont, 2009).

Table 5-1 shows the eight sub-basins of the Nile basin and key parameters:

Table 5-1 Mean river natural flows and catchment areas for the period ~1910-95

No.	Catchment	Outlet Location	Area (Gm2)	Annual Flow (Gm3/yr)
1	Nile	Mediterranean	3310	
2	Nile	Aswan	3060	84.1
3	Atbara	Atbara	180	11.1
4	Blue Nile	Khartoum	330	48.3
5	White Nile	Khartoum	1730	26
6	White Nile	Malakal	1480	29.6
7	Sudd Wetland	Malakal	35	16.1
8	Bahr El. Ghazal	Lake No	585	0.31
9	Sobat	Malakal	250	13.5
10	White Nile	Juba	490	33.3

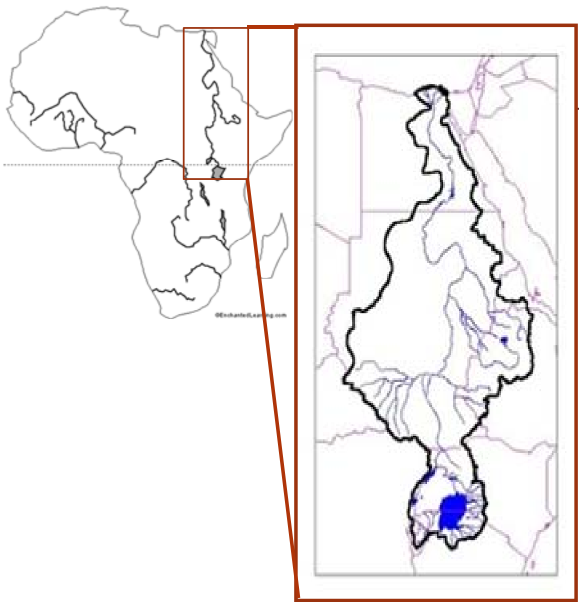


Figure 5-1: Location of the Nile in Africa, showing Lake Victoria in blue

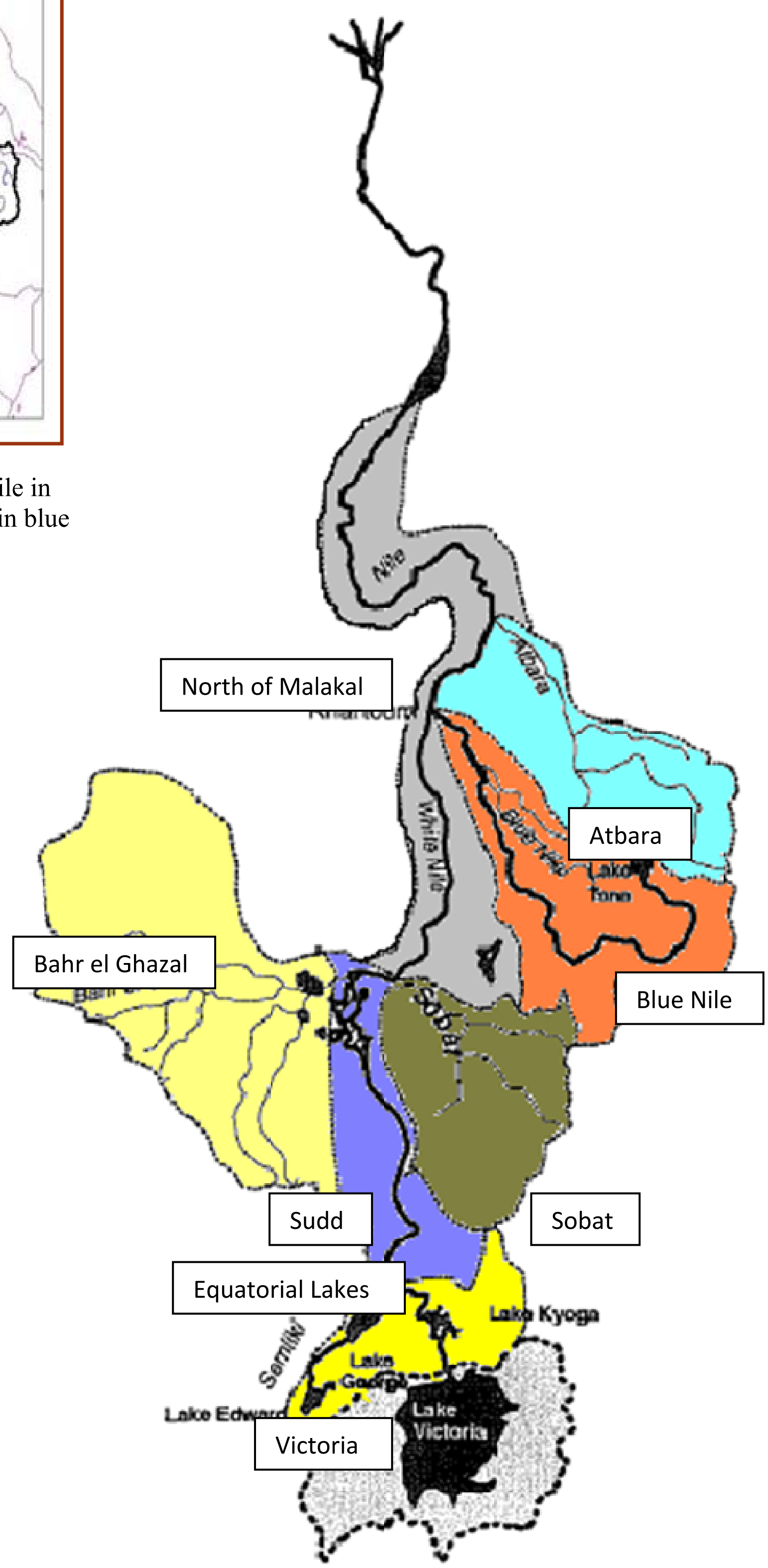


Figure 5-2: Nile basin, with eight sub-catchments

The table shows, for instance, that the Blue Nile contributes most of the main Nile's flows. Also, the Sudd releases at Malakal about as much as it receives from upstream sources, Juba. Figure Figure 5-2 shows the key sub-catchments in the river, which are, starting upstream, Lake Victoria, the other Equatorial Lakes (Albert, George, Kyoga and Edward), Bahr el. Jebel and Sudd wetland, Bahr el Ghazal river and wetland, Machar marshes and Sobat river, White Nile north of Malakal, Blue Nile, and Atbara. The figure also shows the location of the Nile in East Africa, and how flow from each of the sub-catchments relates to flows from others.

5.3 Hydrology of White Nile Basin

5.3.1 Equatorial Lakes

The Equatorial Lakes referred to here are Victoria; below that water discharges into Kyoga and then to Albert. Lake Albert also receives part of its inflow through the Semliki, which drains Lakes Edward and George.

Lake Victoria, the largest of these, has a surface area of 67 000 km^2. The seasonal variations of its outflow are generally stable since would be variations from rainfall and local inflow are attenuated due to its large storage capacity. From studies on the Lake performed over the period 1956-78, a water balance was calculated. The lake's annual rainfall is 1858 mm, evaporation is 1595mm, and inflow and outflow are 22 982 Mm^3 and 35 136 Mm^3, respectively. The outflow regime jumped suddenly in 1960-1963, as is reflected in downstream lakes and eventually inflow into the Sudd at Mongalla. Research attributes this jump in outflow to "unusual variations in rainfall" during the time, and potentially reduced evaporation due to the increased cloud cover at this time (Sutcliffe and Parks, 1999).

Lake Kyoga, below Victoria, is essentially a submerged river valley. This lake then discharges into Albert, which receives its eastern flow from Kyoga and its southern flow from Lakes George and Edward through the river Semliki. Kyoga and Albert have the following water balances, averaged before and after Victoria's jump in flow (Sutcliffe and Parks, 1999):

Table 5-2: Hydrological parameters for Lakes Kyoga and Albert

Parameter	**Lake Kyoga (x 4700 km^2)**		**Lake Albert (x 5300 km^2)**	
(mm/yr)	**1951-60**	**1966-75**	**1951-60**	**1966-75**
Inflow	4098	8474	4788	9303
Outflow	4061	8902	3781	8494
Precipitation	1257	1328	643	766
Evaporation	1595	1595	1595	1595
Balance	+93	-28	+56	-20

5.3.2 Bahr El Ghazal

The only comprehensive study on the Bahr el Ghazal area was done by Chan and Eagleson in 1980. The Bahr el Ghazal region is in southwest Sudan, 4-14^{o} N, and 23-31^{o} E; with a total catchment area of about 5200 Gm^2. The basin comprises of eight tributaries and their catchments, as well as a central swampland made up of permanent and seasonal swamps. The catchment itself is divided into two main areas (flooded and equatorial region), and they differ in vegetation type, rainfall, soil types, underground water table, and seepage capacity. The rivers that contribute to this basin are the Jur, Loll (together contributing 70% of inflow into swamp), Tonj, Pongo, Maridi, Naam, Raqaba el Zarqa and Bahr el Arab (the last two are mostly neglected when area is modeled as they contribute very little). This central swampland is characterized by being very flat (10cm/km), which accounts for the drastic flooding and variations of its size. In fact, heavy or low rainfall does not result in heavy or low discharge levels output from this basin; runoff out of catchment remains constant and very little. That is seen, instead, in how much the area of the basin expands during the rainy season. Consequently, this extreme area expansion results in high levels of evaporation and groundwater seepage. The central swampland is mostly grass and papyrus. Outflow from Bahr el Ghazal (BEG) is flows into Lake No, sitting at the tail of the Sudd catchment. Outflow is so little that it is usually neglected when modeling inflows at Malakal.

5.3.3 Machar Marshes and Sobat basin

The river Sobat makes up approximately half of the W. Nile's waters, and 1/6 of the entire Nile. Since this river does not pass through lakes, it contributes to the seasonal variations of the W. Nile. It spills into the Machar marshes during years of heavy rainfall, forming a relationship similar to that of the Bahr el Jebel and Sudd, which is why the area has also been proposed as a site for water conservation projects. The Sobat's main tributaries are the Pibor and Baro. The Pibor is in turn made up of Akobo and Gila (Sutcliffe and Parks, 1999).

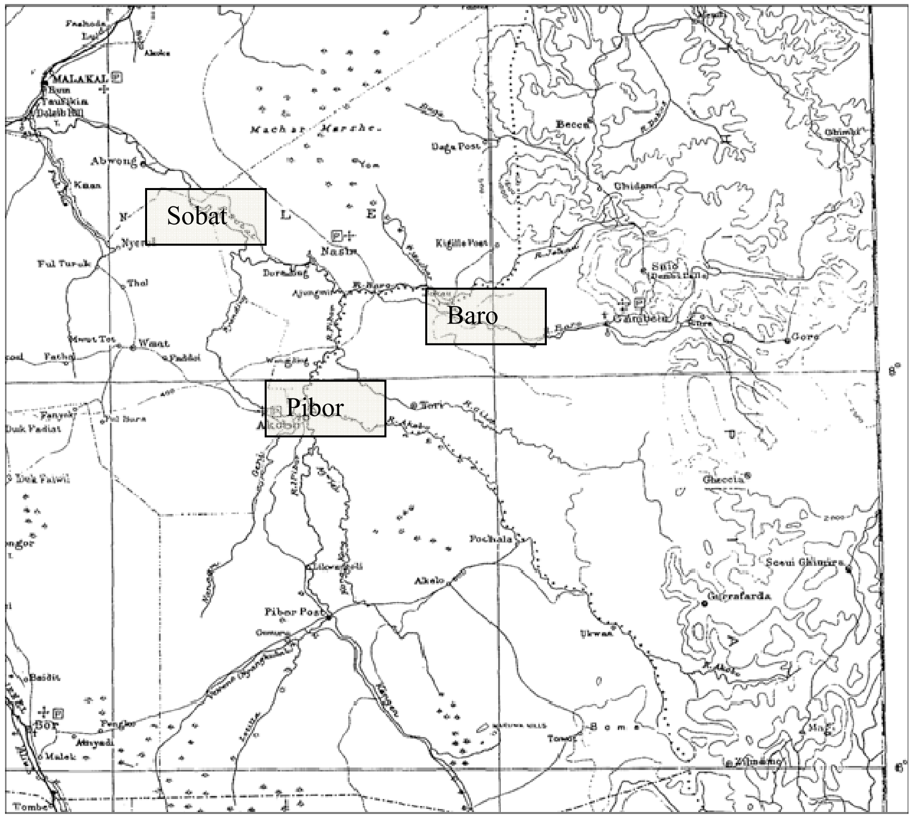


Figure 5-3Sobat basin, showing main river, two tributaries, Pibor and Baro, and Machar marshes

Pibor

In the Pibor catchment, an area of approximately 109 000 km^2, the average rainfall is 950 mm/yr (Apr-Oct). The Pibor also drains neighboring plains (south of Pibor and east of Bahr el Jebel) where annual rainfall is on average 800 mm. The Pibor contributes to the variability of the Sobat, especially during years of high flow. Comparing flows of Pibor and Baro right above their confluence with the Sobat shows a net gain, which suggests that spill from the Baro eventually returns to the river system through the Pibor (Sutcliffe and Parks, 1999).

Baro

In upper Baro catchment, rainfall varies from 1300-2370 mm/yr. There are two rainfall seasons between April and October. Flows in the Sobat catchment have been measured at times daily, or monthly, regularly or intermittently from 1905 up to 1981, when measurements were disrupted due to civil war in Sudan. Flows were published for 1929-1932, for high flow season 1941-1963, and intermittently up to 1981. Comparing flows at Gambeila to downstream locations shows the huge losses through spill when flow exceeds 1.5 km^3/month. These losses inundate neighboring floodplains and make their way to the Machar marshes, a description of which is given below (Sutcliffe and Parks, 1999).

Machar Marshes

Major source of inflow into this wetland is channel flow and over bank spill from the Baro, but also from streams flowing down the Ethiopian foothills. Recent research on this area relies on four major studies previously done, which analyzed flows into and out of wetland, average rainfall regime, and evaporation losses. The first is an analysis by Hurst (1950), which concentrates on losses from Baro, above Sobat head. This analysis estimates the marshes' area to be about 6500 km^2. The second is the JIT (1954), bringing above investigation up to date; this study focuses on spillover from Baro between Jun-Nov. The study found annual spill of about 2.820 km^3, and rainfall measured from 1940-1952 estimated an average of about 788 mm/yr over the area. In 1980, there was a study on the area from El Hemry and Eagleson. It is described in detail below. In 1993, Sutcliffe analyzed water balance for years when all data was available (1950-1955) including measurements of Eastern tributaries, flows along Baro, and flows of the Machar channels. Rainfall is estimated at 933 mm/yr and average area of 3350 km^2.

The 1980 study (El Hemry and Eagleson, 1980) uses Landsat imagery from Feb of 1973 to map drainage of Machar marshes, and vegetation distribution. The study also formulates hydrological models to calculate components of the area's water budget.

Climate, soil and vegetation are considered a coupled dynamic system where energy and water mass are exchanged. PDFs are estimated from Poisson arrivals fitted by the method of moments, using existing hydro meteorological data including precipitation information and data obtained from remote sensing studies. The Poisson function was transformed to give probability distributions of yield and other components using a general water balance equation.

The model was then used to generate discharge-frequency relations at critical sections on a proposed drainage channel. In other words, the study calculates the amount of water that can be reclaimed from this wetland by the then proposed canal construction project. The model used general, one dimensional, stationary, long term processes; soil is assumed to be homogeneous, where soil moisture is related to long-term average; transpiration is assumed to occur at the potential rate; there is no subsurface runoff into the controlled volume; water table is assumed to be constant throughout the year.

The model was then used to compute surface runoff and a water balance model was constructed. Using satellite data, the Machar area was approximated to be 39100 km^2. Four zones were identified: eastern water sheds made up of small rivers that drain into the permanents swamps; toic or flood plains which mostly drain to the White Nile, although this contribution is small; plains lying between river Sobat and the White Nile; and the permanent swamps.

Rainfall characteristics were collected for 1906-1975, but only 20 years of data were analyzed. Thiessen polynomials were used to estimate rate frequency over the entire catchment, using 12 stations.

The authors then examined spillage from neighboring rivers into the investigated catchment and ways of estimating this spillage with the limited data available from field work. The difficulty in this step was finding an outflow point from the catchment. It was found that outflow into the Nile (its quantity and exact location measured) highly depended on amount of precipitation for that year. This is all then used to formulate the water balance and validating it through existing data.

Some of the results obtained are the areas that make up this region: 16 300 km^2 of eastern catchment, 14 100 km^2 plains, and 8700 km^2 of permanent swamp. The authors pointed out that previous studies showed a discrepancy in delineating the area of the catchment. Sutcliffe and Parks comment that this study is also unclear on this point, and especially regarding whether their area calculations include seasonally flooded regions or only permanently flooded ones.

Sobat

Flows from the Sobat are measured at Hillet Doleib, 8 km above White Nile confluence at Malakal. Annual ratings for this river exist from 1905-1983 when, and as was stated above, measurements stopped due to civil war in the region. Flows are also measured at Nasir, right below confluence of two tributaries, Pibor and Baro.

During high flow years, there’s more spill from Baro onto floodplains, which results in reduced flows of Sobat, and a 1-2 month peak flow lag, which appears to be the main function of the otherwise self-contained river (Sutcliffe and Parks, 1999).

5.4 Sudd Wetland Hydrology

The Sudd refers to the wetland area of the White Nile, between Lake Albert and the confluence with Bahr el Ghazal at Lake No, where the combined river, along with the Sobat, becomes the White Nile. Bahr el Jebel, as the river is referred to in this area, receives inflow from L. Albert's discharge at Nimule, and seasonal torrents; at Mongalla, it starts to spill over into the surrounding floodplains, through a complicated series of channels, forming the wetland area referred to as the Sudd. For hydrological modeling, limits of the Sudd wetland are taken at Mongalla, when Bahr el Jebel begins to spill over onto the surrounding area, and ends at Malakal, where the river is formed again. Bahr el Zeraf is one of the channels which flows out of the Sudd, and meets the White Nile between Lake No and the Sobat. Besides el Zeraf, there is debate as to whether these channels return water back to the main river, making the Sudd a reservoir, or whether it is a sink for flooded water (Sutcliffe and Parks, 1999).

Upstream of the Sudd, the torrents flowing into Bahr el Jebel are an important factor, and contribute to the river's waters. Most notably the Aswa and Kit, these torrents are located between discharge of Lake Albert and Bahr el Jebel at Mongalla. These torrents contribute on average 4 km^3, but vary from 1.3 to 11 km^3. The contribution through torrents is made through flash floods during the rainy season (Howell et al, 1988).

In general, about half of water entering the Sudd is discharged at its tail. This has led to the proposal of the Jonglei Canal, which attempts to salvage this water by building a channel that diverts part of the inflow at Bor and releases it at Hillet Doleib, right before Malakal (Sutcliffe and Parks, 1999).

Research on the Sudd has been extensive and spans decades of work. However, because of the inherent scientific complexity of the area, there is still no consensus on the systematic behavior of this wetland – or wetland network as it is sometimes referred. Parameters like total area and evapotranspiration constitute the largest source of disagreement among researchers. Two civil wars (that cumulatively spanned almost 40 years) have disrupted measurement of flows, precipitation and other parameters, which makes it difficult to establish a continuous set of data upon which research can be based. In recent years, this effect has been reversed due to the use of satellite imagery. The following sections present key research on the Sudd, and highlight some limitations and yet to be answered questions.

5.4.1 Topography and Vegetation

This section briefly describes important topographical and vegetation features of the Sudd wetland ecosystem. Geomorphology of the Sudd controls its flows, and it is relevant for questions such as whether flow leaving the river network and flooding the surrounding plains eventually returns back to the river system or evaporates/recharges the aquifer below. This, in turn, is important in determining the relationship between river flow into the Sudd and the area of the Sudd and stands in the heart of modeling flows, and the impact of the Jonglei Canal on these flows. Following Winter (2000), the topography is important for determining the hydrological landscape unit of the wetland, and ensuing climate impacts. As it currently stands, there is some knowledge on the relationship between topography and river flows for certain parts of the Sudd but not the entire area. Vegetation on the other hand, showcases some of the functions provided by this ecosystem in sustaining a wide biodiversity.

Topography

As the White Nile – here known as Bahr el Jebel - leaves L Albert and heads into Sudan, it gently sloping northeast. When it reaches Gemmeiza, it turns westward. The river's width is defined by scarps or small cliffs that also signify the limits of woodlands on either side. These scarps gradually lessen as the river flows to the north, disappearing completely as the river reaches Bor on the eastern bank, and Shambe on the west (Sutcliffe and Parks, 1999).

From Bor to Juba, the river, although confined within a trough, forms many channels, which maneuver through small, isolated islands and basins. These basins lie below the alluvial banks of the trough, so receive spillage from the river, but end in channels that return some of the water to the river (Sutcliffe and Parks, 1999).

Between Bor and Jonglei, the trough widens (about 15km) and eventually becomes indistinct, especially on the eastern side, where it is gradually replaced with seasonally flooded grassland, or *toic*. Between Jonglei and Shambe, although the complex network of lakes and channels is still apparent, on the eastern side the limits of the trough completely disappear and there is extensive spillage to large areas of permanent and seasonal swamps (Sutcliffe and Parks, 1999).

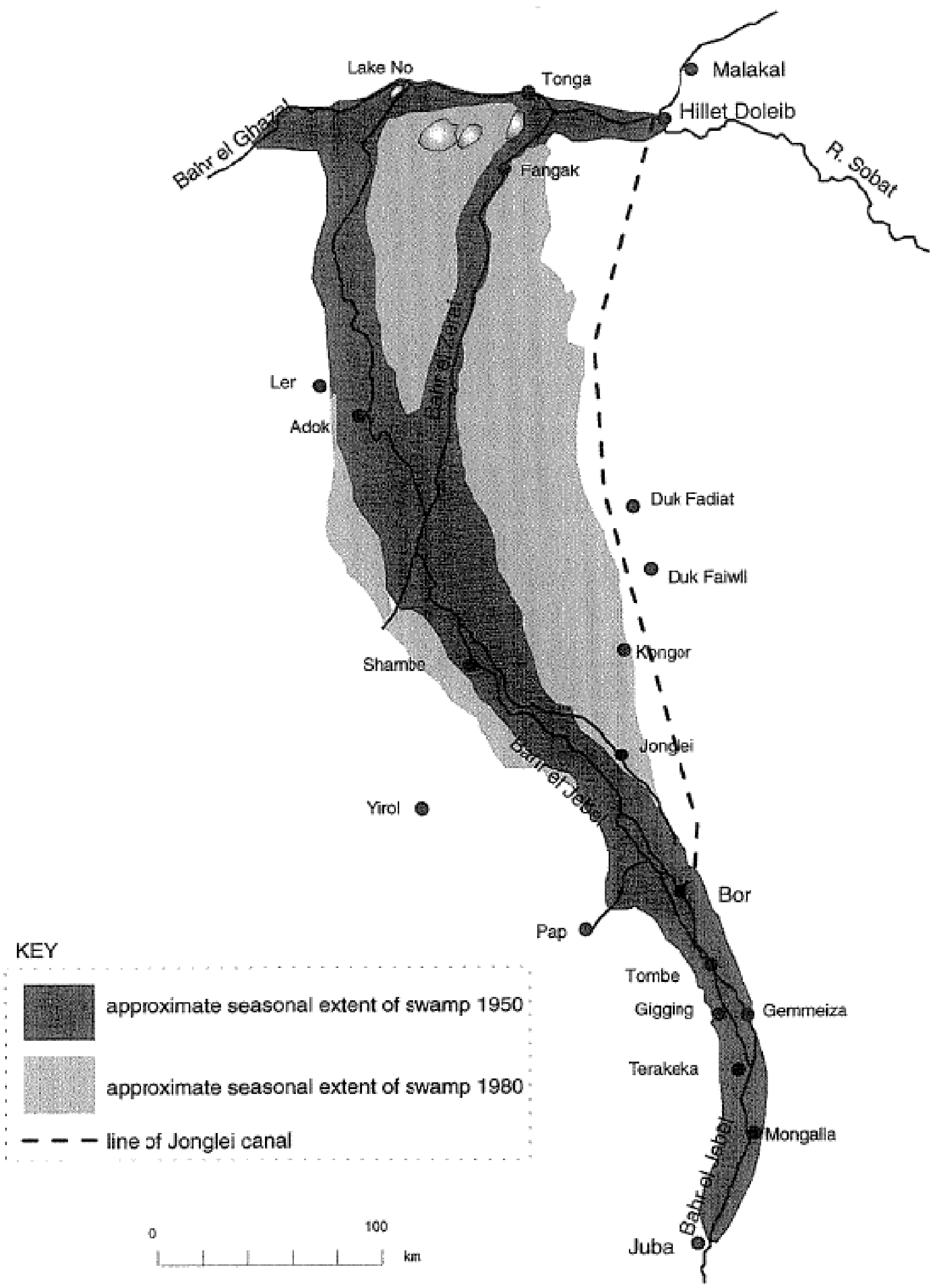


Figure 5-4 Schematic of Sudd (Howell et al, 1988)

Between Shambe and Adok, where the Sudd is at its widest, there are fewer distinct channels, and instead large, mostly inaccessible swamps. Some of the flow along the east, however, forms the Bahr el Zeraf, while some of the side channels on the west either rejoin the main river or spill over onto B. el Ghazal, although the writers express that this happens in insignificant quantities (Sutcliffe and Parks, 1999).

The area covered by the swamps expands and contracts both seasonally and annually (huge increase in area since the 1960s, when discharge from L. Victoria doubled). In general, increase of intake at the head of the Sudd does not result in a *proportional* increase at the tail. Also, *with increased intake, the area exposed to evapotranspiration is increased.* Table 5-3 shows that the greater the increase in inflow, the greater the percentage lost through evaporation (Howell et al, 1988).

Table 5-3 Annual inflow, outflow (in bcm) and percent losses in the Sudd (adapted from Howell et al, 1988)

Period	At Mongalla	At tail of swamp	% loss
1905-60	26.8	14.2	47.0%
1905-80	33.0	16.1	51.2%
1961-80	50.3	21.4	57.5%

The area is characterized by channels, lagoon systems of permanent swamp, adjacent floodplains and flat terrains. In receding order from the river, the terrain system is made up of swamp, river flooded grassland (toic), rain flooded grassland, wooded grassland, and eventually woodland (Peterson, 2008).

Finally, between Adok and Malakal, Bahr (which means 'water body of') el Jebel, Ghazal and Zeraf rejoin at L. No, and then later unite with the Sobat to form the W. Nile at Malakal.

Biodiversity

Toic is a common Nilotic word describing the terrain of the Sudd beyond the permanent swamp. The papyrus bulrush vegetation covering the permanent swamp is paralleled by grasslands flooded during high river, and exposed during the dry season. Beyond that are relatively higher areas covered with rain-grown perennial grasses. These areas are impermeable during the wet-season, but become cracking clays during the dry season. Not native to this area, but becoming more prevalent since 1957 are water hyacinths (*Eichhornia crassipes*) (Howell et al, 1988).

The main vegetation of permanent swamp is *cyperus papyrus, Vossia cuspidate, Phragmites communis,* and *Typha australis.* The main control variables of this vegetation are water depth, current velocity and ground level. A link between vegetation and hydrology was obtained from surveys taken between Bor and Juba and published starting with the JIT.

5.4.2 Precipitation and Meteorological Characteristics

The Nile basin covers a large region with varying climate; from the hot/dry North to the cool/humid South. Despite its variations, climate is controlled by wind movement induced by the ITCZ, local topography, and vegetative cover. The Sudd is located between 6^{o} and 9^{o}N, and 29^{o} and 32^{o}E. Rain lasts for a single season, between April and November, and increases southward, ranging from 800 mm/yr in the north, to 900 m/yr in the south. The temperature is approximately 33^{o}C in the hot season, and drops to 18^{o}C in the cold season. Figure 5-5 shows the average rainfall for the years 1905 to 1981, averaged from station measurements at Bor, Shambe and Kongor.

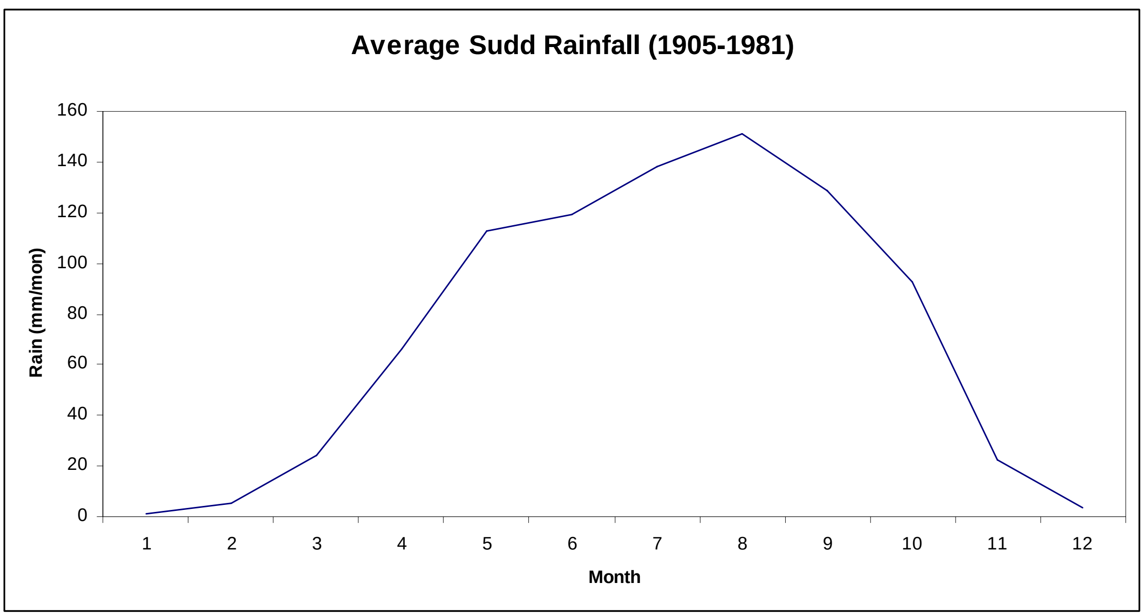


Figure 5-5 Average Sudd rainfall for the years 1905-81

The rainy season of the Sudd, shown in the diagram above, does not coincide with the maximum area of the Sudd; and the minimum extent of the Sudd occurs during its rainy season.

Figure 5-6, from (Mohamed et al, 2005), shows climatic features of 4 meteorological stations around the Sudd, namely in Juba, Malakal, Nyala and Damazin. Maximum air temperature occurs in Mar/Apr, while minimum temperature occurs in Sep. Relative humidity ranges from 20% in the dry season to 80% in the rainy season. E_o here refers to the reference evaporation – and not the actual evaporation – estimated using the Penman-Monteith equation, and ranges from 2400 mm/yr to 2900mm/yr. Rainfall is also included.

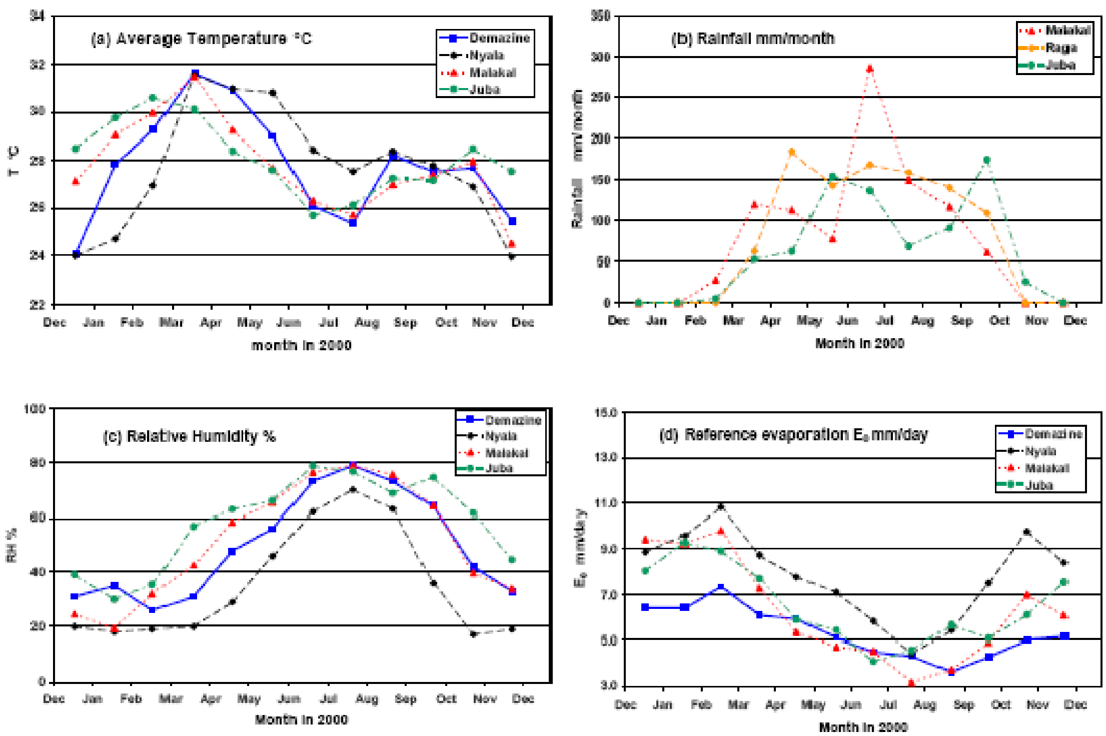


Figure 5-6 Climate features at Damazine, Nyala, Malakal and Juba for year 2000 (from Mohamed et al, 2005)

5.4.3 Inflow from L. Albert and Torrent Flow

As was stated above, inflow into the Sudd through Mongalla originates with the Equatorial Lakes, in combination with torrent flows in the region between Lake Albert and Mongalla. Newhouse (1929), who formulated one of the earliest studies on the Sudd, pointed out the importance of torrent flow to the Sudd's seasonal variability.

Below Albert, the river, known as Albert Nile or Bahr el Jebel, flows along an extremely flat channel up to the Sudan border, turning slightly northwest, before eventually entering the floodplains of the Sudd. In its course from the exit of Albert at Pakwach (Panyango) to the entrance of the Sudd at Mongalla, the river is also supplied by torrent flows, which provide the seasonal component, rather than the steady flow, of the Bahr el Jebel. Inflow into Albert has been measured through several gauges between this lake and Victoria, as well as gauging the Semliki through measurements in Bweramule. Attempts to measure outflow from L. Albert directly are largely unreliable. Instead, L. Albert outflows are estimated through a relationship between lake levels and simultaneous dry season Mongalla flows (adding a 5%, attributed to losses in the river's journey), or through a regression model relating Albert outflow to that of L. Victoria. In general, Lake Albert levels are measured at Butiaba (Sutcliffe and Parks, 1999).

Mongalla river flows have been gauged regularly since 1905, with sparse disruptions up until 1983, when gauging stopped completely due to the civil war in Sudan. Gauging resumed again recently in 2004. The early 1960s increase in L. Victoria discharge doubled inflow into the Sudd. This, in turn, caused a steady river level increase of 0.5m up to 1963 in Mongalla river levels, at which point gauging was disrupted in 1963. When gauging resumed in 1967, the river level was 1m below 1962. This increase caused new spill channels to be formed pointing to the strong relationship between river flows and flooding.

Even though inflow from L. Victoria increased in the early 1960s, this was not the case for the torrent flows, whose contribution is reflected in the seasonal fluctuations of inflow. Torrents have been estimated by comparing dry season inflow from L. Albert with wet season inflow since torrent flows occur only during the wet season of the region, and L. Albert outflow, damped by the lake itself, does not vary much throughout the year.

Torrents largely contribute to the temporary floodplains (toic land). After 1960, the torrent flow did not increase, but the area increased, reflecting increase in discharge from the equatorial lakes (Sutcliffe and Parks, 1999). Figure 5-7 represents Mongalla's different rating curves throughout the years, including the jump in inflow in the early 1960s.

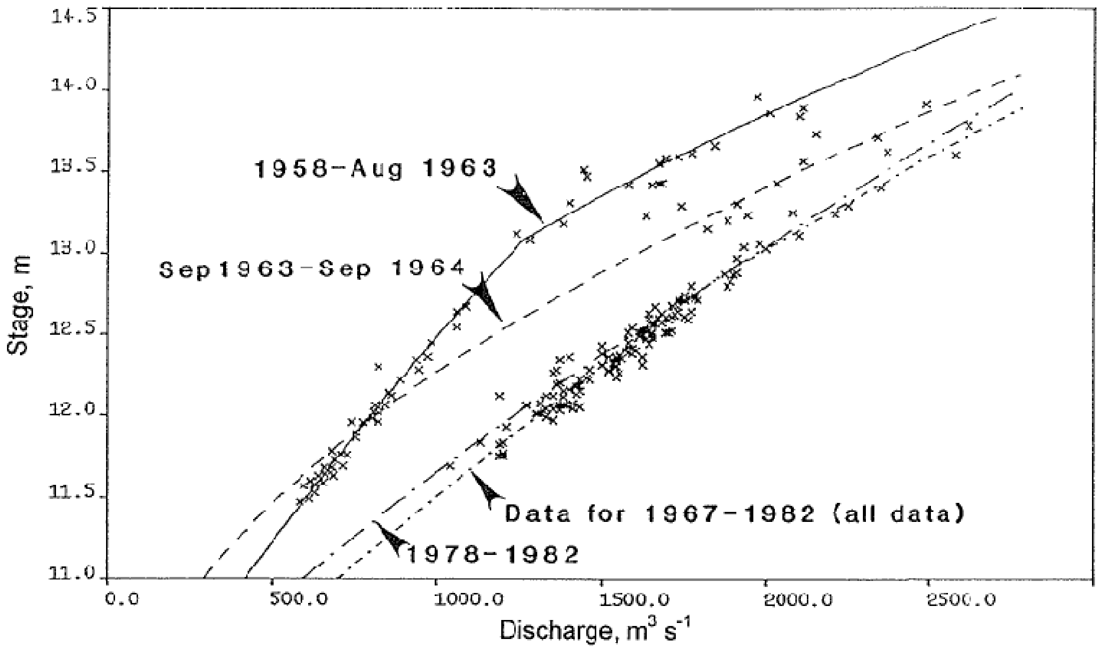


Figure 5-7 Rating curves for inflow into Mongalla, 1958-82 (from Sutcliffe and Parks, 1999)

After 1983, inflow at Mongalla stopped due to the start of a civil war in southern Sudan. Attempts have been made to estimate the inflow into Mongalla during those years of missing data.

Estimating inflow at Mongalla for missing years

Situated in the hilly area between Nimule and Juba, it is estimated that the average contribution to Mongalla from lake flow is about 1700 to 2000 mil m^3/month, while Mongalla flow usually averages around 3300. Therefore, torrent flow has been shown to reach a mean monthly flow of 4500 mil m^3, but as low as 400 mil m^3/month. A study in 2008 derived inflow at Mongalla using upstream flow from L. Albert; modeled torrent flow, and validated against previous derivations. The results provide updated rating curve for the lake outflow as well as an estimate for Mongalla inflow from 1983 up to 1996 (Peterson, 2008). In the study, torrent flows were calculated from rainfall fields, calibrated for a period when both L. Albert and Mongalle flows were measured (before 1983). The study looked at a study area outlined by 438 km of Bahr el Jebel, from L. Albert to Mongalla; hilly terrain to the east and west of the river; rainy season Apr-Nov that yields, 943 mm/yr; using USGS catchment area was determined as 74000 km^2. Deriving and estimating a rating curve for L. Albert, and using a derived rainfall-runoff analysis of torrent flows, the study estimated monthly inflows into the Sudd for 1961-1996. Model resulted in a good representation of normal year flow for Mongalla, but peaks were not well captured. Results yielded a correlation coefficient of R=0.81 (Peterson, 2008).

5.4.4 Outflow: Difference of Malakal and Hillet Doleib

Malakal

Discharge from the Sudd is not directly measured and is instead, taken as the difference of outflow at Malakal and Sobat river at Hillet Doleib. The flow regime at Malakal has been regularly measured since 1905 to the present. Although flow at Malakal exhibits a looped rating curve, gauges have been steadily kept at more than 70 in number and provide accurate measurements of discharge (Sutcliffe and Parks, 1999).

Outflow from Sudd

Authors describe the Sudd's outflow as a highly reduced and damped version of its inflow, and outflow reflects discharge from the Equatorial lakes only to a certain degree, whereas the seasonal component of the inflow (the torrent flow) is mostly damped when exiting the Sudd. Important evidence to this is the doubled discharge of L. Victoria in the period 1961-64, and consequently so has inflow into the Sudd. This was not proportionately reflected in outflow from the Sudd. In fact, it was the area of the Sudd, which has increased dramatically. This also resulted in high evaporation rates in that period within the Sudd.

The relationship between inflow and outflow presents an important point of analysis for the Sudd's hydrology. Butcher in 1938, was among the first to derive a relationship between inflow at Mongalla and Sudd outflow. This relationship is important for assessing the impact of Jonglei Canal on the outflow. This relationship is covered more extensively on layer sections.

5.4.5 Evaporation of Sudd

Early Studies

As was mentioned above, evaporation over the Sudd remains to be a contested subject among different research. Some of the early studies include Butcher, who in 1938 investigated areas of flooding and evaporation. In attempting to account for losses within the Sudd, he postulated that evaporation from the area is analogous to evaporation from a tank of papyrus, and estimated that at about 1533mm/yr, which only accounted for about half the losses of the Sudd.

From there he estimated area to be at 7200 km^2. Hurst and Phillips (1938) discussed water balance in terms of the continuity equation. They ignored recharge, estimated evaporation to be about 30% higher than was estimated by Butcher, and estimated area to be 8300 km^2. Migahid (1948) made higher estimates of the evaporation from empirical measurements of evaporation from swamp vegetation. Penman (1948, 1963) developed a theoretical approach to calculating evaporation from radiation, humidity, wind speed and temperature, and pointed out that swamp evaporation, where there's an abundance of papyrus vegetation, is similar to open water evaporation, which also resulted in a higher estimation of evaporation than previous studies (Sutcliffe and Parks, 1999).

Sutcliffe and Parks, in a 1987 study, followed Penman's reasoning that since the Sudd area contained papyrus, its evaporation was taken to be that of open water, and a value of 2150 mm/yr was calculated using the Penman-Montieth equation. This value is used again in their 1999 comprehensive study of the Sudd. Monthly averages were also calculated and used to estimate the size of flooded areas (which change seasonally).

Recent Studies on the Sudd's evaporation rate

Is the total evaporation from a wetland surface, which includes open water, plant transpiration, and wet/dry soil evaporation, similar to, higher or lower than evaporation from open water under the same climatic conditions? In 2005, Mohamed et al (2004) investigated this question through a theoretical investigation of actual wetland evaporation (Ea) versus open water evaporation (Ew) using the Penman-Montieth equation, under similar climate conditions; an assessment of Ea/Ew variability through literature review; and the use of the satellite images of the Sudd as a case study for this debate

The investigation demonstrated that Ea/Ew is site-specific and is a function of physical properties, and most importantly to the purposes of this paper, Ea/Ew for the Sudd is 60-90% in dry to wet season, respectively.

Since wetlands are a mixture of vegetation types, open water, and (un)saturated soil, Ea does not necessarily equal Ew. Evaporation in wetlands depends on atmospheric demand, bare land and permanent swamp, the region's biophysical characteristics, soil water potential in the root zone of the marshland vegetation, leaf area index, I_{NDV} and vegetation height. If the two latter features are high, Ea can even exceed Ew. This has important implications for the model developed in this research and is discussed in more detail later.

The Penman-Montieth equation is derived from the water balance and energy balance equation, and takes the following form:

$$\rho\lambda E_a = \frac{\Delta(R_n - G_o) + C_p \rho_a \dfrac{e_s - e_a}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)} \text{ .... Penman-Montieth}$$

Where $\rho\lambda E_a$ is the latent heat flux, Δ the slope of the saturated vapor pressure curve, R-G is available energy, C_p is the specific heat capacity, e_s-e_a is the vapor pressure deficit, γ the psychrometric constant, r_a the aerodynamic resistance and depends on wind speed, and r_s is the bulk surface resistance. The latter term includes plant canopy resistance, r_c, soil resistance, and open water resistance.

Under similar climatic conditions, Ea/Ew depends on the values of r_s and r_a. For water surfaces, r_s is zero. However, for wetlands, $r_{a,}$ which is influenced by wind speed, vegetation structure and the buoyancy effect, is lower than it is for open water, resulting in a compensating effect in the term r_a -r_s.

With this theoretical basis, Mohamed et al (2005) calculated the evaporation and moisture storage of the Sudd as well as the Bahr el Ghazal and Machar wetlands using the SEBAL model. The term evaporation in their research included open water evaporation, soil evaporation, interception, and vegetation. It can be measured in three general ways: measuring at point locations and extrapolating to the broad surface; hydrological modeling; remote Sensing techniques.

Each of the three ways above has advantages and disadvantages and a thorough estimation of evaporation might include all three. In the study by Mohamed et al (2005), remote sensing was used in conjunction with hydrological modeling due to the fact that the area of study did not have conclusive meteorological data used for hydrological modeling, and direct measurement is both expensive and highly uncertain. The authors state that errors in the quantification of other hydrological processes will not be propagated into evaporation when it's computed using remotely sensed data. However, since there are temporal gaps in gathered satellite data, a degree of interpolation is needed when constructing monthly, daily or annual averages, which may affect final accuracy of the monthly ET.

Evaporation rates were calculated for the Sudd for the years 1995, 1999 and 2000, as well as for the Bahr el Ghazal and Sobat basins for the year 2000. As was stated above, one of the model's limitations is gaps in time: regression models are used to estimate evaporation on days where satellite imagery could not be obtained or reasonably processed, and meteorological observations are used to check the model's reliability. Using SEBAL shows that the region is not an open water source, but contains vegetation. This results in the balancing of three factors, namely that a) evaporation from the area cannot be estimated by open water models and that it will be lower since there is a limit to the moisture available for evaporation; b) presence of vegetation means that the surface albedo is higher than for open water, lowering the amount of available energy to be used for evaporation, again meaning that evaporation is lower than open water; and c) vegetation means that there's canopy resistance which may or may not also lower evaporation depending on other factors such as wind speed turbulence caused by the presence of vegetation, and area leaf index. Consequently, the study found that the size of the region is about 70% larger than previously assumed, while evaporation is about 20% lower than when calculated assuming open water, corresponding to a range of 1460-1935 mm/yr (Mohamed et al, 2005). Figure 5-8 is taken from the study and shows evaporation rates for the three wetland catchments for the year 2000.

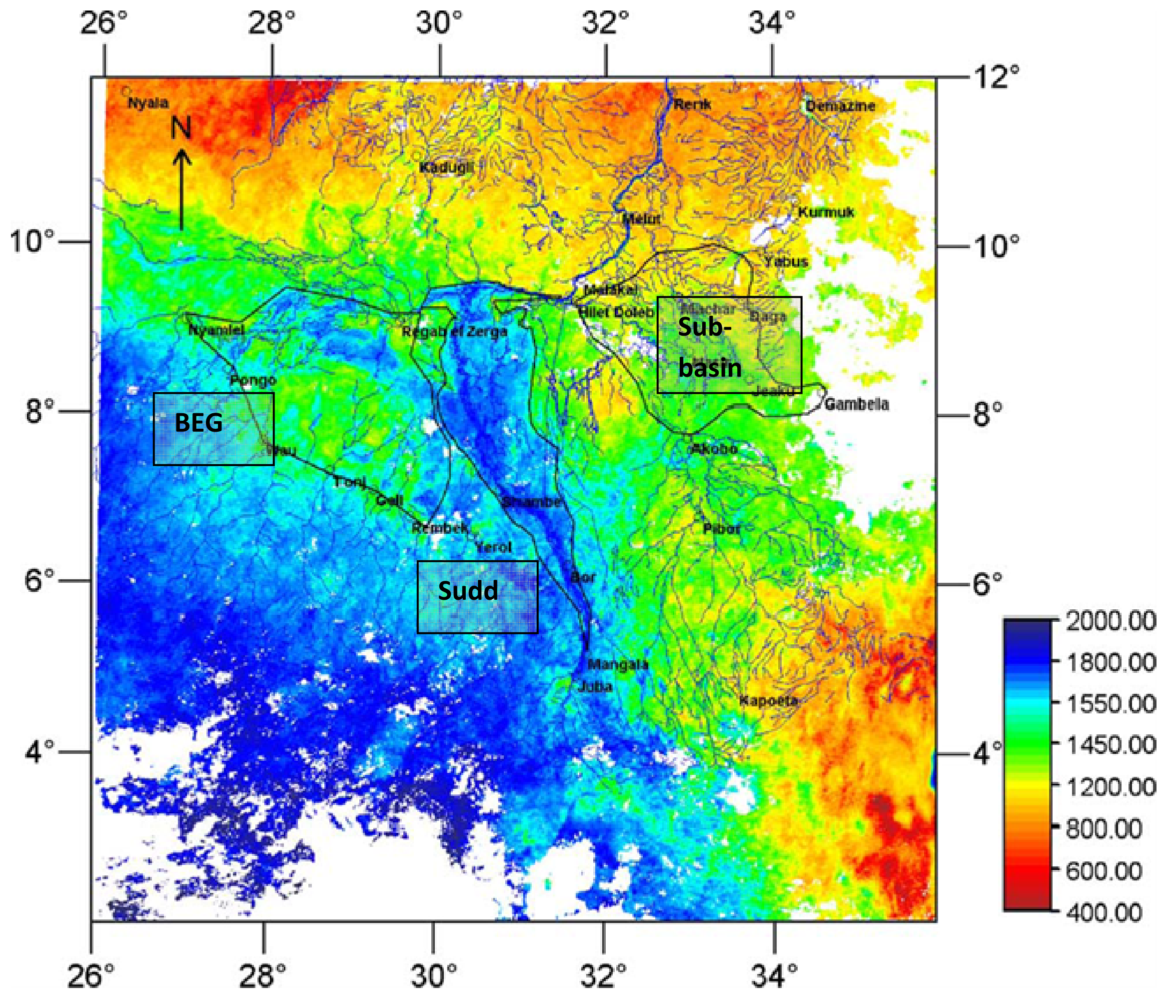


Figure 5-8 Evaporation results, in mm/yr, for the year 2000 (Mohamed et al, 2005)

The following table compares different evaporation estimates and ensuing Sudd areas when the area was derived using evaporation rates in a water balance model. These numbers show that wetland evaporation depends on carefully understanding the land cover of the Sudd. For an area as large as the Sudd, small differences in evaporation contribute to large differences in available water.

Table 5-4 Different evaporation studies, values and resultant area estimates

Source	Average Sudd Area (1000 km2)	Evaporation (mm/yr)
Butcher (1938)	7.2	1533
Hurst and Black (1938)	8.3	
Mijahid (1948)		2400
Sutcliffe and Park (1999)	21.1	2150

Mohamed (2005)	38	1636

5.4.6 Delineating area of the Sudd

The area and evaporation of the Sudd are the two least agreed on parameters. The overview of evaporation above shows a wide range of evaporation values assigned to the Sudd, and the following is a description of methods, results and assumptions made when computing its area.

Hurst and Phillips (1938) concluded through air photography in 1930-1931 that the area was about 8300 km2; scouting of the vegetation landscape done by the Jonglei Investigation Team (JIT) in 1950-1952 found the permanent area to be 2800 km2 and the seasonal to be 11200 km2; satellite imagery in 1973 estimated the area to be 22000 km2; and Mefit-Babtie's (1980) vegetation map in 1979-1980 found the permanent swamp area estimated to be 16600 km^2 and the seasonal swamp approximately 14000 km2. Table 5-5, from Sutcliffe and Parks (1987), summarizes these early studies and their results.

Table 5-5 Different estimates of Sudd area (Sutcliffe and Parks, 1987). P refers to permanent, S to seasonal and T to total swamp area

Source/Type of analysis	Date	Area below Mongalla (km2)
Planimetered air survey maps	1930-31	8300
Vegetation Map	1950-52	2800 (P)
		11200 (S)
		14000 (T)
Flooding Map from Landsat	Feb, 1973	22100
Vegetation Map	1979-1980	16600(P)
		14000(S)
		30600(T)

Another method, used significantly since its development, is through hydrological modeling. It was developed by Sutcliffe and Parks in 1987, and will be described fully below. In 1992, Mason et al investigated the method of remote sensing in estimating the area of wetlands, due to their inaccessibility, and used the Sudd as a case study for this method.

Specifically, the paper showed that accurate area measurements are feasible using thermal imagery depending on the seasonally variable thermal inertia contrast; and that it is possible to submit preliminary measurements of water level and extent from remote sensing.

The paper states that in situ measurements of wetland area is difficult due to the region's inaccessibility. Remote sensing in general is therefore better and allows for monitoring of different parameters, especially the extent of inundation and water level. In this research, satellite remote sensing imagery was obtained for the year 1988, using first Meteosat and AVHRR images, which operate in the thermal infrared wavelength, and also Geosat radar altimeter data, which operate in microwave wavelengths.

Using Meteosat and AVHRR images for the near infrared, the paper showed the Sudd, with its characteristic swamp vegetation is not easily distinguished from surrounding areas, as there isn't a high enough contrast in reflectivity. However, when thermal infrared images were used, the contrast became more apparent. This method measures the thermal inertia of surfaces, or the rate at which a surface absorbs heat; a quantity different for wet versus dry surfaces. This allowed the authors to assess which part of the image is inundated, and therefore the extent of the Sudd's area.

Figure 5-9 and Figure 5-10 below showcase results for Meteosat and AVHRR, respectively.

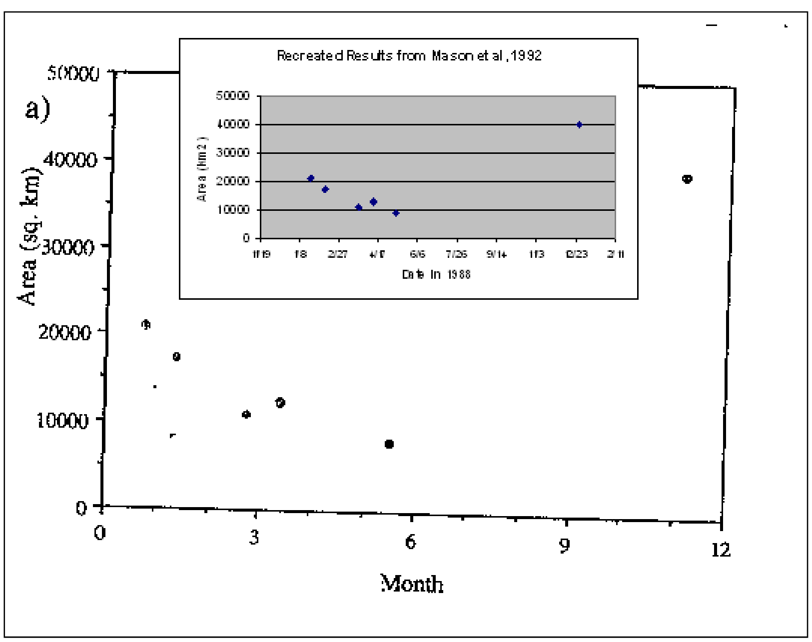


Figure 5-9 Recreated Meteostat results showing how Sudd area changes throughout 1988

(Mason, et al, 1992)

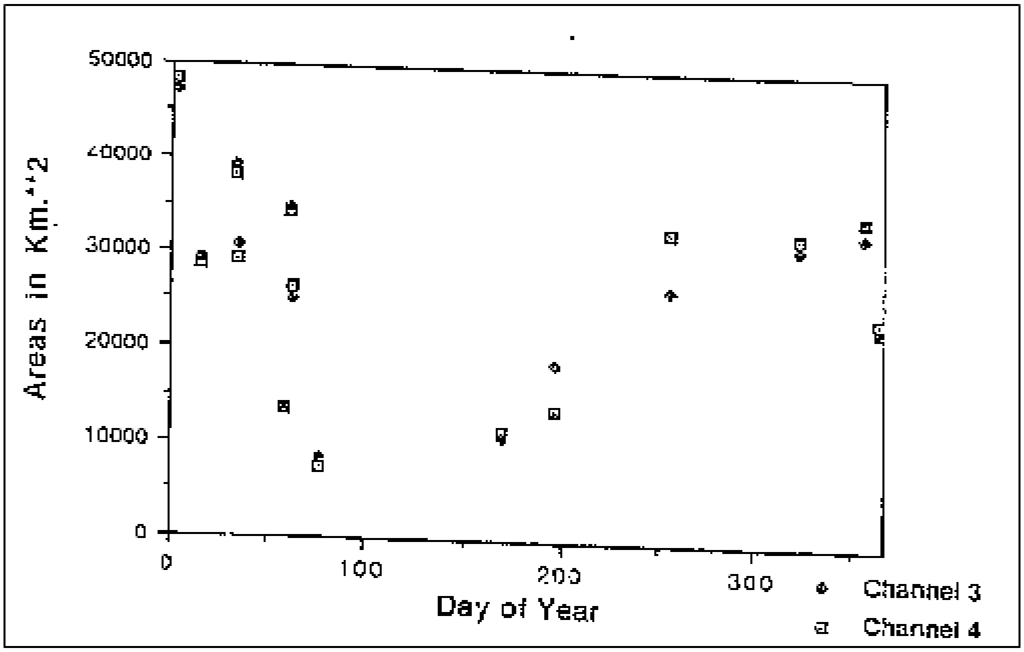


Figure 5-10 Sudd area results for 1988 using AVHRR (Mason et al, 1992)

The above experiments resulted in Sudd's area for 1988 varying from 10 000-50000 km^2. The authors state that their major limitation in the study is that they have no way of verifying their results through ground measurements. They state that, however, Howell et al have cited area estimations in their study; the highest of these areas, in 1979-80, was cited as 36 600 km^2, and although still less than this current study's estimate, they state that Howell's description of the area excludes regions that were assumed to be part of the Sudd in this study.

The paper also introduced the methodology of using microwave-based imagery in order to estimate water levels in the Sudd, as well as other ways of indirectly measuring area and storage volume of the Sudd, but stated that although these methods had great potential, currently carried too big a margin of error to be useful.

Building on the ideas of thermal inertia introduced above, another team of researchers in Travaglia et al (1995) also investigated the Sudd's area using remote sensing, this time as part of a study compiling fishery information. Wetlands constitute both an important and sensitive ecosystems for fishery. This study was conducted to evaluate the use of NOAA AVHRR LAC thermal data in monitoring the seasonal and inter-annual variation of several wetlands in Zambia and Sudan, including the Sudd.

This study builds on the concept of thermal inertia already outlined above in the Mason et al study. In fact, the paper builds on the former study's findings by choosing 12:00 GMT as the most suitable time for differentiating between wet/dry areas of the wetland. Cloud-free days in the following months have been chosen, and Table 5-6 represents the study's finding:

Table 5-6 Sudd area measurements adapted from Travaglia et al, 1995

Sudd flood plain area variation	
Date	Km^2
30-Dec-91	46000
7-Jan-92	48000
8-Apr-92	28000
28-Sep-92	36000
30-Mar-93	34000
10-Sep-93	31000
19-Jan-94	36000
14-Mar-94	29000

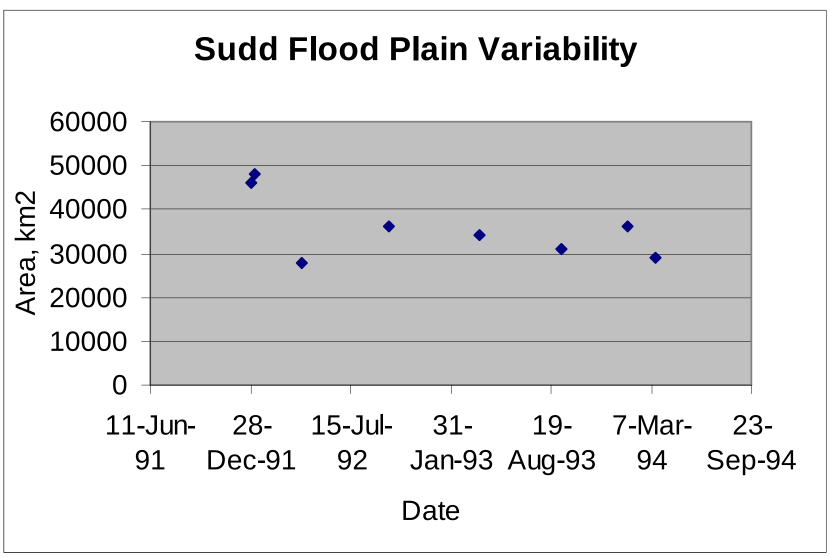


Figure 5-11 Graphic adaptation of area measurements for Travaglia et al, 1995

Note the seasonal as well as inter-annual variability in the Sudd's size. The authors state that some of the difficulties involved in this study were finding ground identifiers against which to calibrate satellite images. This was partly due to the relatively low resolution of the image compared to identifiers. In calculating the area of the wetland, regions of contrasting thermal inertia were color-coded to emphasize their difference; superimposed on this were NDVI (Normalized Difference Vegetation Index) images, which were used to eventually differentiate between wet, vegetation covered and bare soil regions of the wetland. No images were included in the paper, so they are not provided here. The authors also state that they were unable to validate their results based on ground measurements, although there are plans to do so in the future.

Finally, using remote sensing to investigate the area of the Sudd is another team of researchers in Shamseddin et al (2006). This paper acknowledges the lack of consensus concerning the area of the Sudd, and uses the MODIS-Terra satellite imagery to add to the ongoing debate on the wetland's size. Images obtained from MODIS-Terra were geo-referenced, not to ground identifiers like other studies cited here, but through a method called the Isodata Unsupervised Classification Technique, which relied on vegetation maps for Jonglei area. The study measured the annual mean area of the Sudd for the years in question to be 20400 km^2, with 71% certainty. The study also points out that the swelling and shrinking pattern of the Sudd follows L. Victoria, although concedes that average areas for Mar, May, Sep and Nov are questionable. This study's resulting area is 96% of results obtained by Sutcliffe and Parks (1987) using a hydrological model rather than direct measurement of area (21000 km^2). Mohamed et al used the same hydrological model as Sutcliffe and Park, but arrived at a different evaporation rate and an area of 35000 km^2.

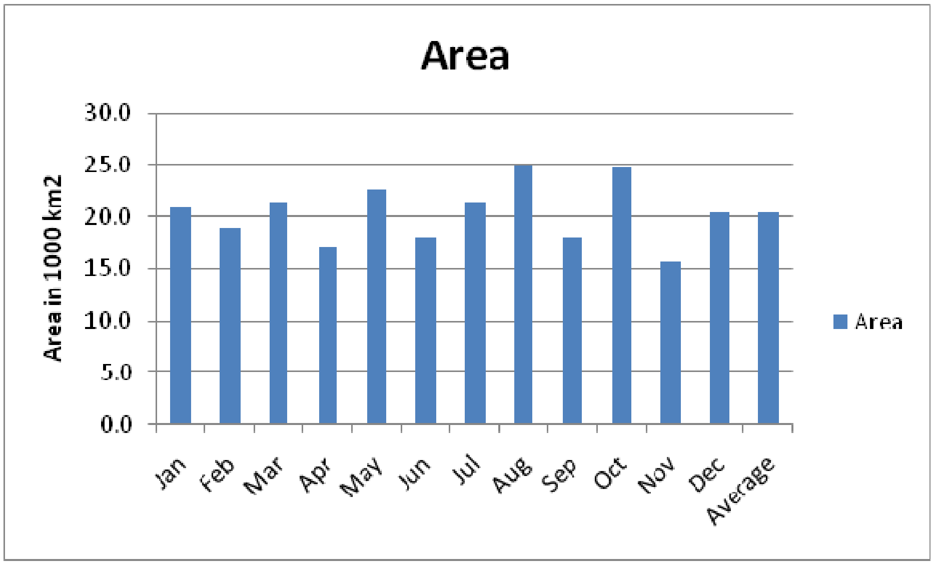


Figure 5-12 Monthly mean Sudd area (1000 km^2) for 2001-05, from Shamseddin et al (2006)

The authors compare their results to those obtained in Travaglia et al, finding their results to be approximately 67% of Travaglia et al. The authors state that discrepancy is due to the fact that Travaglia looked at the entire wetland, whereas this study only investigated flooded areas.

These studies show the high disparity between results for area, which range from 7000-50000 km^2. Ignoring earlier studies, the range for area appears to be 20-35 1000 km^2. Aside from disparities in results, one major point of difference is what each of these studies *identifies as what's considered part of the wetland system*; for some it is only the permanently flooded region, while for others it is the permanently flooded, rain-flooded, river flooded and surrounding flood plains.

5.4.7 Hydrological model of the Sudd

What has been said so far about the Sudd shows its hydrological parameters when they're investigated and assessed independently. The following is a hydrological model developed for the Sudd by Sutcliffe and Parks in 1987. It has been frequently cited, and stands to be one of the most important theoretical frameworks for studying the Sudd. The Sudd swamps are treated as a simple reservoir model, which is used to create a water balance model; measured inflows, outflows, evaporation and rainfall for the years 1905-1980 were used to develop the model; the area of the Sudd is central to reservoir model, which is estimated by balancing the water cycle. This depends heavily on calculated evaporation; theoretical outflows replace measured outflows to predict the effect of the Jonglei Canal on the region.

The model developed for this area to evaluate its water balance equation is that of a simple reservoir. The surface area flooded for a given storage volume is necessary to identify, and a relationship for the two (storage volume and surface area) is defined. The area looked at is generally below Mongalla, and the basic water balance equation is as follows:

$$\delta V = \left[Q_{in} - q_{out} + A(P - E)\right]\delta t - r\delta A$$

Where V is the storage volume, P and E are precipitation and evaporation, respectively, A is the surface area of the flooded area, and r is recharge. r is more than zero when the area is expanding (dA>0) and 0 when the area is contracting (dA<0).

The authors begin by assigning a linear relationship to the area and volume, A=kV, where k is some constant, and where A and V exponentially increase with the water level. This allows for one of the terms (A) above to be eliminated. Next, the net evaporation for a month is defined as (E-P)A_i, where Ai is the area in the beginning of that month. In an iterative way, starting with an initial storage volume on Jan 1, 1905, the data is used to make the hydrologic model fit so that by the end of the chosen time period (1980), using available and reliable measurements of rainfall and evaporation, the current volume is found.

Measurements of Hydrologic Parameters

Measurements for inflow to the Sudd are made at Mongalla for the period in question. Since construction of the Jonglei Canal ends at Bor, authors deduced inflow at Bor from this data. Only 10 stations provided monthly rainfall data for the years 1941-1970. Authors used this data to fill in gap of monthly precipitation for remainder of investigation period and other stations. Authors used the Penman-Montieth equation to calculate evapotranspiration assuming Sudd's evaporation is that of a body of open water.

Discussion of Model

The authors assert that holding evaporation at 2150 mm/yr is correct; varying r by 25% results in only a 1% change in the total area so it's not a sensitive parameter; changing the relationship of A and V to other forms was also tested; for example, the relationship was taken to be a=kV^x, and k and x were varied independently and together. Comparing model data to measured data shows that holding k and x at 1, or A=kV provides the best fit for the available data.

Other Studies that use this Model

Mohamed et al used their calculation of the evaporation (since this is one of the two main unknowns in the model) to reconstruct Sucliffe and Parks' model for calculating the water cycle of the White Nile's wetlands, and found the Sudd to be 70% larger than what's concluded by Sutcliffe and Parks.

The same techniques were used to calculate the water balance of the other two neighboring wetlands. The study on Bahr el Ghazal was deemed inconclusive as runoff data obtained for the region was largely unreliable.

Also Shamseddin et al (2006), based on their area results and calculating ET using the SEBAL method outlined above in Mohamed et al as well as open water evaporation, estimated the annual storage volume, assuming an initial water depth of 1 m. The rate of storage change was generated for the study period and was found to be 21.7 Gm^3 for open water evaporation, and 23.0 Gm^3 for wetland evaporation.

5.4.8 Recent Field Studies on southern area of the Sudd Basin

In 2008 (Peterson), an extensive study was done on a small area of the Sudd basin, between Mongalla and Shambe, mainly between Mabior and Bor. The field work spanned 3 flood seasons between 2004 and 2006, and included direct measurements of parameters such as evapotranspiration and recharge. The study was aimed at evaluating the water balance and hydrodynamics in the system, including local and external driving factors, ranging from the significance of Equatorial lakes inflows to local rainfall and ET

Between Juba and Bor

An earlier study described this area as having moderate flows and river levels; the river spills through its alluvial banks in successive channels along the bank, some of which are deep and may become part of the main channel network, while others are very shallow. In 1952, more than 500 channels were surveyed in less than a 120 km stretch of land along both banks. During high river flows, however, widespread spillage occurs. These channels form from breaks along the banks. However, even the large ones may eventually silt up and become obsolete, to return again. In Peterson (2008), it is pointed out that above Bor, the basins of the floodplains act as reservoirs, which receive water and return it, lower down. When the river level is high, this temporary storage feature increases. Below Bor, this feature disappears along with the eastern edge of the trough, and flooding occurs with no limiting barrier (Sutcliffe and Parks, 1999).

Between Bor and Shambe

Between Bor and Shambe, the area transitions from defined river along incised trough, to the flat unlimited floodplain area where river becomes an inland delta. This transitional area is dynamic, and a description of its physical features offers guidelines regarding its behavior. The channel system is constantly changing due to sedimentation, erosion, and blockages by floating vegetation. The Peterson study provides an updated description of the Sudd, by breaking down its total area into five distinct regions:

a) Nimule to Juba: rapid runoff zone where base flow from Equatorial Lakes is received, as well as torrent flow
b) Juba to Bor: incised river widens, and river starts splitting up within constraining trough; surrounding floodplain receives and returns water to main channel over riverbank
c) Bor to Shambe: inland delta is where previous trough disappears, and flow is signified by flooding, unrestricted except through evaporation and vegetation; multiple channels and lagoon systems start; Bahr el Zeraf forms and starts its northward journey, whereas Bahr el Jebel starts to flow in a northwesterly direction; downward slope is about 10 cm/km
d) Shambe to Lake No: wide papyrus fields; lagoons and meandering and blocked channels; slope of surrounding floodplains is about 1.5 m/km
e) Lake No to W. Nile: all river systems – Zeraf, Jebel, Ghazal, and Sobat – gather; banks of W. Nile become more defined and then quite high as the river makes its way towards Kosti and Khartoum

Interaction of Morphology and Hydrology

The study then provided an analysis of the interaction between the morphology and hydrology, stating that in the flat toic land, khors (or narrow water streams) play more important role of carrying floodwaters than rainfall – except during very high rainfall. This is an important point since it is not thoroughly understood whether rainfall or overbank spillage dominantly contributes to the size of the area. Consequently, there is uncertainty to how reducing inflow through the Jonglei Canal will affect the area of the Sudd. In addition, understanding the role played by these khors will help properly demarcate the area of the Sudd. The study states that river flooding is the main source of flooding, rather than rainfall. Channels constitute 2% of land cover, lagoons 18%, and swamps 80% of land cover. Channels, however, are responsible for 93% of flow, while lagoons and swamps share remaining 7%.

Spatio-temporal water body and vegetation changes in upper Sudd area

This study also described an assessment of the Sudd's spatio-temporal changes to its channel and lagoon system, using Landsat images from the years 1973, 1979, 1997 and 2003. Sizes were compared to establish and quantify changes in between the years. This assessment was then compared to L. Victoria flow to try and establish likely correlations. The study found such correlation for the water level-depended lagoon system. However, changes in channel system were not correlated to the Lake's outflow; more likely these changes are correlated with other factors such as wind draft and vegetation. Results show that the main channel system is stable, and decreases in width as flow goes upstream. Channel movements were outwards in 1973-79, but moved inwards in 1997 and 2003. There was no clear trend between 1997 and 2003. For lagoons, location is stable, but size changes with L. Victoria discharges.

Evapotranspiration

Finally, the study makes evaporation measurements using a "depression experiment" as well as the Penman Montieth. The two were then compared and both approaches resulted in an average daily evaporation of 7.3 mm/d during Oct/Nov 2005, although the depression experiment shows more fluctuations. Taking Penman-Montieth results as representative of actual evapotranspiration, the total ET for the southern Sudd region is calculated to 2075 mm/yr. The study also made measurements of recharge and found that soil recharge for the southern part of the Sudd exceeds 350 mm/yr, a figure which is often cited as Sudd recharge, when recharge is considered at all.

5.4.9 Hydro-Climatology of the Sudd

In the sections above, hydrological and climatic features were introduced. This section summarizes the results of Mohamed et al (2005), which looked at the coupling effect of these features for the Nile's sub-basins Blue Nile, White Nile, Atbara River, and the Sudd, with a focus on the last region. The model looks at hydrology-climate interactions by examining atmospheric fluxes, land surface fluxes, and land surface-climate feedbacks. Such a coupled model outputs results in terms of moisture recycling ratio, precipitation efficiency, moistening efficiency, and feedback ratio for the Nile basin. Meteorological data used in this paper includes radiation, precipitation, evaporation and runoff at various stations and locations surrounding the 4 sub-basins.

The model investigates the importance of the Nile's water cycle to the regional climate and vice versa. This is important considering that both climate and water resources are expected to change due to climate change and proposed projects on the Nile's waters. After a literary review, including some preliminary studies of climate change impacts on the Nile's hydrology, the paper outlines data and methodology used. The paper uses the Regional Atmospheric Climate Model (RACMO), which inputs radiation, precipitation, evaporation and runoff data for 1995 to 2000. The model then calculates coupling features such as the moisture recycling ratio. The authors caution, however, that although this feature provides important insight into climate-water cycle interactions, the information given is non-prognostic; changing the recycling ratio does not tell us how precipitation will change, for instance.

Regional Climate Model

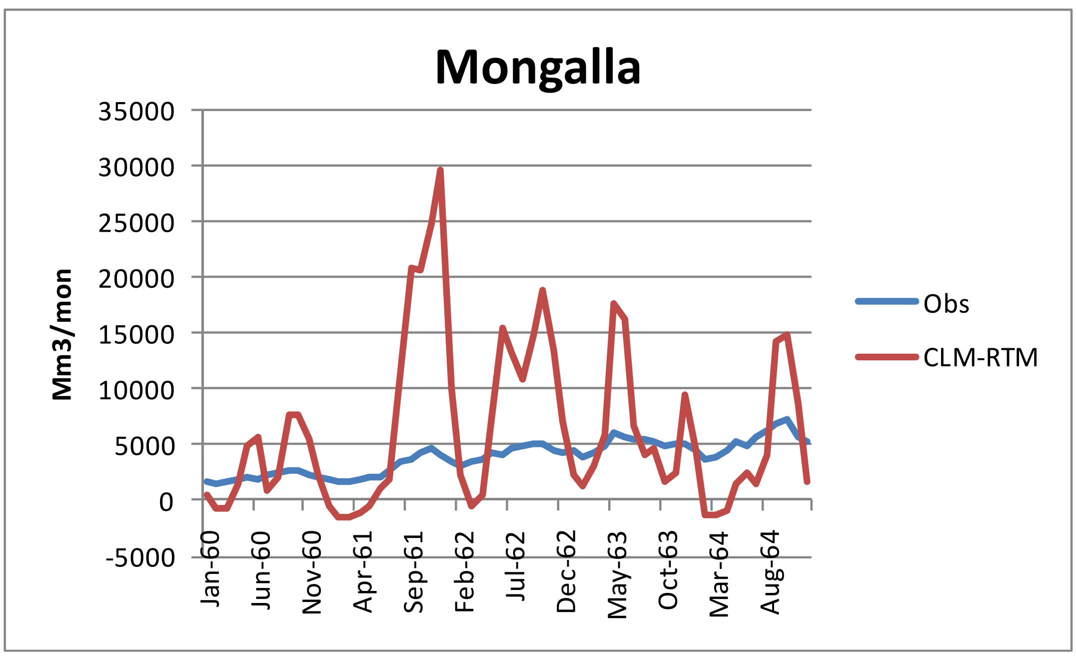
RACMO models physical processes such as radiation, convection, orography, turbulence and land surface. They are simulated using different parameterization schemes. Adjustments had to be made to the model to account for local canopy resistance, upstream runoff spreading to the Sudd, also incoming shortwave radiation, hydraulic conductivity, and the orography's influence on precipitation also had to be adjusted. Observations used in the model are precipitation, radiation, evaporation and sub-basin discharge. Based on the model's principles, results obtained show that the Nile basin uses about 40% of its atmospheric moisture for precipitation during the rainy season, of which 12% originated from local evaporation. The feedback ratio reaches 74% during the rainy season. The precipitation efficiency drops to 20% outside the rainy season.

These are the major scientific studies on the Sudd, which inform many of the customization decisions that went into applying CLM-LW to the White Nile, and to the Sudd in particular. The following sections describe exactly how CLM-LW was applied to the area, and results obtained from the model.

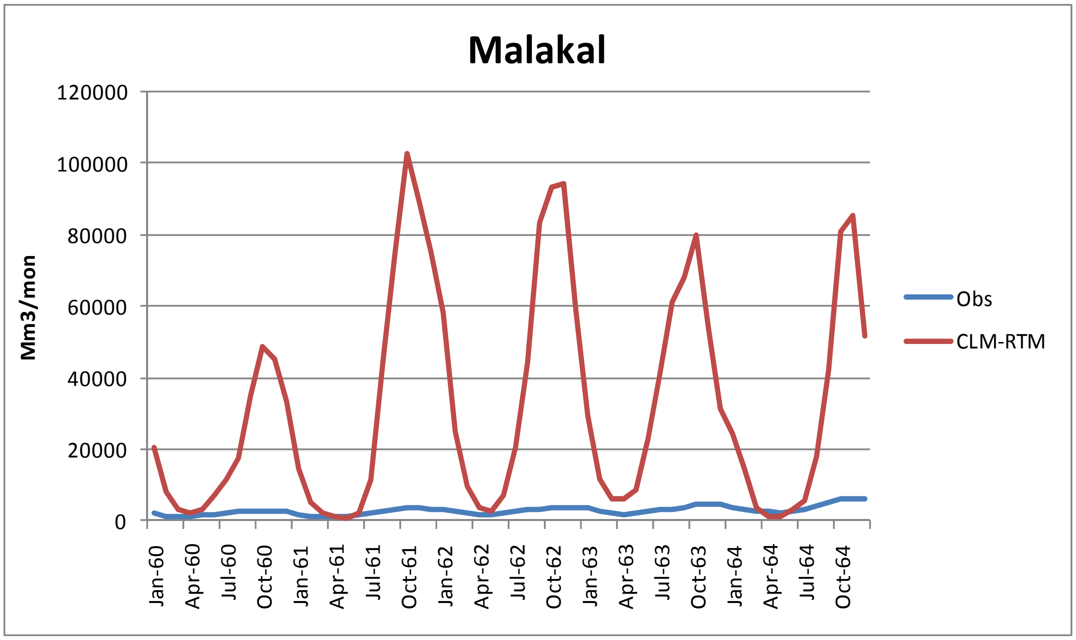
5.5 Application of CLM-LW to White Nile

The following describes how the generic form of CLM-LW described above is particularized for the White Nile. They are presented below as the specific structural changes made to CLM, and assessments of and changes to parameters input into both CLM and CLM-LW. Input parameters to CLM are the forcing data used, while input parameters to CLM-LW are evaporation and runoff data calculated by CLM. CLM-LW is applied to the ecosystems of L. Victoria, L. Kyoga, L. Albert, the Sobat basin and Machar marshes, the Sudd, and B. el Ghazal.

However, before these descriptions are presented, the following graphs show CLM-RTM flow results for the White Nile Basin before implementation of CLM-LW. The first graph shows flows at Mongalla, the place where the Sudd swamp is considered to start, and also represents discharge from the lakes. The second graph is at Malakal, a town directly downstream of all six catchments. For both graphs, data is provided as monthly flows, in Mm^3/mon, for the years 1960-1964. During this period, L. Victoria experienced a sudden jump in flow, which reverberated in all downstream locations. Therefore, it is considered particularly interesting to investigate how well CLM-LW captures catchment responses during this period and most results will be presented for this time period.



5-13 Flow at Malakal, taken from observations and compared to CLM-RTM streamflow, for 1960-1964



5-14 CLM-RTM flow at Malakal, downstream of six catchments, compared to observations

There are three main observations to point out. 1) The mean annual CLM-RTM outflow from the three lakes is 76.3 km^3, compared to that given by observations, 46.9 km^3, so CLM-RTM is not evaporating or storing as much from the catchment below Mongalla. The same observation can be made at Malakal where CLM-RTM flow was 10 times as much as the observed value. 2) There are instances, such as in early 1961, when CLM-RTM produces negative flows. 3) Not only are annual means overestimated, but CLM-RTM lakes and wetlands do not dampen flows, and the high variability in runoff gets translated into streamflow rather than being diminished by the presence of land storage capacities. When applying CLM-LW to the White Nile, these are the types of analysis that will be done to assess the performance of CLM-LW.

5.5.1 Structural Changes

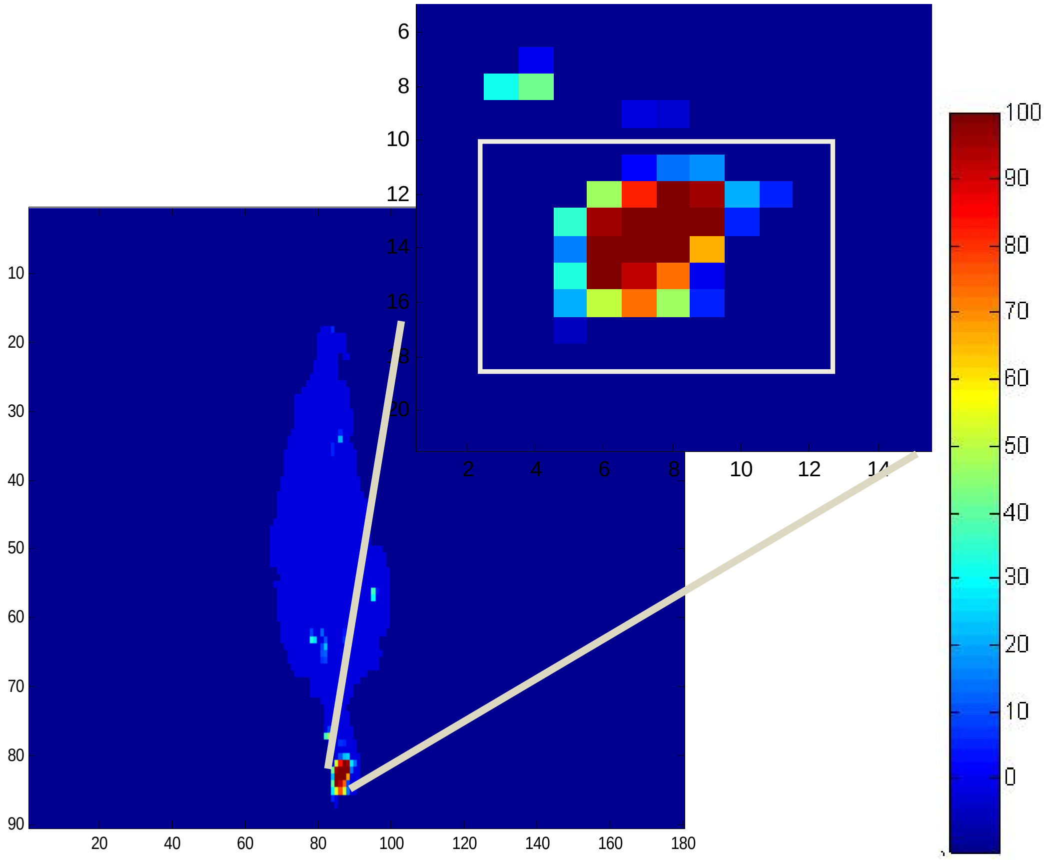
As was stated above, CLM lake and wetland spatial distributions and area extent are based on Cogley (1991). This database was shown to consistently underestimate areas compared to what is documented in other studies and databases. This was found to be the case in the White Nile, specifically for wetlands. As such, the areal extent of the wetlands in the Nile basin were changed according Table 5-7, showing previous and new (or unchanged) areas of the lakes and wetlands in the White Nile. Recorded area values are obtained from Sutcliffe and Parks (1999) for lakes, based on average Sudd area from various studies, and Yates and Strzepek (1998) provided areas of the other wetlands:

Table 5-7 Previous and new CLM areas for lakes and wetlands in the White Nile

	CLM Area Km^2	Recorded Area Km^2	New Area Km^2
Victoria	56648.74	67000	Unchanged
Kyoga	432.6764	4700	Unchanged
Albert	2935.254	5300	Unchanged
Sudd	3151.728	~20000	24484.19
BEG	2138.291	11328	9161.69
Sobat	396.9785	6877	6106.387

The Sudd wetland area is the most important to get right, since it will be used for the policy analysis further on. For the other ecosystems, discrepancies in area were captured in how the model was calibrated so as to produce the correct outflow from their basins.

The CLM-LW mechanisms for creating wetland/lake clusters apply to lakes and wetlands within the White Nile as well. Here too ecosystems are large enough to span at least 2 cells each. 5-15 shows the cells making up the Nile basin, and those among them which make up the lakes and wetlands in the White Nile, as well as L. Tana, and L. Nasser of the Aswan Dam – cell colors indicate the percent of cell that's covered by a lake or wetland ecosystem. The second box enlarges the three Equatorial Lakes with L. Victoria's cells shown prominently in the White box.

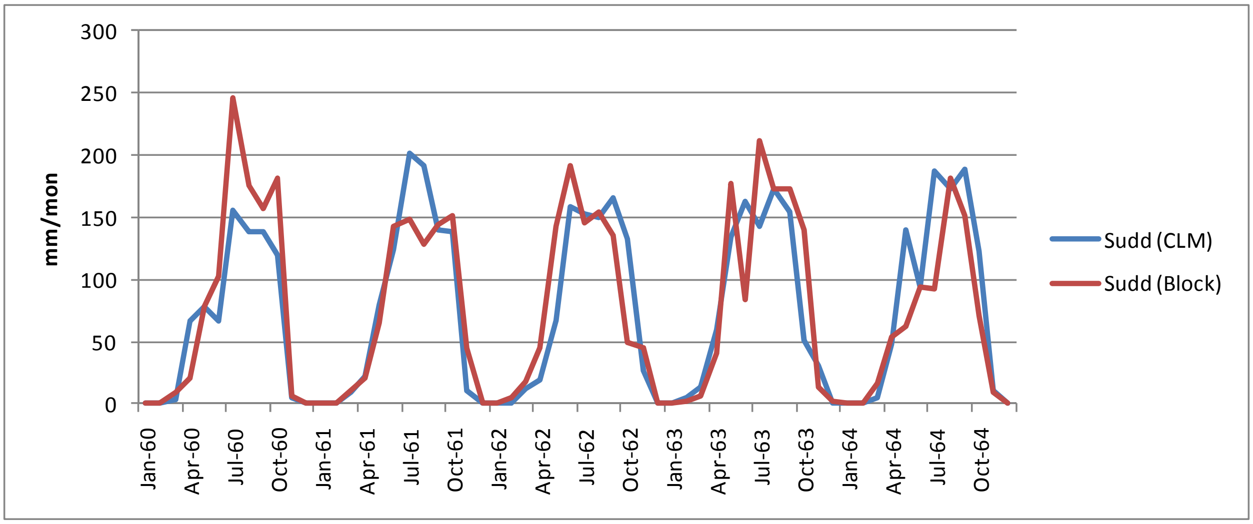


5-15 Nile basin cells on a 0.5x0.5 grid, with the cell percentages in lakes and wetland shown. The box in the upper right shows lakes Victoria, Kyoga and Albert

5.5.2 Model Input Parameters

Meteorological Data

The forcing data used to run CLM for the White Nile CLM-LW is the "NCEP Corrected by CRU" (NCC, Ngo-Duc *et al.*, 2005) dataset, an NCEP/NCAR reanalysis of CRU global data. It is calculated over land at a 1x1 degree resolution, at 6-hourly time steps. It is available for the period of 1949 to 2000. The NCC forcing data includes precipitation, temperature, radiation, pressure, specific humidity and wind speed. Runoff from CLM when forced with NCC data was shown in Strzepek et al (2010) to perform well against other forcing data sets used. As was shown by Qian (2005), accuracy of precipitation is the most important factor for CLM's hydrology. As such, NCC precipitation data was compared to those used by Block and Rajagopalan (2009) (hereto known as Block) in their White Nile modeling, for the years 1960 through 1964, yielding Figure 5-16:



5-16 Comparison of NCC and Block precipitation for years 1960-64

Block's precipitation data is based on CRU reanalysis data, but includes direct observations. Table 5-8 compares annual average precipitation for the two datasets, and monthly correlation coefficients for the 6 sub-basins as:

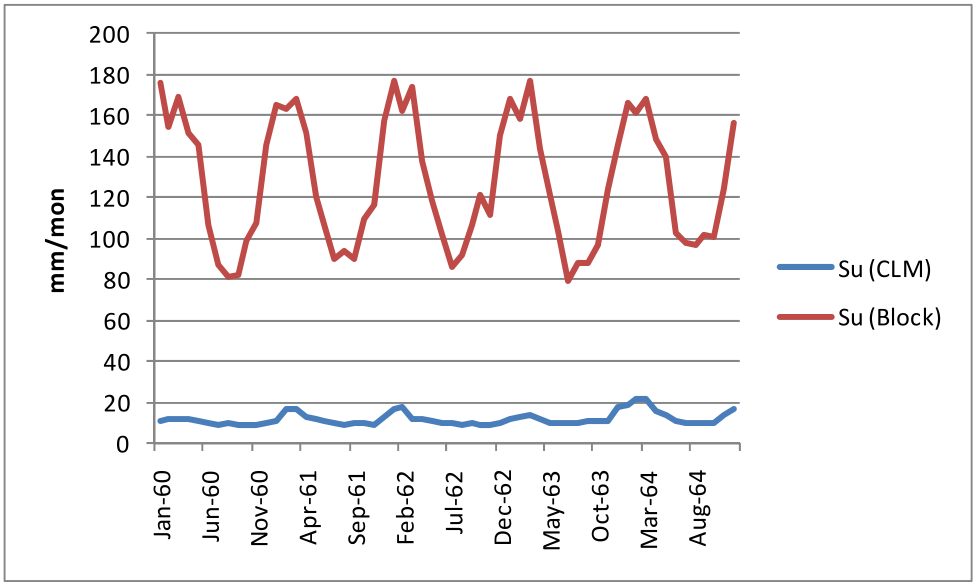
Table 5-8 Comparison of NCC and Block precipitation for Sudd rainfall

	Victoria	Kyoga	Albert	Sudd	B. el Ghazal	Sobat
R^2	0.37	0.26	0.37	0.86	0.91	0.85
NCC Annual P	528.12	1499.26	1364.63	894.115	955.23	1236.06
Block Annual P	1489.97	1481.34	1285.83	905.026	947.23	1264.36
% CLM/Block	35.4%	101.2%	106.1%	98.8%	100.8%	97.8%

Aside from Lake Victoria, NCC precipitation values are comparable to those of Block. Since for runoff production, Precipitation – Evaporation (P-E) is more important, steps were taken to ensure that P-E is satisfactory and NCC precipitation values were left unchanged.

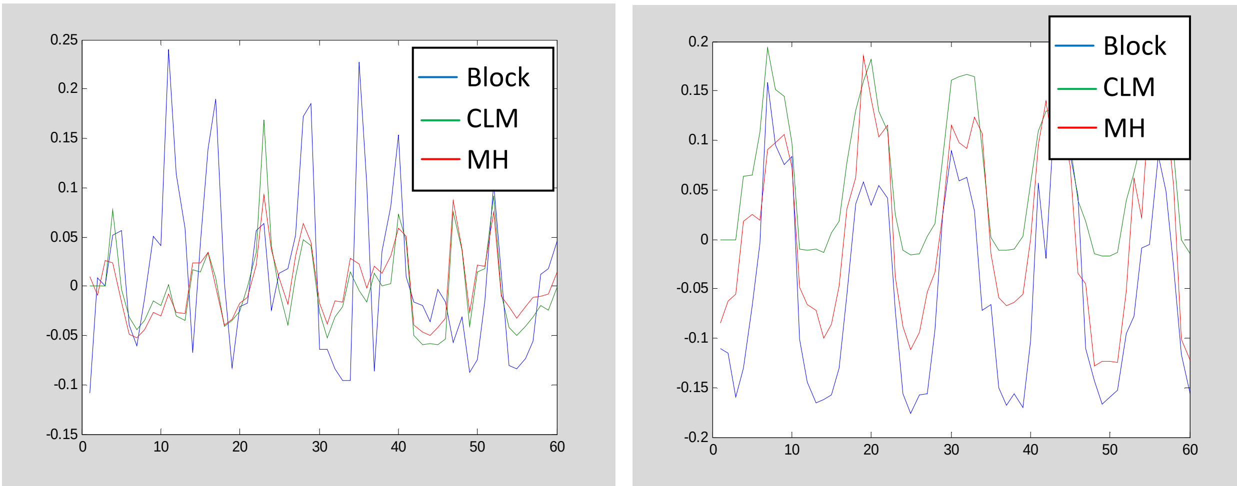
Evaporation

One of the main changes to CLM-LW is creating the option for recalculating wetland evaporation based on the daily Modified Hargreaves, rather than using CLM's techniques. In the case of wetlands in the White Nile, evaluations of evaporation rates showed that CLM's evaporation rates for wetland land surfaces are not comparable to those of Block, which were calculated using the Penman-Montieth equation. Evaporation is looked at for the years 1960-1964, since this is where the White Nile experienced a large change in precipitation and ensuing flow. Figure 5-17 is CLM's evaporation results (using the default Penman-Monieth estimate) for the Sudd as compared to Block's evaporation values, for the years 1960-1964:

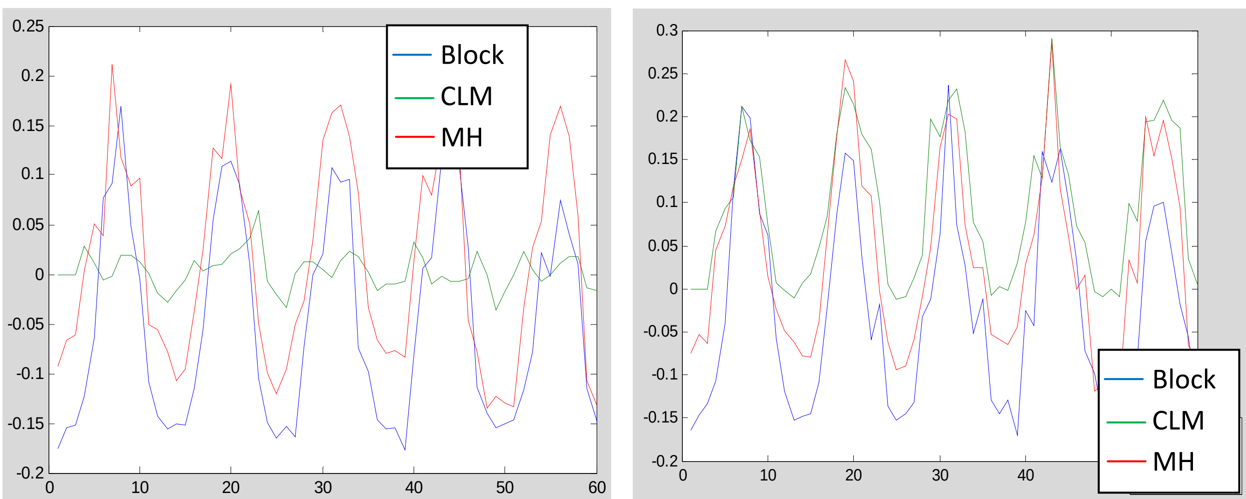


5-17 Comparison of CLM and Block Sudd evaporation, 1960-64

As the graphs in Figures 5-18 and 5-19 show, CLM evaporation rates for lakes are comparable to those of Block; however, CLM highly underestimates evaporation from the wetlands. Again, P-E is the important input parameter to CLM-LW, based on the equations of flow. As such, a comparison made for P-E is more important than that made for each of those variables separately. The following graphs describe monthly P-E for the Sudd, Sobat, BEG and Lake Victoria for 1960-1964. Each graph compares CLM P-E, to that used in the Block model, and to that derived using MH for evaporation:



5-18 P-E as computed by Block, CLM and the Modified Hargreaves (MH) for L. Victoria (on the left) and Sudd (on the right). Values are in m/mon.



5-19 P-E as computed by Block, CLM and the Modified Hargreaves (MH) for BEG (on the left) and Sobat (on the right). Values are in m/mon.

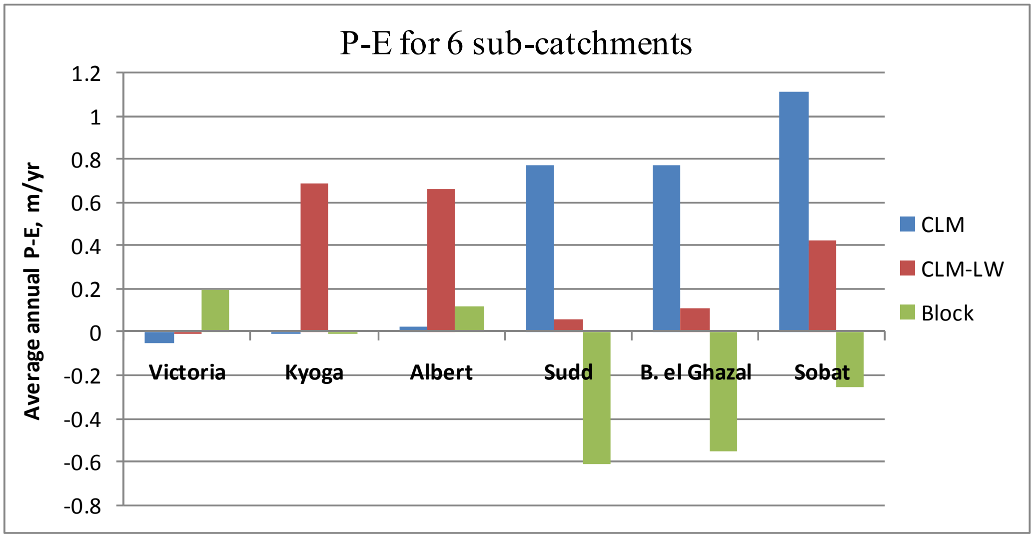
The above results can also be represented in Table 5-9, which shows the average annual P-E for the 6 sub-catchments, as computed by CLM's native mechanism, CLM-LW and Block's model. The table also shows whether CLM-LW represents an improvement or not for the wetland or lake.

Table 5-9 Average P-E (m/yr), for the period 1960-64, as computerd by CLM, CLM-LW and Block

	CLM	CLM-LW	Block	Improve
Victoria	-0.05352	-0.00156	0.194576	Slightly
Kyoga	-0.00209	0.686124	-0.00278	No
Albert	0.022133	0.662348	0.118884	No

Sudd	0.770171	0.060785	-0.61062	Yes
B. el Ghazal	0.774443	0.110225	-0.55115	Yes
Sobat	1.111984	0.421338	-0.25731	Yes

Results from Table 5-9 are shown in Figure 5-20 below, to demonstrate how CLM-LW improved P-E for the wetlands only.

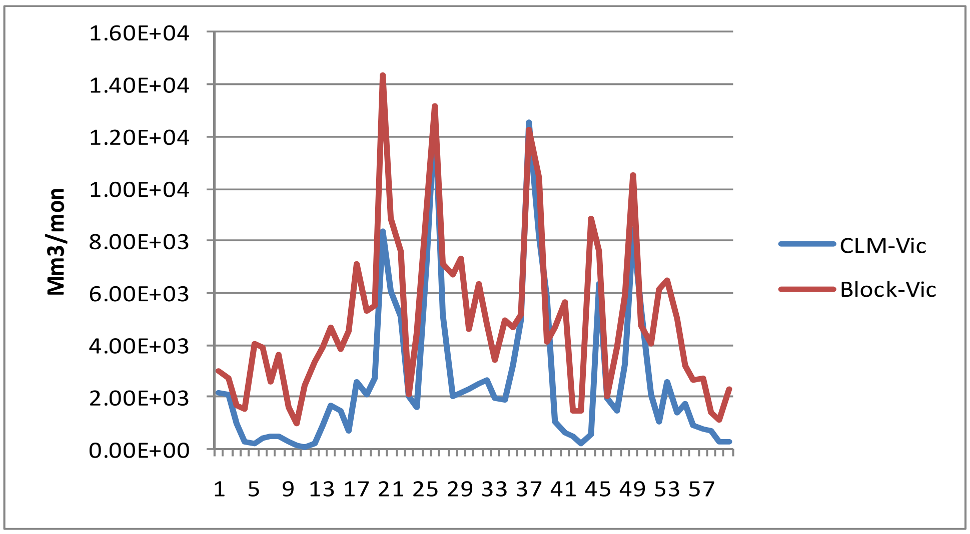


5-20 P-E computed using CLM, CLM-LW and Block, for the period 1960-64, in m/yr

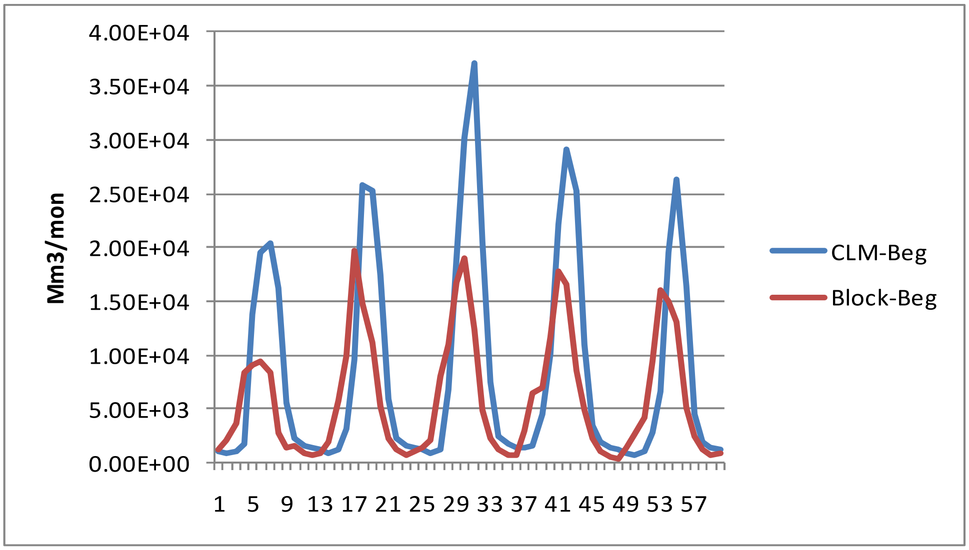
As results for Lake Victoria show, P-E, whether derived from MH evaporation or CLM's equations, are very similar, while the Modified Hargreaves makes P-E for the other lakes worse. For that reason, CLM's evaporation is maintained for lakes. On the other hand, over wetlands, using the Modified Hargreaves produces vastly different values of evaporation, as is shown by the graphs. Although MH does not capture all of the evaporation from wetlands, this process performs better than CLM. One source of the discrepancy between MH and Block evaporation is that for the former, wetlands are treated as open water surfaces, while for the latter wetlands include vegetated surfaces. As per the discussion of evaporation on 5.4.5, that distinction does produce different results. The error can also be attributed to the forcing data used; Qian (2005) shows that CLM produces better results when the forcing data, particularly precipitation, is corrected.

Runoff from the Catchment

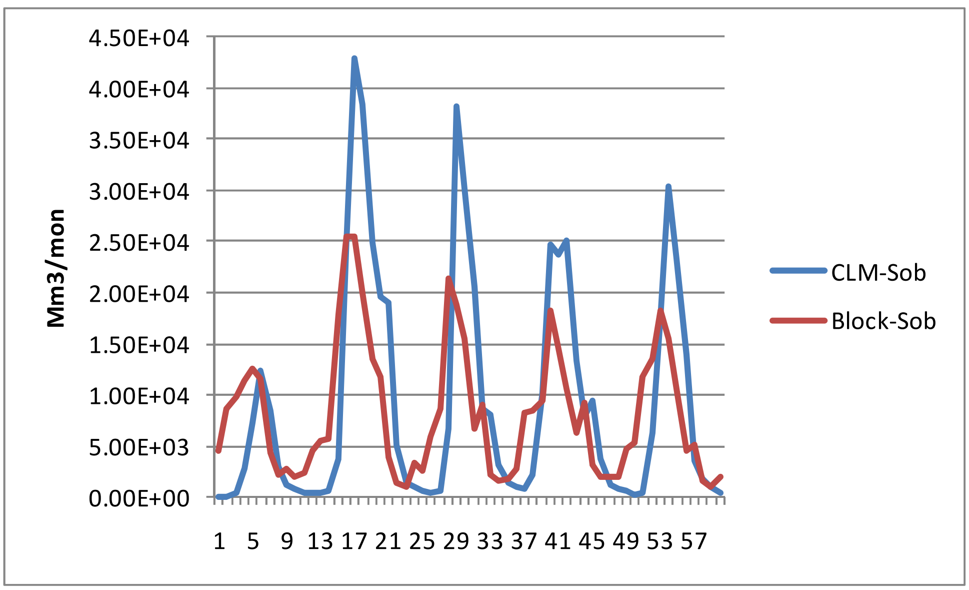
Each lake and wetland unit in the White Nile sits in a catchment that, apart from upstream flows, produces runoff that contributes to the total inflow into the lake/wetland unit. In the case of the Sudd, this runoff is known as torrential flows. Although more will be said about the equations that calculate river flow later, this section looks at what CLM produces as the catchment runoff for the 3 sub-basins for which there is no upstream lake/wetland, namely L. Victoria, the Sobat basin and B. el Ghazal. In each case, runoff refers to how much water is collected at the entry point of the lake/wetland unit. This CLM runoff is produced by the vegetated area in the catchment. As in other cases, monthly results for 1960-1964 are looked at to evaluate how well CLM captures the famous jump in flows:



5-21 Runoff from Lake Victoria's catchment as given by Block, and compared to CLM runoff



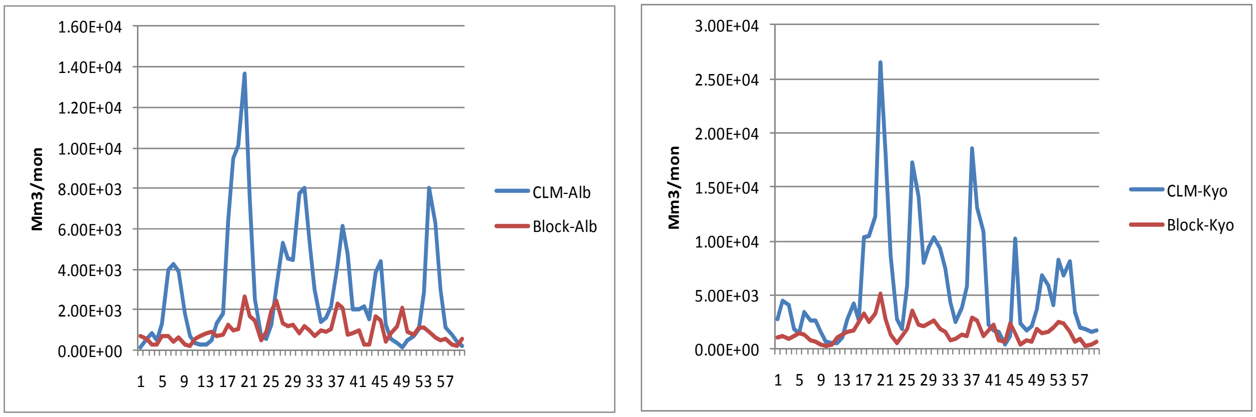
5-22 Runoff from B. el Ghazal's catchment as given by Block, and compared to CLM runoff



5-23 Runoff from the Sobat catchment as given by Block, and compared to CLM runoff

In each case shown in the graphs above, CLM follows the peaks and dips in Block's data. Apart from the Lake Victoria catchment, CLM produces higher runoff than Block's values. In terms of runoff for the other basins, the way that RTM routes discharge from each cell to its downstream neighbor means that at the entry point of lake/wetland units, there is no distinction between catchment runoff and river streamflow. In this analysis, the two components were separated out for Lakes Albert and Kyoga by subtracting outflow from the upstream unit from the inflow at the lake in question. For example, in L. Kyoga where the upstream unit is L. Victoria,

Kyoga catchment runoff = Kyoga inflow – Victoria outflow



5-24 Runoff at Lakes Kyoga and Albert, calculated as outflow from upstream lake subtracte from the inflow at current lake

As in the other cases, CLM produces runoff that's larger than what's reported by Block. Table 5-10 provides annual averages of runoff, as well as correlation coefficients, R^2 for the 5 catchments:

Table 5-10 Average annual runoff for 5 sub-catchments in the White Nile

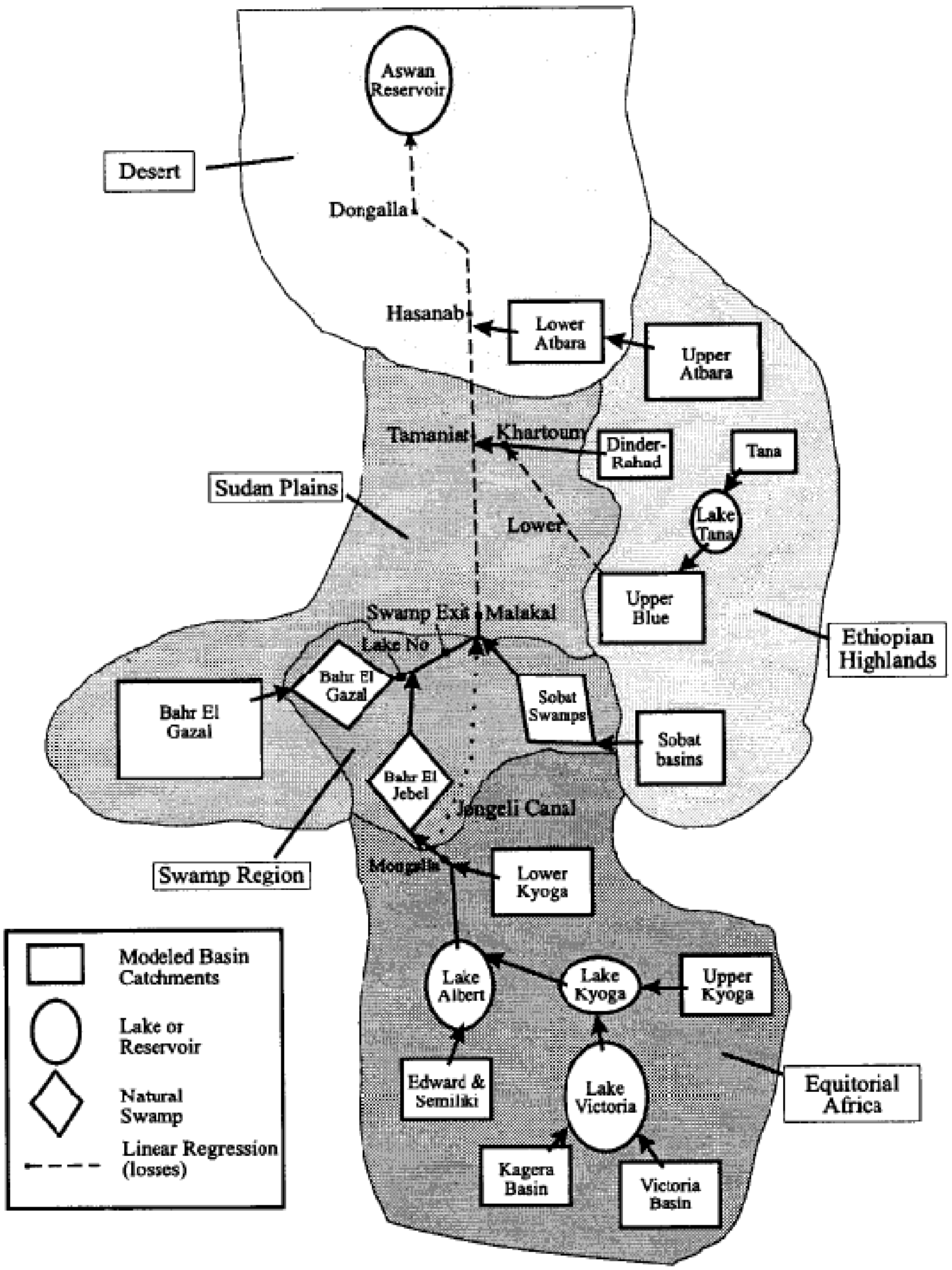
	CLM	Block	% CLM/Block	R2
Victoria	3.21E+04	6.00E+04	53.6%	0.83
Kyoga	6.94E+04	1.90E+04	366.0%	0.81
Albert	3.60E+04	1.16E+04	311.8%	0.44
BEG	1.02E+05	7.16E+04	141.9%	0.71
Sobat	1.12E+05	9.94E+04	112.9%	0.71

The table shows that Albert and Kyoga have the highest overestimation of runoff among the 5 catchments. In addition, Albert has the worst correlation between CLM and Block catchment runoff. In all 5 catchments, the equations that determine their volume variability and outflow are calibrated such that these differences in runoff are reflected by how the volume changes, so that outflow values are similar to those obtained by Block, as well as available observed data. In the case of the Sudd, special steps were taken so that errors in runoff (in inflow in general) were corrected before it is allowed to enter the wetland. The section on Model Equations and discussion of results delves deeper into how the Sudd was treated.

5.5.3 Lake and Wetland Equations

CLM-LW equations were derived from Yates and Strzepek (1998), which developed them as part of their WBNILE model, and following Sutcliffe and Park (1987). Due to the dearth in observational data, WBNILE is an average-monthly water balance, based on the parameters for which data is available. The three constituents of this model are a soil moisture accounting scheme, describing flows into and out of a simulated basin; the second is a calculation of the potential evapotranspiration based on the Priestly-Taylor method (Priestly and Taylor, 1972); and the third models the lakes and wetlands as reservoirs to assess their hydrologic response. The model was used for 3 regions in the Nile Basin: the Equatorial Lakes, which include the Kagera basin, Lakes Victoria, Albert, Kyoga and their basins, as well as the region directly below Kyoga; the second region is the White Nile wetlands comprising of the Machar marshes (in Sobat), Bahr el Ghazal, and Sudd wetlands in the Bahr el Jebel basin; and the third region is the Blue Nile, Lake Tana, Atbara basin, all of which originate in the Ethiopian Highlands. Figure 5-25 taken from Yates and Strzepek (1998) shows a schematic of the modeled regions.

Using the basin soil moisture component to calculate runoff at the catchment, the wetland and lake models in this component follow a reservoir-based hydrologic response, and calculated evapotranspiration to calculate lake/wetland storage and outflow.



5-25 Schematic that describes the 3 regions modeled in Yates-Strzepek (1998) WBNILE model

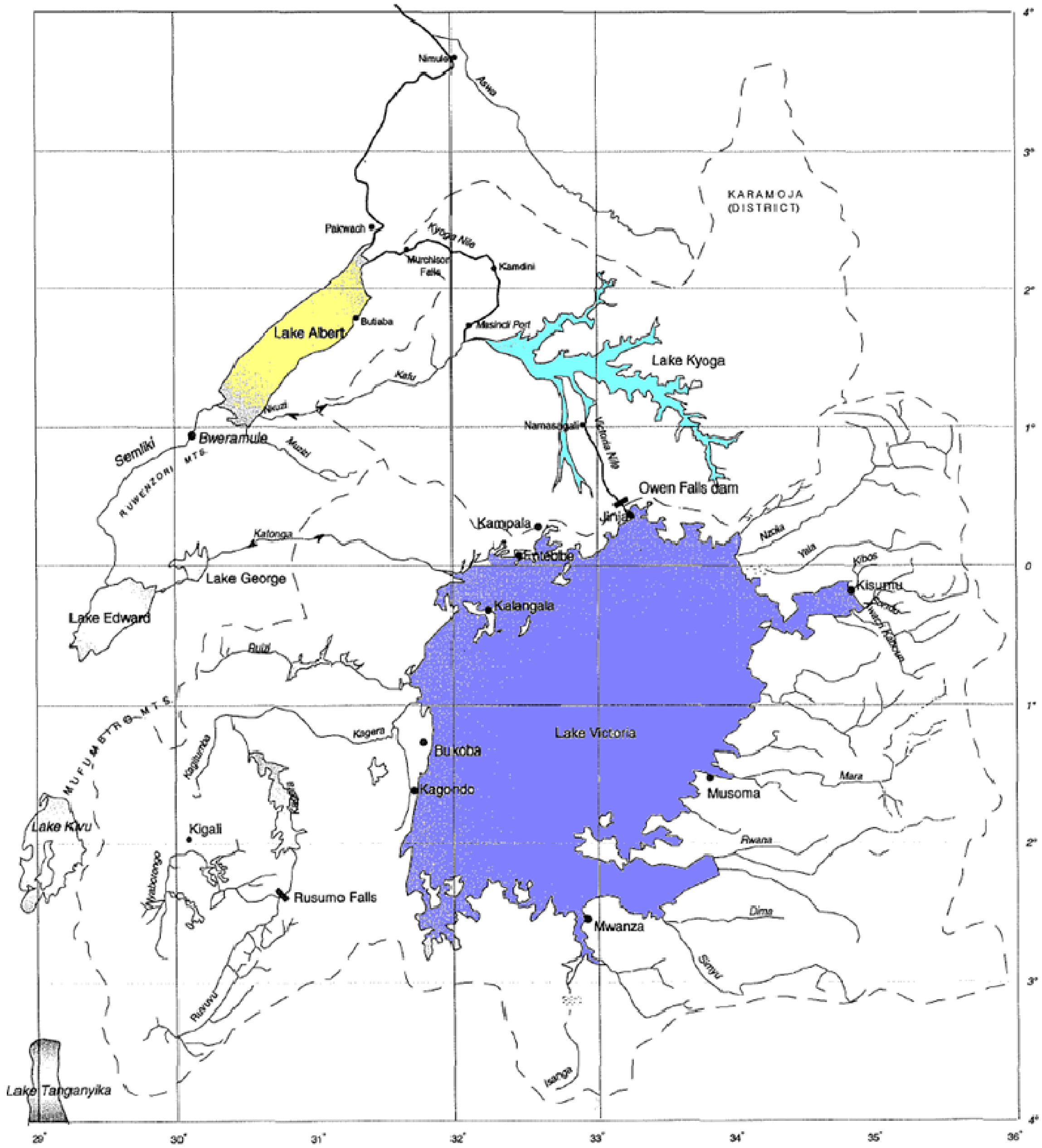
Since CLM calculates evaporation (there is no explicit vegetation in the lake and wetland land units), and (surface and subsurface) runoff for the lake and wetland catchment, as well as routes upstream rivers into this catchment, only the final component of the Yates-Strzepek model was utilized in CLM-LW. This model also evolved into a combined statistical-dynamical model in Block and Rajagopalan (2009), where the dynamical model is what has so far been described; the statistical model "incorporates a nonparametric approach based on local polynomial regression, utilizing principle components of precipitation and temperature;" and the two are combined through linear regression (Block and Rajagopalan, 2009). While the Yates-Strzepek version is used for CLM-LW, performance of CLM-LW is evaluated based on available observational data and results from the Block and Rajagopalan model.

CLM-LW equations are based on the (reservoir equations) above, but were changed when applied to the White Nile wetlands/lakes for two reasons:

1) *CLM-LW runs at a daily time step*
    a. All previous manifestations of the reservoir equations were run for monthly time steps.
    b. The architecture of the equations implies the geometry of the reservoir, as well as implies the memory extent of the reservoir. In other words, how flow moves across a reservoir as large as L. Victoria, for instance, in a month is vastly different from how it moves in a day; the affected shape of the volume in daily time steps, is different and is reflected in how CLM-LW equations look like here.
2) The model was calibrated in order to *produce the correct outflow values from the reservoir*s
    a. Since ultimately this research is interested in how the area of the Sudd changes, and to a lesser degree, what the flows at Malakal looks like, inflow into the Sudd (partially determined by outflow from upstream reservoirs) is of primary interest to this study.
    b. However, as shown above, input parameters into these reservoirs were not exactly the same as Block's input parameters (for instance, runoff in L. Albert's catchment is 3 times as large as it should be) the equations were changed so that other reservoir variables, like area or volume or depth, were different from those of Block and other previous studies in order to capture the errors in these input parameters.

Lake Equations

Figure 5-26 shows the three lakes in the upper White Nile: L. Victoria, Kyoga and Albert.



5-26 Lakes Victoria, Kyoga and Albert (from Sutcliffe and Park, 1999)

Flow from between these lakes is such that L. Victoria discharges into L. Kyoga, which in turn flows into Albert. Albert, receiving water from the Semiliki to its southwest, receives Kyoga's outflow close to its exit point. The River Albert, as it is known at that point, proceeds onto the Sudd wetland.

The CLM-LW equation for describing daily L. Victoria's flow is as follows:

$$\frac{dV}{dt} = (P - E)(a_1 V + a_2) + Q_{in} - (b_1 V + b_2)$$

In the above equation, V is the volume, P is precipitation, E is open water evaporation, Qin in catchment runoff inflowing to Victoria, the parameters a_x are coefficients for changing volume to area, and b_x are coefficients for changing volume to discharge. There is a threshold volume below which no outflow can occur. Obtaining the parameters for a *daily* reservoir response model for L. Victoria proved to be difficult; Karogo and Torfs (2005) offer an explanation to this challenge by stating that "the lake is a big reservoir whose volume is very large relative to the average input components of its water balance and therefore has a proportionally large memory." In other words, daily time steps might be too short for the response time of this reservoir due to its size. Only when the parameters were varied so that daily outflow values are based on small perturbations in P-E and volume, was it possible to come up with equations that fit observed outflow values.

The equation determining Lake Kyoga flows, were of the following form:

$$\frac{dV}{dt} = (P - E)(a_1 V + a_2) + Q_{in} - (b_1 (V + b_2))$$

Lake Kyoga's equation follows the same format as that of Victoria, with slight change in the outflow term. In general terms, outflow from L. Kyoga follows closely with that of Victoria. The parameters were different from Victoria, however, reflecting the much smaller volume of the latter lake.

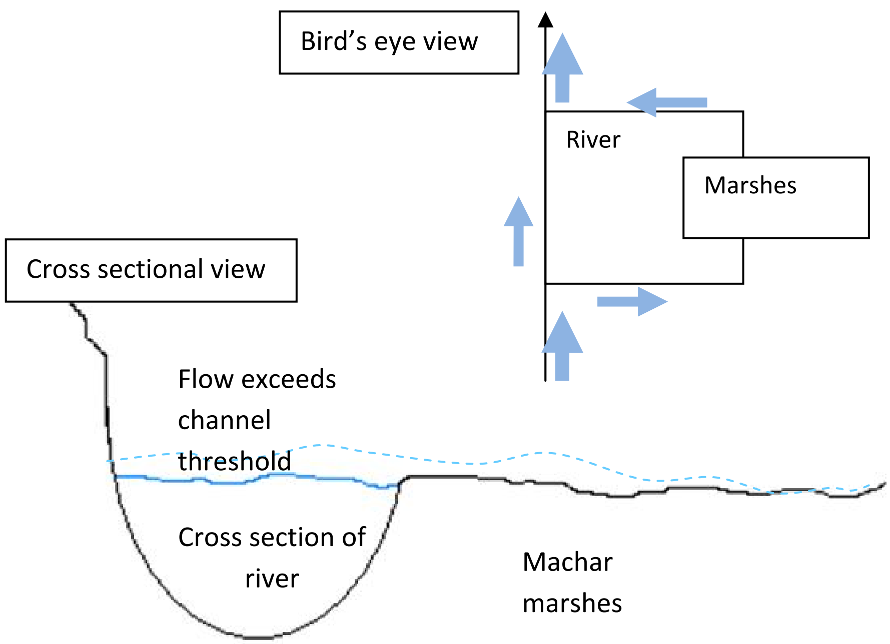
Lake Albert has an interesting hydrology in that it receives inflow from its catchment and from the River Semiliki, and these two inputs determine much of the lake's hydrology. Only close to its exit point does it receive flow from L. Kyoga, which mostly adds to its already computed outflow. In RTM, when a cell receives inflow, no distinction can be made as to where each fraction of this inflow originated from. The cell simply takes in its total inflow as one value. Therefore, initial parameterization of this lake involved finding the correct way of partitioning its inflow into that on which the change in volume depends, and that which simply gets added to outflow. However, results actually showed that maintaining the two as one unit, and changing the equations such that outflow values are calibrated to observed values yielded the best results. As such, the Lake Albert equation takes the same form as L. Victoria, however, with a very different interplay between the equation coefficients.

Wetland Equations

The Sobat River is such that once streamflow exceeds a certain amount, this extra amount spills into neighboring Machar marshes; some of this spilled flow returns back to the river system. The Sobat equation in CLM-LW reflects this phenomenon and appears as follows:

$$\frac{dV}{dt} = (P - E)(a_1 V + a_2) + (Q_{in} - c) - (b_1 V^2 + c)$$

The equations are implemented such that only when Q_{in} exceeds a threshold, is the remainder of inflow given to the wetland. Outflow from the wetland, as recorded further downstream, is supplemented by the difference between the inflow and threshold parameter. Figure 5-27 is a schematic describes this process:



5-27 The diagram shows the cross sectional view and bird's eye view of flow in the Sobat river

The Bahr el Ghazal basin, on the other hand, is characterized by very little outflow, even though the catchment itself produces a lot of runoff. This is due to the high evaporation rates of this basin. The equation determining outflow from this basin is:

$$\frac{dV}{dt} = (P - E)(a_1 V) + Q_{in} - b_1 V^2$$

Sudd Basin Equation

The Sudd basin's equation implemented in CLM-LW differed from that first developed by Sutcliff and Park (1987) and then later employed by other studies investigating the hydrology of the Sudd. One important difference between the two is the dependence of outflow on the other parameters. In the Sutcliffe and Park model, outflow is a function of only inflow, according to the following equation:

$$V_i = V_{i-1} + (P - E)(a_1 V_{i-1}) + I_t + I_u \pm a_1 r_c \Delta V - 120 I_{u,i-3}^{0.3}$$

I_t is catchment tributary flow (torrent flow), I_u is upstream flow, r_c is the recharge, and the last term $120I_{u,i-3}^{0.3}$ is the expression for outflow, calculated as a function of upstream flow 3 months before the current time step. The equation for Sudd hydrology was changed where now outflow, area, volume are allowed to vary as a function of all input parameters, and as a result of their internal interplay. The equation takes the following format:

$$\frac{dV}{dt} = (P - E)(a_1 V) + Q_{in} - b_1 V^c$$

Q_{in} is a combination of tributary and upstream flow, a_1 is the wetland constant depth, b_1 is a coefficient that changes volume to discharge. There is a non-linear relationship between outflow and volume based on the wetland's geometry. The term c was tested for different values including 2, 0.5, and 1. Finally, an optimization tool was utilized to obtain the best fit value of c. This process resulted in c=0.235 yielding the best results.

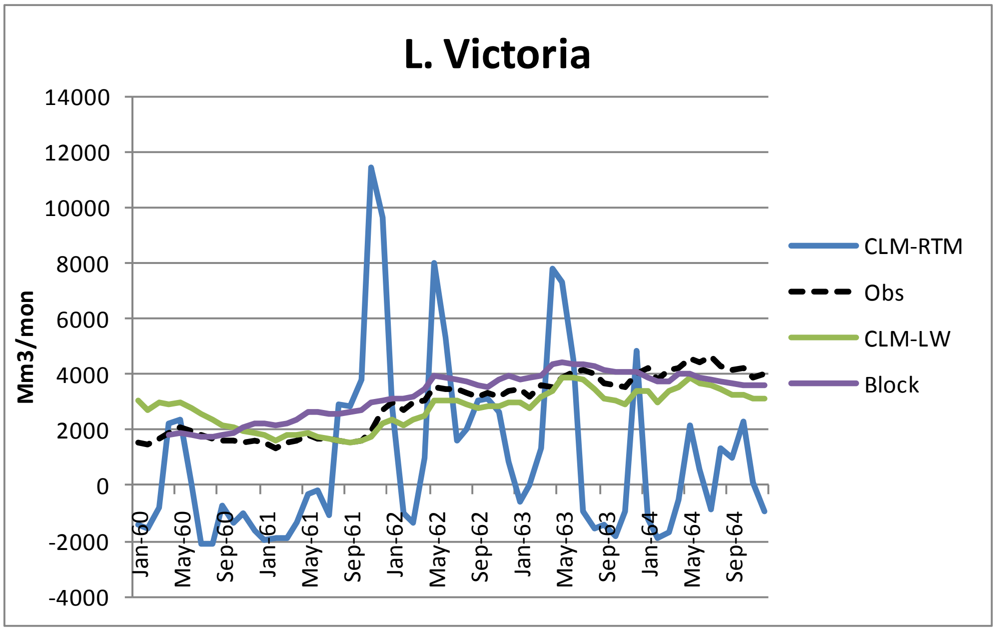
5.6 Model Results

This section presents and discusses the volume and outflow results for each of the catchments. It should be noted that monthly results are being presented for the time period 1960-1964. This period saw a sudden jump in L. Victoria, which reverberated in most of the White Nile basin. Special attention is given to the Sudd wetland as results from this wetland will be used for policy analysis later on. Results are presented in upstream order (from Victoria to the Sudd). It should be noted that CLM-LW runs at a daily time step, but results were aggregated to a monthly time step for the sake of comparison.

5.6.1 Results from CLM-LW for Lakes

Lake Victoria

The graph in Figure 5-28 shows L. Victoria monthly results as obtained by CLM-LW. These results are compared to observations of Victoria outflows, CLM-RTM, and Block results. The last comparison is to show how CLM-LW compares to other models used to simulate L. Victoria flows.



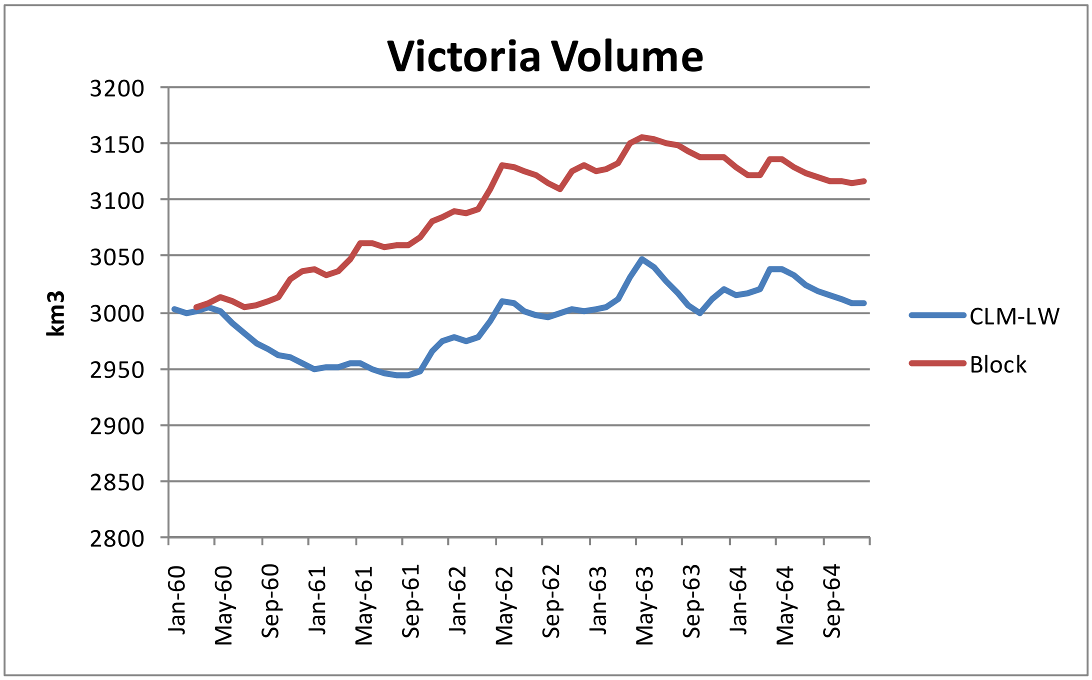
5-28 Lake Victoria flows as obtained from observations, CLM-RTM, CLM-LW and Block

CLM-LW 1) removes the possibility of negative flows, 2) dampens the seasonal variability of outflow, which is instead captured by the reservoir's storage variability 3) CLM-LW makes sure that the mean is comparable to observed mean, 4) the sudden jump in outflow experience by L. Victoria is also captured by CLM-LW. Table 5-11 below shows these annual means and standard deviations for the four flows:

Table 5-11 Lake Victoria annual flow means and standard deviations

	CLM-RTM	Obs	CLM-LW	Block
Annual Mean (km^3)	12.21	34.99	33.00	37.21
StdDev (km^3)	15.32	13.87	7.97	13.26

CLM-LW for Lake Victoria, which had catchment runoff values most comparable to Block, produced the following volume results for the same time period:

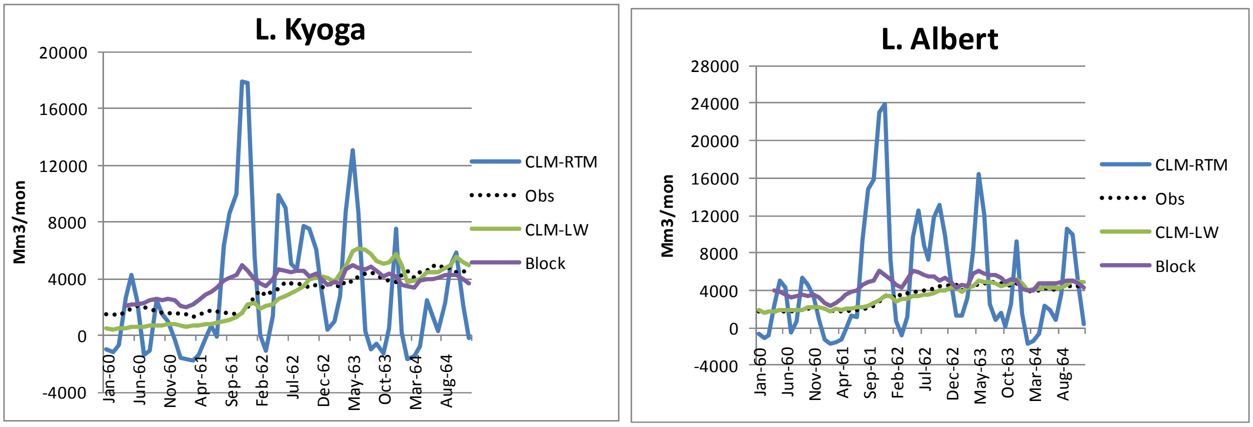


5-29 Change in Lake Victoria volume

Although the catchment's runoff was in the same order of magnitude as that of Block, it was consistently less. In order to calibrate the reservoir's outflows to observed outflows, the reduced runoff values are reflected in volume. Error is also due to the difference in P-E values.

Lakes Kyoga and Albert

The following are outflow results from Lakes Kyoga and Albert, followed by a table of annual means and standard deviations, followed by how errors in input data are reflected in each catchment's volume:



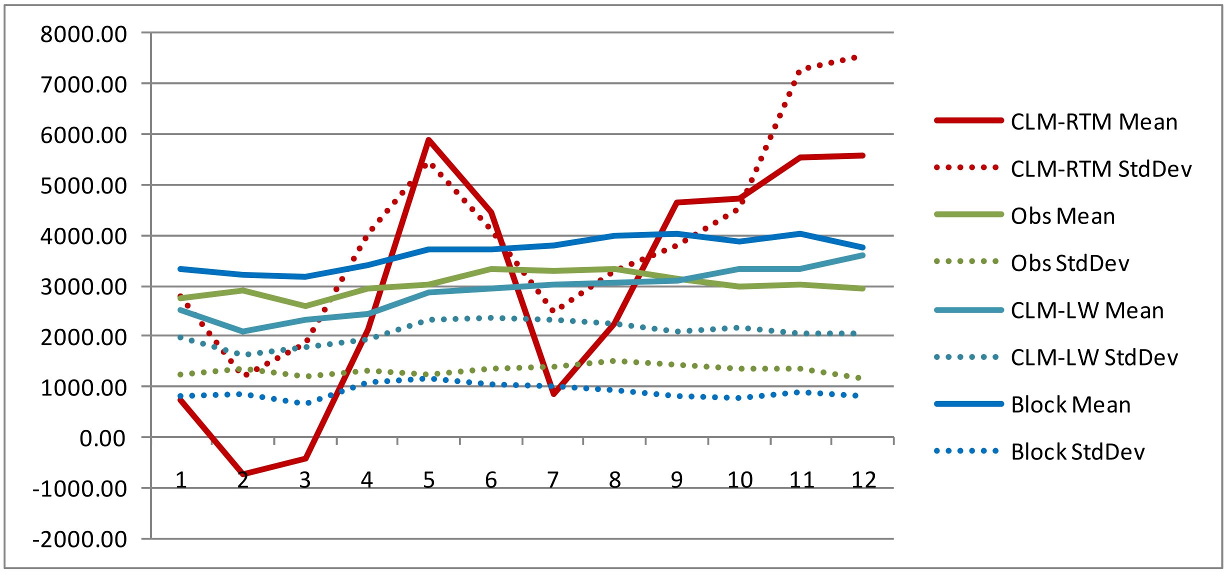
5-30 outflows from Lakes Kyoga and Albert as obtained from measurements, CLM-RTM, Block and CLM-LW

The graphs in Figure 5-30 show outflow from Lakes Kyoga and Albert. In the former, the famous jump in outflow is captured; however, there is a lag so that this jump occurs 4 months later than it does for observed flows. Lake Albert flows, on the other hand, are captured very well as compared to observed flows at Jinja, Uganda. The table breaks down these Kyoga flows into average annual flows and a graph of monthly averages and their standard deviations:

Table 5-12 The annual average Lake Kyoga flows and their standard devations

	CLM-RTM	Obs	CLM-LW	Block
Annual Mean (Mm3)	35,533.97	36,181.6	34,580.36	43,943.95
StdDev (Mm3)	22,648.51	15,878.07	24,609.21	12,512.13

It is interesting to note that for L. Kyoga, the annual means previously calculated by CLM-RTM were not entirely different from observed or those obtained by CLM-LW. For this lake, the damping of the simulated seasonality of the lake is what needed to be addressed, as can be seen by the monthly flow results shown below.

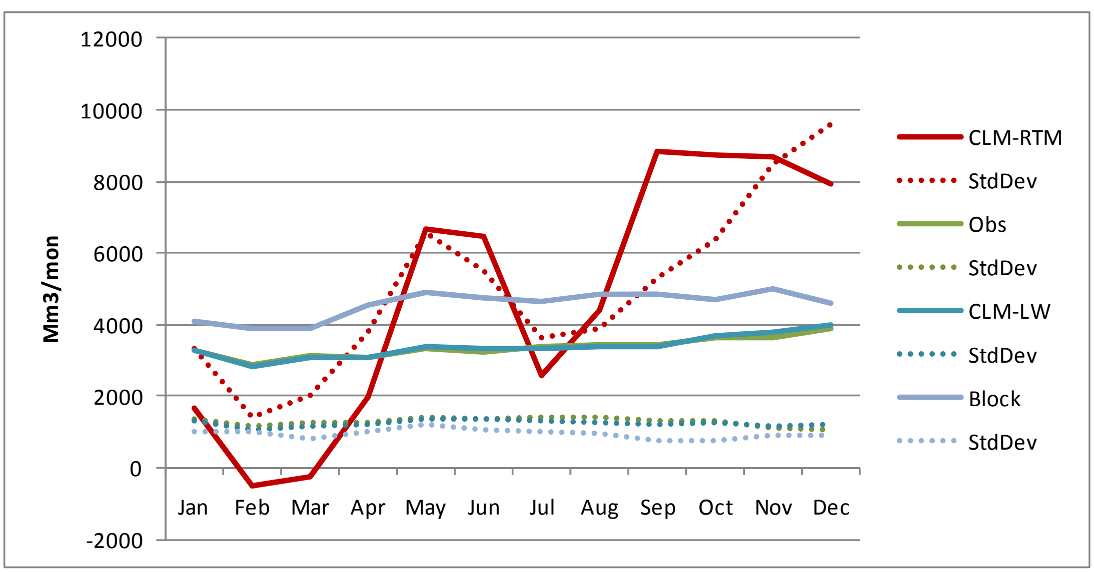


5-31 Monthly mean flows from L. Kyoga along with their standard devation

Results from L. Albert are important as the lake's flows constitute the steady inflow into the Sudd, while runoff generated at the Sudd's catchment create the inflow's monthly variability. The following table presents annual means and standard deviation for the period of 1960-1964, following by the same information, presented for monthly averages.

Table 5-13 Annual average flows from Lake Albert and their standard deviation

	CLM-RTM	Obs	CLM-LW	Block
Annual Mean (Mm3/yr)	57,115.72	40,342.2	40,557.04	52240.37
StdDev	28,708.28	15,311.77	14,790.8	12,892.92



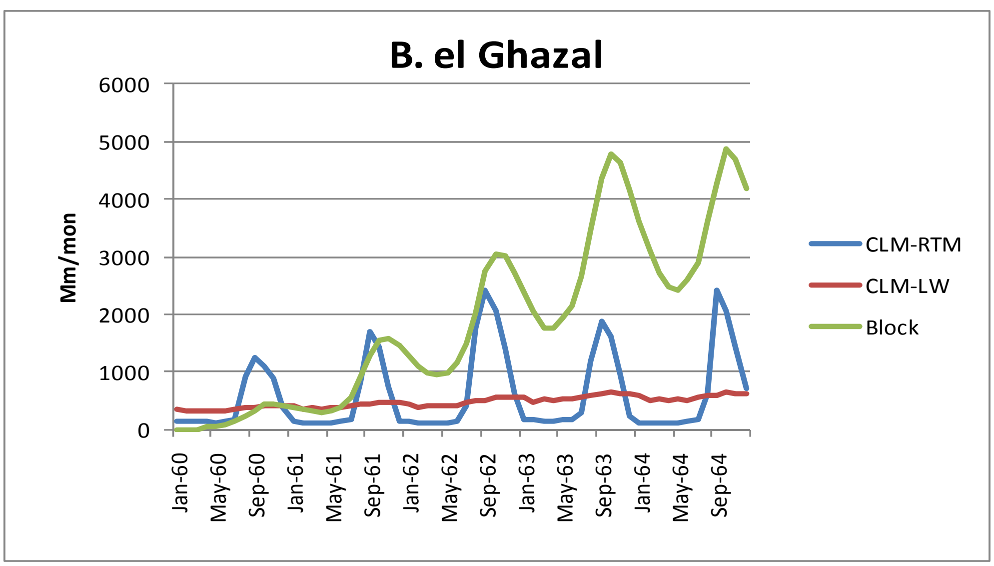
5-32 Monthly average flows from L. Albert and their standard deviation

For Lake Albert, as in Kyoga, flow magnitude and how it varies monthly, in addition to the sudden jump that occurred in the early 1960s, were captured.

5.6.2 Results of CLM-LW for Wetlands

Sobat and Bahr el Ghazal Wetland Results

Very little information is known about outflow from Bahr el Ghazal. From the table provided in section 5.5.2, Block data estimate that the B. el Ghazal catchment produced 71 km^3 annually in 1960-1964; the Eagleson and Chan (1980) study estimates that the catchment produces 38.5 km^3 annually. This study, and that of Sutcliffe and Park (1999), state that these inflows, as well as the high precipitation rates over the catchment, mostly evaporate, so that *outflow* from the catchment is negligible. The scarcity of information on the wetland means that there is uncertainty on how accurately CLM-LW reflects its hydrology, other than in making its outflow small compared to outflow from the Sudd and Sobat, which along with B. el Ghazal, produce flows at Malakal. Recall that runoff generated in this catchment was found to be larger than what has been measured, and even with the Modified Hargreaves being implemented for wetlands, P-E was higher than was computed in Block. Therefore, in calibrating CLM-LW so that outflow from the wetland is small means that these discrepancies were contained by the wetland's volume. Finally, Block's model was found to produce high outflows for the wetland. The graph in Figure 5-33 represents CLM-RTM compared to CLM-LW:



5-33 Flows from B. el Ghazal as obtained from CLM-RTM and CLM-LW

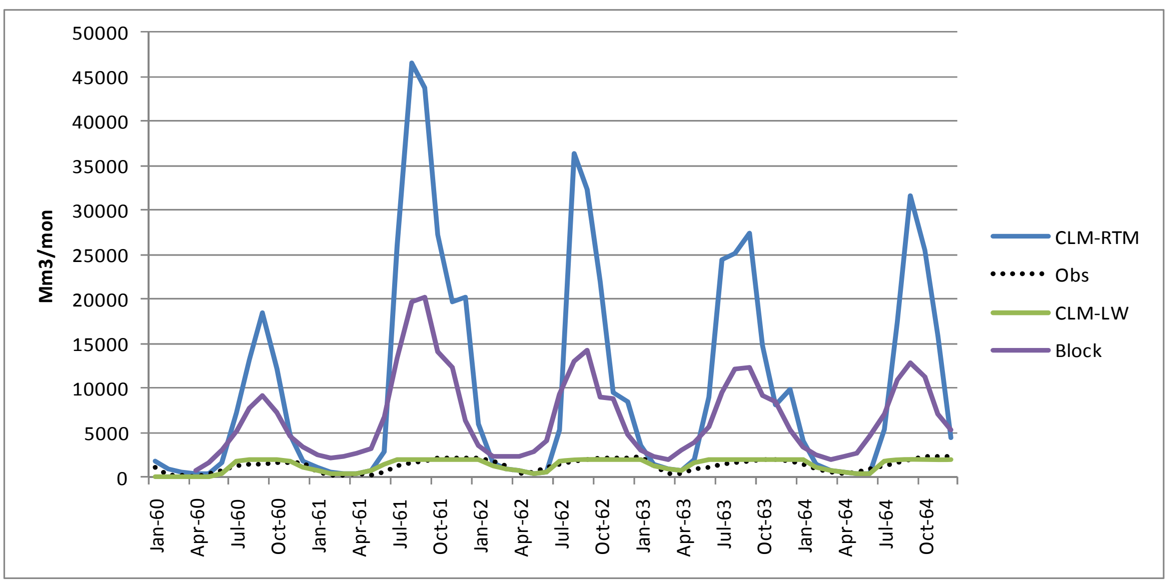
Annual flows as computed by CLM-RTM, CLM-LW and Block are:

Table 5-14 Bahr el Ghazal annual mean flows

	CLM-RTM	CLM-LW	Block
Annual mean (Mm3/yr)	7,162.13	5,701.389	22,135.63

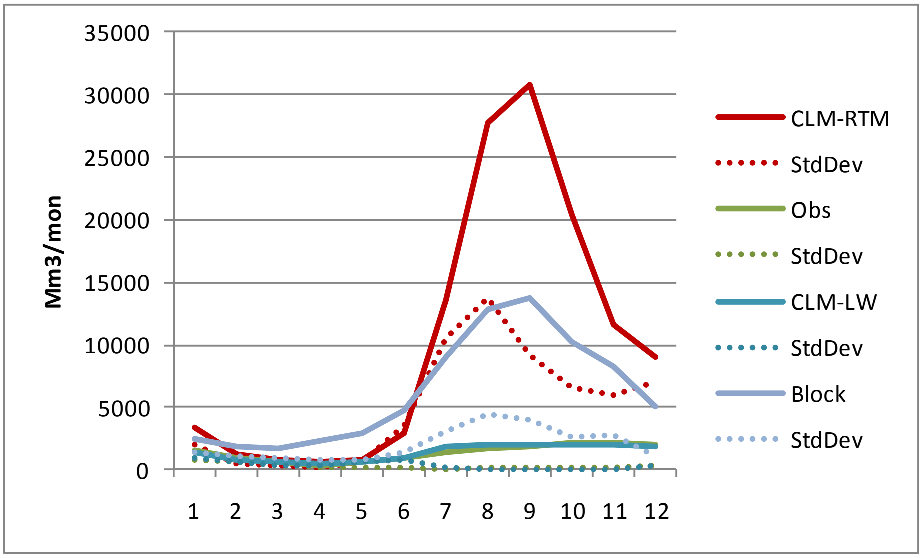
It is believed that CLM-LW results are most likely still higher than in reality; on the other hand, CLM-LW reduces the amount in outflow as well as substantially reduces its monthly variability.

The Sobat basin, on the other hand is characterized by high flows at Hillet Dolieb, where the river is gauged. Outflow from the Sobat is estimated to produce half of the White Nile's flow, as well as its seasonal variability, since the other tributary of the White Nile, B. el Jebel is what flows out of the Sudd and is dampened by the presence of the wetland. The following graph shows how CLM-LW Sobat flows compare to CLM-RTM, observed measurements and results from Block. CLM-LW's new evaporation mechanism, coupled with its process for allowing the river to spill over when it reaches a certain threshold, contributed to reducing the Sobat's flow, although it was found that CLM-LW does not capture peaks well.



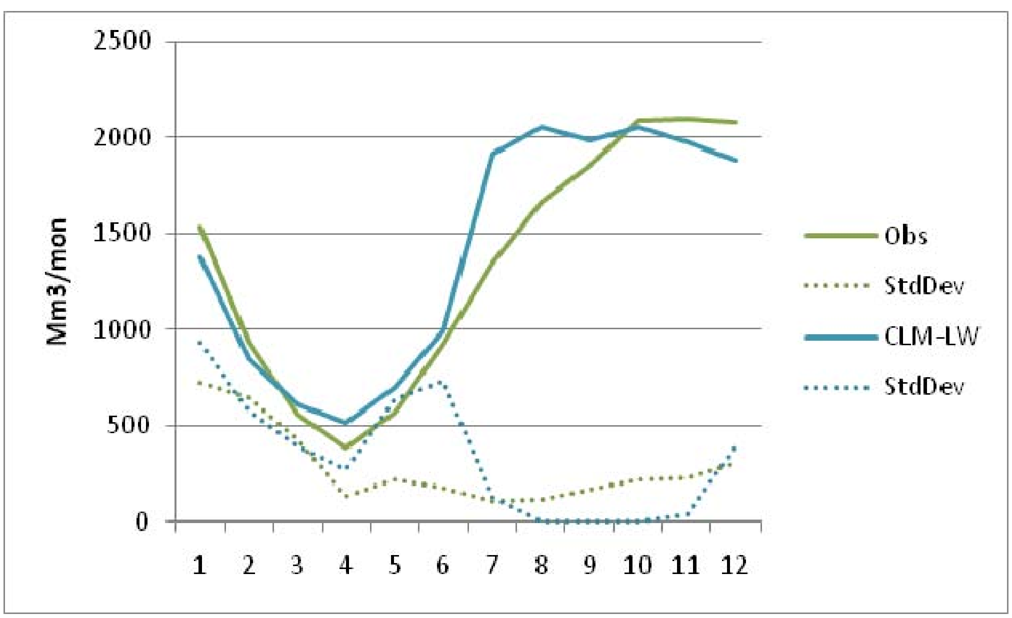
5-34 Outflow from the Sobat basin as obtained from observations, Block, CLM-RTM and CLM-LW

The graph in Figure 5-35 displays the monthly averages as well as their standard deviations for the 4 outflow datasets from the Sobat basin.



5-35 Average monthly flows from the Sobat, with their standard deviation

Taking a closer look at how CLM-LW compares to observed results of the monthly averages and their standard deviation yields the graph in Figure 5-36. It shows that while CLM-LW performs well in calculating the magnitude of outflow, it shows an earlier onset to a peak flow period in July, while observations shows this onset to occur in October. Also, the small standard deviation for the peak months (Jul-Nov) in CLM-LW, as compared to that of observed data shows that CLM-LW does not capture this wetland's peaks very well.



5-36 Comparing the average monthly Sobat flows and standard deviation of CLM-LW and observed measurements

In any case, the Table 5-15 shows Sobat's mean annual outflow and its standard deviation for the 4 sources of data:

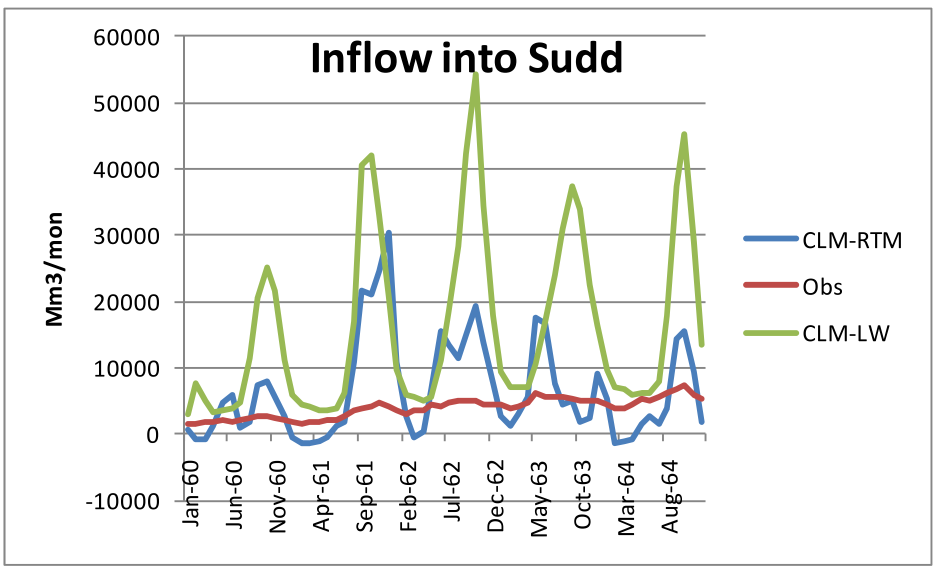
Table 5-15Annual mean flows from Sobat and their standard deviations

	CLM-RTM	Obs	CLM-LW	Block
Annual mean (Mm3/yr)	122,807.5	16,041.4	16,929.44	75,083
StdDev	45,236.68	2,831.989	3,358.172	22,292.07

CLM-LW's annual flow is within 94% of observed data, with a comparable standard deviation, reducing annual flows by more than seven times.

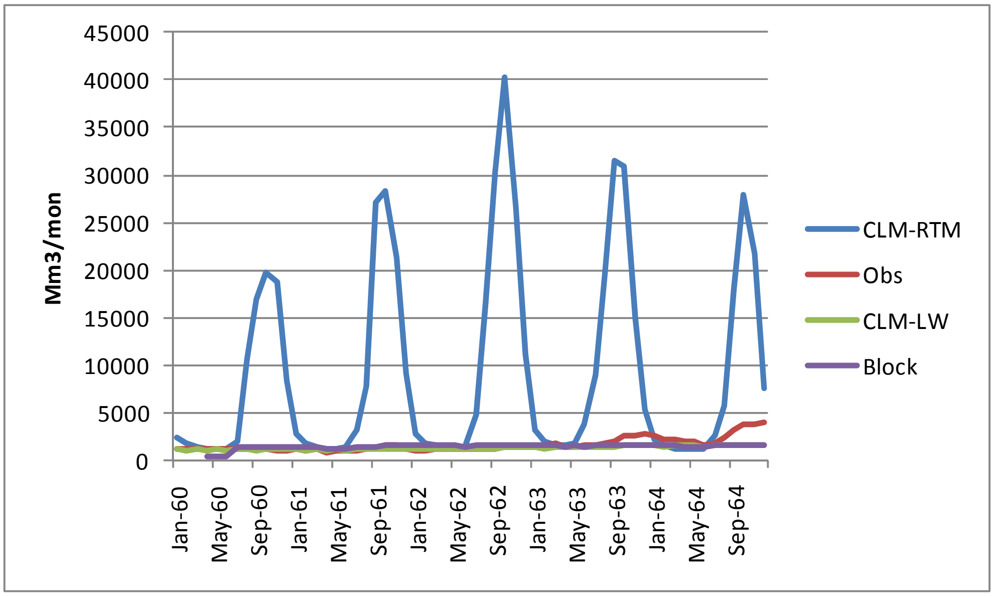
Sudd Wetland Results

The Sudd wetland receives inflow as discharge from L. Albert combined with seasonal torrential flows. The inflow has been conventionally measured at Mongalla, which is widely regarded as the starting point of the Sudd (Sutcliffe and Park, 1987). The figure in the beginning of this section shows how CLM-RTM flow at Mongalla compares to observed data. The graph also displays these two flows in addition to how the flow has changed as a result of CLM-LW applied to L. Albert:



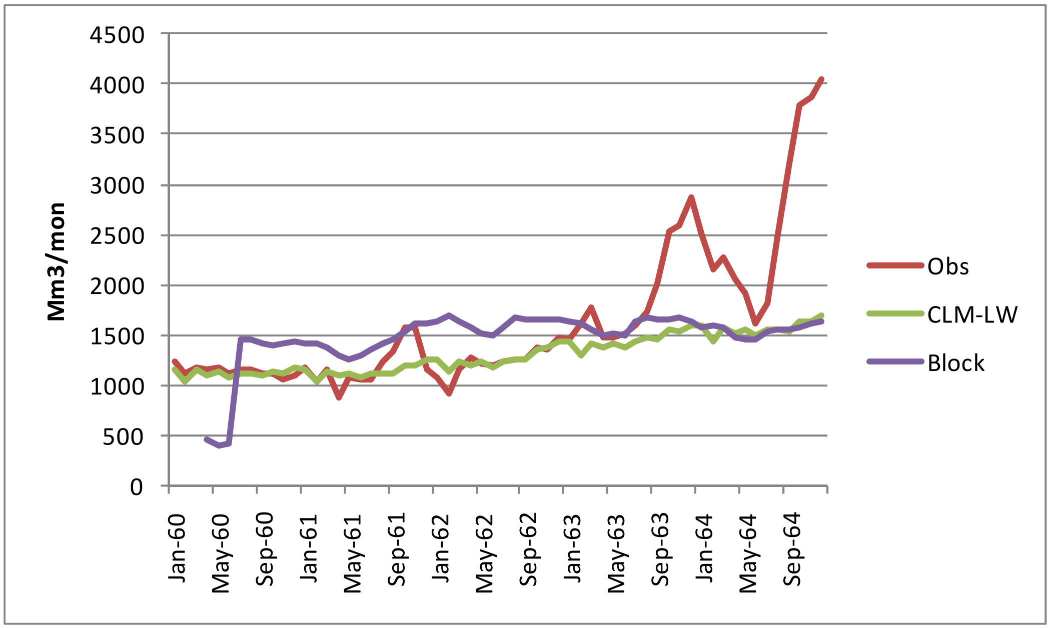
5-37 Inflow into the Sudd as represented by CLM-LW, CLM-RTM and observed measurements

Flow at Mongalla actually increases rather than decreases when CLM-LW is applied to points upstream. This can be attributed to several things: negative L. Albert outflows, have been removed; as opposed to the generic way that RTM was previously diverting flow, CLM-LW assigns importance to how the White Nile basin cells are being partitioned into each of the six sub-basins so that runoff into a wetland or lake depends on what is considered its catchment rather than all upstream runoff; finally, the fact that CLM produces high runoff values in the Sudd's catchment remains a factor that actually results in inflow at Mongalla being higher than what it was in CLM-RTM. This new inflow at Mongalla, in addition to P-E values, was used to run CLM-LW for the Sudd, yielding the following outflow results:



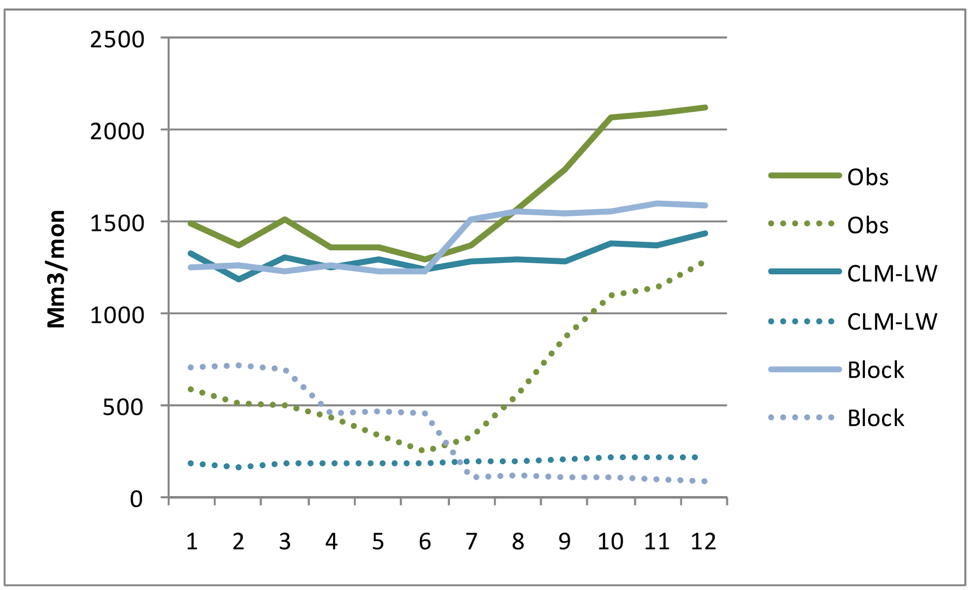
5-38 Sudd outflows from the four datasets

As is shown above, CLM-LW diminishes outflow magnitudes by 7 times, and reduces some of the monthly variability displayed in the CLM-RTM data, although it doesn't capture some of the later peaks as compared to observed data. Taking a closer look at CLM-LW, observed data and Block results yields the graph in Figure 5-39:



5-39 Sudd outflows from CLM-LW, Block and measured data

CLM-LW only captures the slowly rising trend in outflow present in these 5 years, but does not show the sudden jump shown in the last 6 months of observed data. This set back is reflected in the outflow's standard deviation as computed from the three data sources, and the average annual flows:



5-40 Monthly averages of outflow and their standard deviations from three of the four datasets

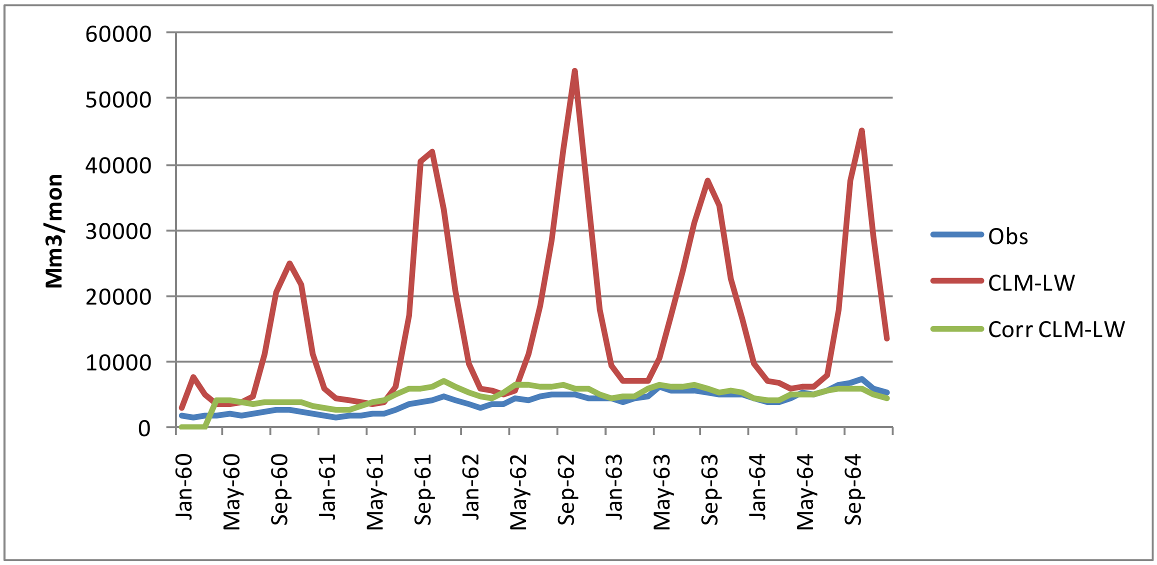
The graph shows that CLM-LW does not reflect the seasonal variation displayed by observations for this time period. While studies show that the Sudd dampens out most of seasonal variations, CLM-LW has done this too strongly. Annual averages and standard deviations also confirm this point:

Table 5-16 Sudd average annual outflows from the three datasets

	Obs	CLM-LW	Block
Annual mean (Mm3/yr)	19418.6	15682.89	16835.76
StdDev	7788.381	2346.917	4012.797

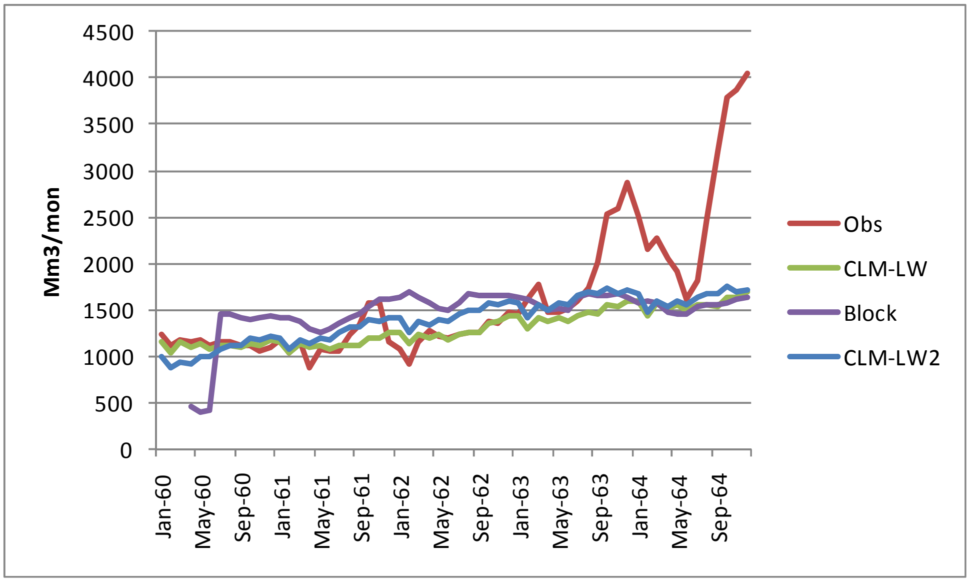
The above has so far compared CLM-LW produced outflows for the 6 sub-basins of the White Nile; it was shown that outflow values can be made much closer to their respective observed data when CLM-LW is applied to CLM-RTM. In fact, CLM-LW is modeled in a way such that the useful parts of CLM-RTM were retained, and otherwise key changes were made. In this way, outflow values, more so than any other wetland or lake characteristic that can be derived from CLM-LW – such as volume, area or depth – were shown. In the case of the Sudd, however, and particularly for the purpose of this research, there is interest in how the wetland area changes with respect to the other hydrologic parameters. Area, as is shown later, is important for quantifying many wetland services, and for the management policies that stand to be enacted for the Sudd. However, the research has thus far shown that P-E and inflow into the wetland did not represent their observed counterparts. These errors in input data are reflected in what CLM-LW produces as the wetland's volume and area. To demonstrate this point, Block produces an average Sudd volume of 38.9 km^3, and has estimated the wetland's constant depth to be 1.17 m, which produces an average area of 33.26 $x10^3$ km^2, a value within the range of areas in other Sudd studies, shown in chapter 3.3. CLM-LW, on the other hand, yields an average volume of 1626.6 km^3 for the same time period. In order for CLM-LW to produce the same outflow, it calls for a much smaller coefficient on outflow but a larger depth. This depth is 31.3 m. These variables result in an average Sudd area of 50.9 $x10^3$ km^2. Although this estimation is not much different than other studies, and falls within the higher estimates of area provided in 3.3, the value is based on unrealistic input parameters.

In addition, as inflow is intentionally varied, in a diversion scheme, for instance, the fact that the depth is so different from what it should be means that the resultant area and outflow do not reflect the correct reservoir response mechanism. And the correct response mechanism is exactly what's important when using a Sudd model to inform policy decisions, as is done here. As a partial solution to this issue, daily inflow into the Sudd was corrected using observed monthly values of inflow; dividing Block monthly inflows by monthly CLM-LW inflows yielded a monthly correction ratio. This monthly correction ratio was then used to correct the daily CLM-LW inflows.



5-41 Corrected CLM-LW Sudd inflow as compared to original CLM-LW and observed inflow

As the results above demonstrate, this method yields inflow values that are more similar to those Block and observed inflows, than were those produced by CLM-LW only. The average volume and area of the Sudd then become 13.3 km^3 and 11.7 $x10^3$ km^2, respectively. The constant depth of the Sudd becomes 1.13 m. This method is deemed more appropriate to policy analysis of the Sudd. The resulting outflow values from the adjusted CLM-LW (CLM-LW2) are shown Figure 5-42:



5-42 Outflows from Block, observations, CLM-LW and corrected CLM-LW

In conclusion, a presentation of results for the six sub-basins of the White Nile when their outflows are calculated using CLM-LW, a modification of CLM-RTM has been provided. The results show that CLM-LW produces results that are comparable to those observed as well as to those produced by other models, such as that of Block and Rajagopalan (2009). CLM-LW was further modified to be used specifically for the Sudd. The following sections describe how CLM-LW can be used for policy analysis, and to inform some of the management options available for the Sudd's development.

6.0 POLICY ANALYSIS OF THE SUDD

Wetlands perform many types of services. As section 2 showed, wetlands contribute at the ecosystem, population and global levels, performing functions such as regulating basin flow, contributing to the soil water content and nutritional make up, regulating emissions of gases key to climate variability, providing area for farming, fishing and acting as a habitat for many animal and vegetation species. This chapter discusses the environmental, social and economic services performed by the Sudd wetland specifically. The chapter then discusses historical management options proposed for the Sudd wetland, and some of their projected environmental, economic and social impacts. For all of these different types of impacts, a review of available literature is given below to make the argument that the wetland area can be used as a proxy for their availability, quantitatively and/or qualitatively. CLM-LW is then used to assess the impact of some of these management options on the Sudd, followed by a discussion of results and policy implications.

6.1 Sudd Wetland Services

Much discussion and studies on the Sudd wetland services have been conducted as a result of the proposal to build the Jonglei Canal, a canal designed to divert water from entering the Sudd, whose location starts at Bor, dumping water further downstream at Malakal. As a result, much of the studies that describe Sudd wetland services are articulated with regards to the impact of this Canal on the wetland system. The following describes some of these services; it is presented as ecological and socio-economic services that are available due to a *natural* flow of the river system. At the end, some of the threats that the wetland currently confronts due to recent human activities are highlighted.

6.1.1 Ecological and Environmental Services

In April, 2010, the South Sudan Ministry of Water Resources and Irrigation hosted a "Stakeholder Workshop on the Sudd Wetland" from which some of the below information was obtained. It was reported that parts of the Sudd's catchment have been designated by the Ramsar Convention as a Wetland of International Importance due to the diversity of ecological services provided by the area. These parts are two game reserves and two National Parks: Fanyikang

Game Reserve, Zeraf Island Game Reserve, Shambe National Park and Badingilo National Park. The four locations together span a total area of 11-12000 km^2, or approximately 50% of the Sudd's area. The total area in South Sudan granted this recognition by Ramsar is 5,700,000 ha (Ramsar Convention website).

The hydrological services provided by this wetland include those which have been presented above, namely dampening river flow, covering approximately 10% of South Sudan, the areal extent of the wetland, providing hydro-climatology feedback mechanisms with the atmosphere, and its role in possible ground water recharge, although little quantifiable information is known about the latter function. This environment supports a wide diversity of flora and fauna including 350 plant species, 470 bird species, 100 species of mammals, 100 fish species and 120 insect species, some of which are referred to as "crop pests," so contribute to the economic services of the wetland. Insect species, however, are also a source of disease and health problems for people living in those areas (Deng Bar, Stakeholder Workshop on Sudd Wetland, 2010).

Animals supported by the swamps are zooplankton, frogs, snakes, crocodiles, hippopotamus, and African Elephants. The wetland also supports a wide array of migratory birds including "weavers, warblers, flycatchers, kingfishers, ducks, herons, ibises, egrets, storks, kites, crows and vultures. Even the rare shoebill stork can be found in the swamps" (El Moghraby, Stakeholder Workshop on Sudd Wetland, 2010). It was reported that more than 20,000 migratory birds stop at the Sudd annually. Furthermore, 50 of the mammal species that inhabit the Sudd are listed under the IUCN Red List categories of "vulnerable, endangered, and critically endangered" species (El Moghraby, Stakeholder Workshop on Sudd Wetland, 2010). Animal species in the Sudd wetland were reported to have lifecycles that follow the seasonally and annually changing water levels and vegetation of the wetland.

6.1.2 Socio-Economic Services

South Sudan, where the Sudd is situated, is made up of three provinces: Bahr el Ghazal, Equatoria and Upper Nile. The population of people living in the South has been estimated to be 2,881,300 in the 1956 census. This census also estimated that the entire country had 14 million then. In 1956, the Jonglei Investigation Team estimated that of this population, a total of about 292,000 or 10% of the population of South Sudan would be affected by the Jonglei Canal (JC), or changes to the Sudd region; El Sammani (1984) estimates that 1.7 million will be affected by construction of the JC. The population of South Sudan is currently taken to be 8 million (Deng Bar, Stakeholder Workshop on Sudd Wetland, 2010) based on a census conducted in 2008. The mostly Nilotic tribes living on the wetlands depend on cattle herding, subsistence farming and fishing as their main sources of income. Other services provided by the wetland are drinking water, water treatment, building materials, game hunting and navigation (El Moghraby, Stakeholder Workshop on Sudd Wetland, 2010). Although the Sudd provides economic and social support, climate variability and years of high flood stand to cause substantial damages as well.

For example, De Mabior (1984) states that the annual variation and the even more pronounced monthly variation of rainfall on the region make up the most important environmental factor effecting the economy of the Jonglei area. However, the climatic conditions of the region pose a problem for agriculture in that they're characterized by periods of "intense heat and isolation", high impermeability of the soil, and spells of intense rainfall, producing an environment difficult for agriculture. He continues that a management option that includes drainage systems during the heavy rainfall and irrigation during the dry season would be more conducive to agriculture (De Mabior, 1984).

The climate conditions outlined above dictate that economic activities follow an "ecological equilibrium" (de Mabior, 1984), where during the wet season, most inhabitants rely on fishing for economic sustenance, while during the dry season, residents of the mostly highlands of the wetland area come to the previously flooded regions of the wetland for farming and grazing livestock. Indeed, as "the rains stop in the late October, both rain and river floods will begin to recede gradually causing people to move with their livestock for long distance in search of pasture and water" (Mustafa Abin, Stakeholder Workshop on Sudd Wetland, 2010). Thus livestock population information also follows an environmental trajectory of the wetlands in South Sudan; Howell et al (1988) provides estimates of the livestock populations as of 1982, as following the movement of livestock herders to mid-wet, early-dry and late-dry locations. They are given in the Table 6-1 for Bor only:

Table 6-1 Livestock populations in Bor, distributed according to the seasonal variation of ht ee Sudd

District		Mid-wet	Early-dry	Late-dry
Bor (5,474 km2)	Cattle	36,980	61,513	63,333
	Sheep/goat	10,920	19,785	28,101

The cyclical nature of cattle herding is of economic importance; on the other hand, cattle possession and exchange is central to many social rituals for people living around the Sudd such as initiation rites, marriage, religious rituals, payment of penalties, and accumulation of wealth, so cattle is of primary importance to the Sudd tribes (El Moghraby, Stakeholder Workshop on Sudd Wetland, 2010). Although animal husbandry is an important economic and social activity, there are no reliable census data on the livestock population; the Jonglei Investigation Team only provided estimates of livestock in 1954 as being 200,500 cattle and 29,400 sheep; other estimates put these numbers at 427,367 and 130,254, respectively in 1976 or as little as half these values (de Mabior, 1984). These gaps in data are attributable to the two civil wars that spanned most of the history of Sudan. Regardless of this gap in data, all of the above studies cited on information on animal husbandry note the importance of using the dry area of the Sudd, having been flooded previously in the wet season, for the maintenance of this economy and lifestyle.

6.1.3 Current Threats to Wetland and its Services

The signing of the Comprehensive Peace Treaty in 2005 saw many new potentials for development and management of the Sudd region – among them the conductance of such conferences as the Stakeholder Workshop on Sudd Wetland in April, 2010. However, El Moghraby states that the wetland has seen many recent threats to its ecology and ability to provide services to its local population. These include administrative problems like: poor planning and legislation, “ineffective management, lack of participation and coordination with important stakeholders”. The administrative shortcomings cannot address human environmental impacts on the wetland such as: overgrazing, poaching and commercial hunting due to the lack of alternative sources of livelihood, limited access to water and general poverty of the area (Deng Bar, Stakeholder Workshop on Sudd Wetland, 2010). Another source of ecologic degradation to the wetland is oil extraction and oil production activity; it was reported that “produced water” that results from oil extraction is the most important source of water quality degradation, where 10 barrels of produced water is released into the wetland area for every barrel of oil extracted. The transportation of oil has lead to a construction of a road that cuts through parts of the wetland area; Figrure 6-1, from El Moghraby (2010) shows the dramatic effect of the road on the wetland vegetation. The region in the lower part of the diagram has access to river flooding, while the region on the other side of the road has been cut off by the road’s construction. On the other hand, oil is the major source of income for the newly formed country of South Sudan, so that presents an important tradeoff space between benefits and drawbacks to oil extraction.

6-1 Dramatic effects of a road on the Sudd (from El Moghraby, 2010)

The following section outlines the important management options presented for the Nile basin, with focus on the Sudd wetland. These management options, which vary flow, areal extent and other hydrologic parameters in the White Nile system will invariably also impact the services provided by its regions. CLM-LW will simulate management options to see how the availability of wetland services stands to be impacted by these different management options. ***In this research, wetland area is used as a proxy for the environmental, economic and social services that the wetland provides.***

6.2 Area as Policy Indicator

Area of a wetland can be used as a stand-in for many of the environmental functions or services provided by said wetland. For wetland ecology, wetland functions and services increase with its area. Oxygen production and fish production, for instance, "may be directly proportional to area, [while] carbon sequestration will be a function of area times depth. [Species] richness (biodiversity) generally increases with area as $c(\text{area})^z$" where c is greater than 2, and z and c are empirically determined for the specific wetland. In fact, "whatever the research and conservation goal [for the wetland,] area demands attention" (Dugal, 2005). The following diagrams are taken from Dugal (2005) and provide examples of how area correlates to the amount of shrimp caught in kg, and (plant, bird and mammal) species richness:

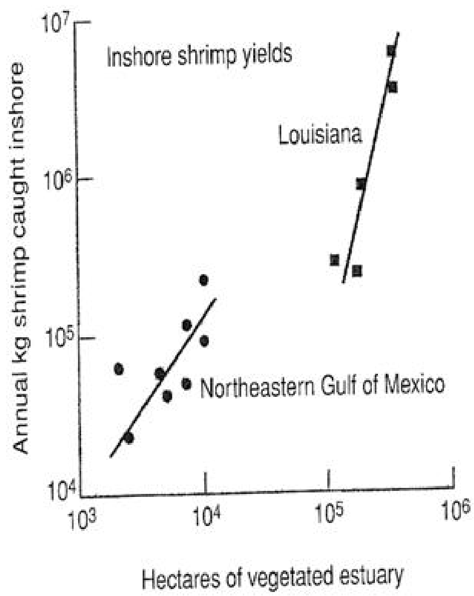


Figure 6-2 Linear relationship between area of wetland and annual shrimp catch, from Dugal 2005

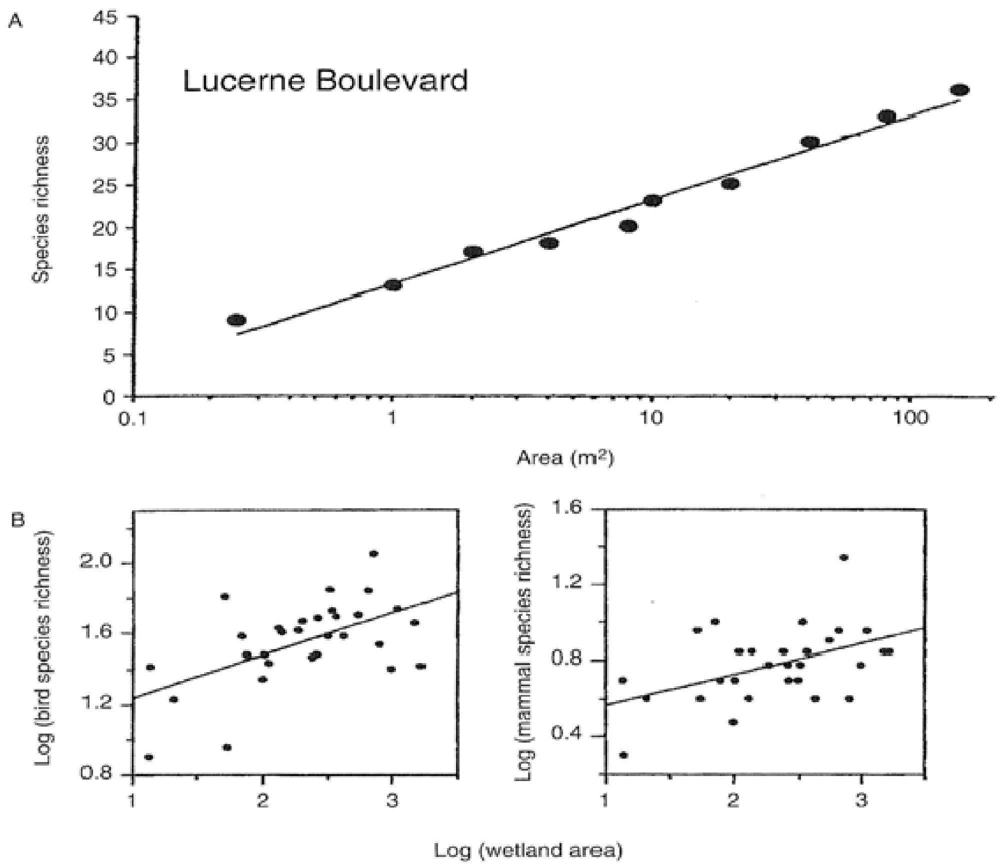


Figure 6-3 Figure A shows linear relationship between small scale areas (less than a hectare) and plant species. Figure B shows linear relationship between log of large scale areas and bird and animal diversity

Interestingly, although the first figure shows a linear correlation between area and shrimp caught, this relationship is not the same for all wetlands. In any case, it is clear that area is an important indicator of wetland functions and biodiversity.

Another reason why area is important is its connection to hydrological processes. For the Sudd wetland in particular and for wetland hydrological modeling in general, area is an important factor in determining the hydro-period or hydrological signature of the particular wetland. "The prime factor controlling the seasonal fluctuation in the vertical and horizontal extent of a wetland is its topography," and low-gradient topography, which characterizes wetlands, influence the area over which water can spread before runoff relieves it of additional water inputs (Mitsch et al, 1988). Unlike lakes, for instance, it is area in wetlands that is more variable than its depth, and functions to dampen high river flows by varying in size. Therefore, investigating area provides key insights as to how climate change stands to impact ecological services of the wetland. The importance of area to modeling, understanding and managing wetlands is not as contested as demarcating the actual area of the wetland in question (Mitsch, 1988). A wetland's transitional quality, between aquatic and dry land surface, contributes to this difficulty. As research on the Sudd above shows, some researchers identify the area as the permanently flooded region, while for others the area is that which at any point was flooded by waters from the river. The above discussion on Sudd wetland services has also shown that many of the economic activities in the region follow the seasonal variation of the Sudd's area.

A third reason and one directly important to the purpose of this research is in the way the Sudd's model is formulated in this research. The discussion on management options below introduces the Jonglei Canal (JC) where water is diverted from inflows into the Sudd and released further downstream (Figure 6-4), and this management option will be used in CLM-LW. Sutcliffe and Parks in 1987 and subsequent research on the Sudd (Strzepek and Yates, 1998; Mohamed et al 2005; Block 2010) assume an empirically derived and direct relationship between inflow and outflow of the Sudd. In their model, outflow from the Sudd is a function of inflow only, where diverting a percentage of this outflow into the JC, results in a gain of flow at Malakal. Missing from this construction is 1) how area stands to react to lower inflow values; 2) whether the wetland's spreading effect reduces natural outflows from the Sudd or increases it; and 3) whether this effect ultimately reduces or increases flows at Malakal from what they would have been without diversion.

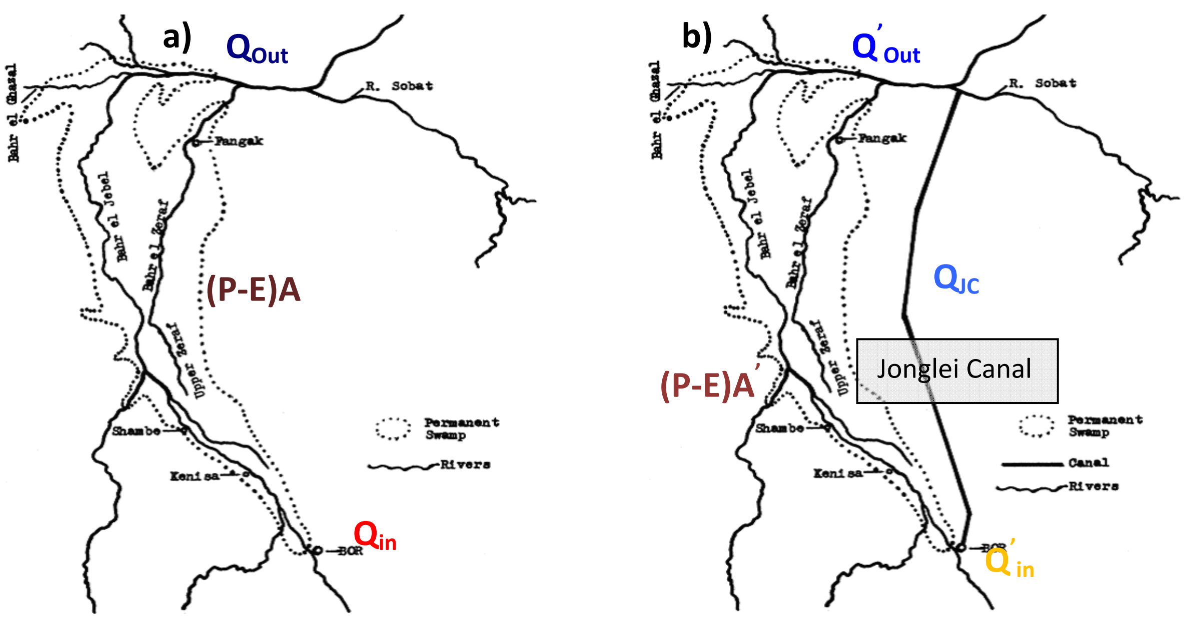


Figure 6-4 a) Sudd water balance without Jonglei Canal; b) Sudd water balance with Jonglei Canal. Diagram adapted from (Sutcliffe and Parks, 1987)

In Figure 6-4 a) above, Q_{in} is inflow into the Sudd, (P-E)A is the precipitation and evaporation balance, multiplied by area, and Q_{out} is outflow from the Sudd. The same parameters are shown in b). However, the latter figure also includes Q_{JC} (flow to Jonglei Canal), a new area and a new natural outflow from the Sudd, as a result of diversion. The question then becomes on how the sum of Q_{JC} + Q_{out}' compares to Q_{out} without diversion. Are there more, less or comparable flow values at Malakal in these two scenarios? Does it depend on how much is diverted or precipitation and evaporation balance at the time of diversion?

From the perspective of area, one can ask, how much can be diverted before there is a significant change in the Sudd's area? The water balance model used here for the Sudd, assumes a relationship between all these parameters (area, precipitation, evaporation, and inflow) in determining outflow from the Sudd, so area has a different level of importance from what it had in the equations used by Sutcliffe and Park.

6.3 Management Projects

This section describes the several projects that have been proposed or constructed within the Nile basin, with a special focus on those designed for the Sudd region. The section ends with particular attention to the Jonglei Canal, which has dictated much of the conversation and studies on the Sudd sub-basin.

6.3.1 Historical Roots of Structures along the Nile

The first major construction on the Nile basin, the first Aswan dam, was completed in 1902, with a capacity of 1 km^3; and periodically heightened until 1934 to reach a capacity of 5.3km^3. In 1904 plans for storage on Lake Tana and dams along the Blue Nile and Atbara were proposed; studies pointed to the advantages of storage in Equatorial Lakes, including saving water lost along the Sudd; plans along the Sudd included raising river banks in the Sudd, and constructing a diversion canal. Historical account of this period point out Egypt's significant role in all projects aimed at controlling the Nile's waters. In Sudan, a dam was completed in 1925 in Sennar, another in Jebel Aulia in 1937, which were followed by the Roseires dam, completed in 1966, and the Atbara dam in 1965. In 1947, a plan that was proposed outlined storage proposals in both branches of the Nile, which was later abandoned in favor of the largest construction on the Nile, the High Aswan dam in Egypt, construction of which consummated in 1959. 1929 saw the first Nile Waters Agreement, which allocated Egypt 48 km^3, and the Sudan 4 km^3. While negotiations with Ethiopia were begun but interrupted, other riparian countries were not included in the agreement (Howell et al, 1988).

Besides the Jonglei Canal, there have been other projects proposed on the W. Nile to save water and increase downstream flow. Lake Victoria being very big could provide enormous storage. However, its banks are not very steep, and it may cause many surrounding areas to be inundated. Lake Albert on the other hand, has a much smaller surface area, but has very steep banks. Therefore, not only will it be able to occupy bigger volumes of stored water, but it is less susceptible to losing parts of this water through evaporation and flooding (Howell et al, 1988).

6.3.2 History of Projects and Early Studies of the Sudd Area

The 1920s saw an interest in a diversionary project on the Sudd; the first option was a canal that began at Jonglei and discharged onto B. el Zeraf (100 km). Although this plan was approved by the Egyptian government, the Sudanese government was advised – by an independent researcher – to reserve its position on the basis that the canal might not save a significant amount of water for Egypt, and more importantly, will adversely affect the local population, as was later shown in detail by John Winder, District Commissioner of the Zeraf Valley District. Another plan was to divert B. el Jebel to the Pibor, which was also eventually abandoned, though for technical reasons (Howell et al, 1988).

In 1946-48, a Jonglei Investigation Team/Committee was created in Sudan. It included the Financial Secretary, Directors of Irrigation, Agriculture, Surveys and Veterinary Services, Irrigation Adviser, and the Governor of the Upper Nile Province, with H.A.W. Morrice, an engineer of the Sudan Irrigation Service, and Winder as chairman and secretary/political adviser, respectively. During this investigation, the Team was first introduced to the ambitious Equatorial Nile Project, outlined by Butcher in 1936, and highlighted below (Howell et al, 1988).

Here was proposed substantial storage in L. Victoria, a reservoir at L. Kyoga, a smaller dam at L. Albert, a balancing reservoir in Nimule-Bedden, and the diversionary canal at the Sudd (Howell et al, 1988).

Principles introduced were the concept of "timely flow" and "century storage": the former enabled water from the Lakes to be released downstream in Dec-Jun, coinciding with the Sudd's dry season and also the time when flow from the B. Nile would be too low to meet downstream demands. This would reverse the natural seasonal portioning of flow; the latter envisaged over-year storage on the Great Lakes. It came to be known as century storage because

100 years was the period over which the desired water was to be made available (Howell et al, 1988).

Although construction of the High Aswan Dam resulted in both concepts losing relevance, the following are three important lessons that were outlined by the Jonglei Investigation team: 1) ecological data, although are now supplemented by more recent studies, are still relevant; 2) the Team's conclusions, those of which are still relevant, as well as the ones that can be discarded as they are no longer applicable; and 3) although inflow into the Sudd and its consequent size have increased dramatically since the early 60s, and therefore the physical conditions, there's a possibility of a return to a previous period, and therefore the Team's records and investigation is relevant (Howell et al, 1988).

One recommendation made by the Team is for a "Direct Line" canal, running further east of the Sudd, starting at Bor, and ending close to the mouth of the Sobat, at Hillet Doleib. They showed that this line would have less effect on the local community, and will reduce costs. Construction of this new line began in 1978 (Howell et al, 1988).

Based on reports from the first Team, a second team and study were assembled, as the following was realized (Howell et al, 1988):

- Little was known of the intricate channel networks in the upper Nile wetlands
- Little was known of the sheet flooding phenomenon known as "creeping flow" created by rainfall and augmented by river spill
- Need for additional flood protection – highlighted by high flows of 1916-18, and later in early 1960s
- Need for hydrological modeling in the context of changing proposals for storage
- Little was known of interaction with soil, ecology and fisheries

Note that some of the constraints which were listed by the first team investigation (such as inaccessibility of area) are still in effect today, although satellite imagery and other technology has allowed the limited bypass of these constraints.

The team was instructed to make no consideration of economic development of local area during their investigation. In communicating effects of "timely flow," the team made the following classification of the Sudd basin, along with impacts of the canal's construction (Howell et al, 1988):

- Southern Zone (between Nimule and Sudd's head): dry season grazing area, which would be impossible with construction of canal. During the time when this place is exposed for grazing, it would now be under water and subject to extreme ecological changes
- Central Zone (from canal head to Buffalo Cape and Fangak): large volumes of water siphoned down the canal and annual rise and fall of river would be greatly reduced, reducing plant species and fisheries. These are same affects as are predicted with current canal, but more extensive
- Northern Zone (up to Kosti): very high year-long river flow, submerging grazing ground below water

The second report was completed in 1953-4. Recommendations were made to improve flood protection capacity of L. Albert as up to 1 million people would be adversely affected by hydrological change of project; the new river regime under a diversionary canal would reduce grazing land by 36%. The Team recommended a Revised Operation, in sync with natural seasonal flow that would result in only half of the above losses to grazing land, and would increase downstream flow by 6.8 km^3, only 0.31 km^3 (4.5%) less than that predicted under a "timely flow" project (Howell et al, 1988).

The JIT's recommendations are aimed to maintain the physical conditions as much as possible. Although advised to the contrary, the JIT recommended the creation of the Southern Development Investigation Team, a multi-disciplinary body aimed at investigating the development potential of the region (Howell et al, 1988).

6.3.3 The Jonglei Canal Project

Interest in the Equatorial Nile Project lessened after the construction of the High Aswan Dam, in 1959. The year also saw the next Nile agreement, which this time allocated 55.5 milliards (km^3) to Egypt, 18.5 milliards to Sudan, and out of 84 calculated as the mean at that time, the remaining 10 milliards were allocated to evaporation and seepage losses, predicted to occur as a result of the High Dam. Interests of the remaining riparian countries were acknowledged, and it was agreed upon that water allotments would be conceded by Sudan and Egypt, if ever claims were made by remaining set of countries. In this Agreement, it was agreed upon that Egypt and Sudan would share costs and benefits of water made available through projects on the Sudd, and the two set up the Permanent Joint Technical Commission (PJTC), which reaffirmed earlier projects. The PJTC saw reduction opportunities for the Sudd, Bahr el

Ghazal and Machar marshes. The PJTC referred to the Jonglei Canal as Jonglei Stage 1; this modified project includes no over-year storage, and was reported to have the dual function of a) reducing losses in the Sudd due to spill and evaporation; and b) therefore, increasing discharge of water at Malakal (Howell et al, 1988).

In 1974, the decision was made to initiate construction, with no mention being made of local effects, thus sparking tension and opposition from Sudanese in the southern region that will be affected by this construction. To alleviate fears, the Sudanese government created a statutory body, the National Council for the Development Projects for the Jonglei Canal Area. The body's Executive Organ saw the following as a mutual benefit of the canal (Howell et al, 1988):

- Reducing navigational distance between Kosti and Juba by 300 km;
- Improve road transport through an all-weather road along the canal;
- Provide year-long water supplies along the line of the canal;
- Reduce damaging effect of flooding from B. el Jebel during years of high discharge.

The Canal (Stage 1) will divert about 20 mil m^3/day; its dimensions are a length of 360 km, width of about 38-50 m, and depth varying from 4 to above 5 m (Howell et al, 1988). Jonglei Stage 1 is what's referred to by Jonglei Canal, and different diversion schemes are employed as the management options to be simulated using CLM-LW.

6.4 CLM-LW Management Schemes

The following is a description of how the model is used in incorporating the JONGLEI CANAL into the Sudd wetland hydrology. Later, a policy analysis and stakeholder response to this project will be presented. It is followed by results of the model, as well as how the policy analysis changes as a result of climate change and adaptation measures. The period of analysis looked at is 1960-1990; there is observed datasets for the Sudd for 1960-1982, and modeled values for 1960-1990; also, this period saw a strong jump in the White Nile flows, as well as low flows. As such, the period will be divided into 5 years of High flow (1960-1964), 5 years of Low flow (1986-1990) and Mean flows for the entire period.

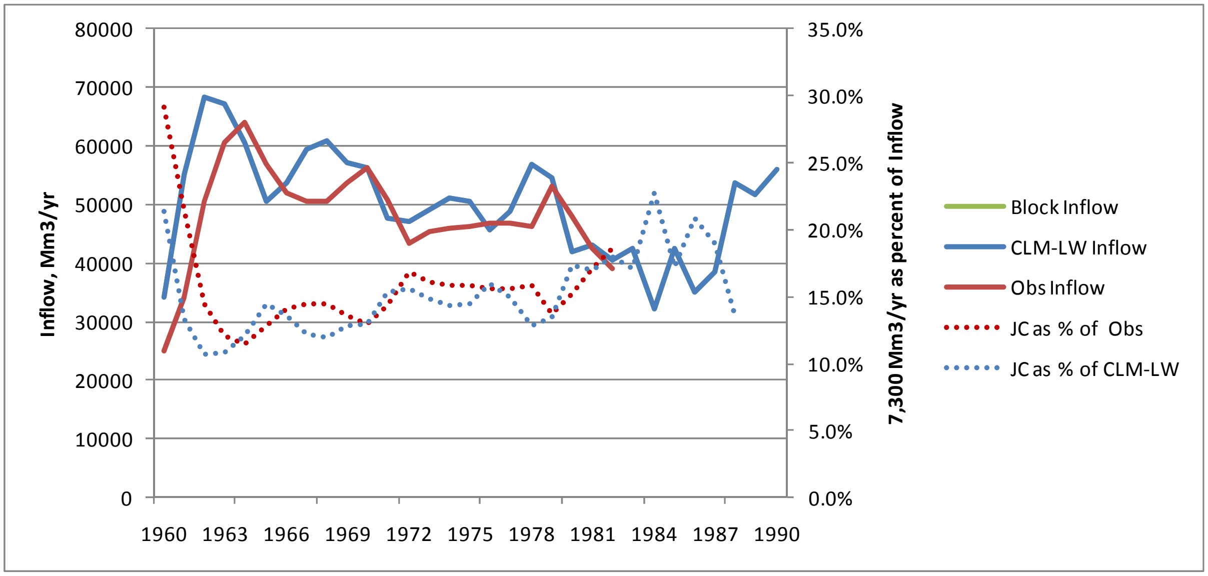
6.4.1 Incorporating the Jonglei Canal into CLM-LW

The Jonglei Canal is said to divert 20 Mm3/day (or 7,300 Mm3/yr). Table 6-2 shows this value as a percentage of average annual inflow into the Sudd for the period of 1960-82 (period for which there are observed measurements of the inflow):

Table 6-2 High, Mean and Low inflows during the period of 1960-1990

	Observed Inflow			CLM-LW Inflow			Block Inflow		
Period	High	Mean	Low (1972-76)	High	Mean	Low	High	Mean	Low
Inflow	56800	48182	45522	60386	52184	40366	60136	52184	40366
JC %	12.9%	15.2%	16.0%	12.1%	14.0%	18.1%	12.1%	14.0%	18.1%

Figure 6-5 shows how the percentages look like for different years:



6-5 Inflows into the Sudd and proposed diversion as percentage of inflow

The Jonglei Canal will divert 10% to upwards of 20% of inflow depending on the amount of inflow. CLM-LW investigates how inflow, wetland area, natural outflow, and resultant flow at Malakal, combination of the wetland's natural outflow plus the JC, will look like as different diversion schemes (inflow percentages) are diverted.

6.4.2 Stakeholders of Sudd Management under Jonglei Canal

From the outline of wetland services, stakeholders are identified as the following: local inhabitants of the Sudd area who depend on sustenance services such as farming, livestock grazing, and so o n; local governance of the Sudd area, who can play an important role in advocating the needs of local populations; government of South Sudan who has to weigh the different economic directions of the country, not just this particular location; downstream governance bodies such as Sudan, with its political and developmental goals vis-a-vis South

Sudan; Egyptian government who has pushed for construction of this project and stands to gain from an increase in downstream flows; and the Nile Basin Initiative, the governing agency for the Nile basin, which can play an important role in mitigating these tradeoff spaces and advocating for holistic management of the Sudd. For each of the identified stakeholders, the following outlines the reasons for and against construction of the Sudd, to the best knowledge of the author. The purpose of the following discussion is to provide a comprehensive view of the various players who have a stake in the development of the Sudd, and to construct the tradeoff space created by these different players. Such analysis can then be used to inform policies, negotiate different development goals and allow players to identify win-win situations.

Ecology

Assuming that the area-ecological services relationships from section 6.2 hold for the Sudd wetland, then it can be clearly stated that ecological services will be reduced according to how area is reduced as a result of diverted inflow. The question that remains is whether these area reductions will impact such protected areas as the two game reserves and national parks. This has implications for the South Sudan's ability to meet international agreements as well as impacts economic value of fishing in the region. Also, one of the alleged benefits of the canal is that its construction will be followed by the construction of an all weather road alongside the canal; the figure from section 6.1.3 shows the impacts of building a road that disconnects part of the Sudd from the river network.

Local Population and Local Governance

Outlined in the wetland services section are all the benefits that the local population gains from the Sudd, including farming, grazing, fishing, and so on. On the other hand, the section on threats to the wetland demonstrates that these services are being jeopardized due to the reduced water quality of the wetland, ongoing conflicts, unmanaged urbanization and poverty. For this reason, the work done by De Mabior (1984) sees the issue not as a choice between diverting and not-diverting inflow, but how can diversion occur in a way that helps local populations develop their agriculture, mitigating the harsh climatic characteristics of the region (with irrigation schemes). Based on surveys and interviews of the local population, De Mabior reports that residents are not opposed to inflow diversion, but are instead interested in how diversion can be done in a way that returns benefit to them.

Government of South Sudan

The Republic of South Sudan, being the newest country to be formed, will face many issues and obstacles that range from security, economic development, border disputes, foreign affairs, and managing international business contracts. The official position of the Ministry of Water Resources and Irrigation as presented in the Stakeholder Workshop for the Sudd Wetland, in Juba, South Sudan in April, 2010, is that construction of the Jonglei Canal will stop pending further study. Aside from the particular water demands of the Sudd and its various stakeholders, the government also has to consider the effects of oil extraction, and other economic plans in relation to the wetland. Construction of the Jonglei Canal is a source of income for the new country, but still uncertain are the losses to local inhabitants and ecological services provided by the wetland, for although some of these services are known, yet to be studied is a complete assessment of their economic value to the country.

Downstream Countries

The two downstream countries are Sudan and Egypt. In 1959, following their signing of the Nile Waters Agreement, Sudan and Egypt agreed to build canals that divert water from the Sudd and Bahr el Ghazal wetlands; the agreement stipulates that the "net yield of these projects shall be equally divided between the two republics, and each of them shall contribute equally to the cost" (El Sammani, 1984). It should be noted that currently, Sudan does not utilize all of the water allotted to it in the Nile Waters Agreement of 1959 (Howell et al, 1988); water coming into Sudan without the Jonglei Canal. Therefore, construction of the Jonglei Canal does not add economic benefit to the country. Egypt, on the other hand, continues to push for construction of the Sudd. In a news article in Al Jazeera, dated March 27th, 2011, it was reported that the Egyptian water resources and irrigation minister, Hussein Ehsan el-Atfi, met with his counterpart in South Sudan and discussed continuing construction of the JC.

Other stakeholders are the Nile Basin Initiative, which can help mitigate some of these competing demands to arrive at solution to which all can agree. For instance, the NBI is leading discussion on the most recent Comprehensive Framework Agreement, the follow-up to the Nile

Waters Agreement of 1959. In the same way that the earlier agreement contained stipulations for constructing the JC, this one can also do so taking into account new information, and the current position of South Sudan. A researcher at NBI has expressed that one goal of the agency is to remodel the Sudd so that flooded area is a function of a threshold inflow value, in the same way that the Sobat is modeled (personal correspondence, 2009). Finally, climate change poses another environmental risk, but also introduces the larger international community in the form of global adaptation policies.

For the purpose of modeling the Sudd wetland in CLM-LW, the Table 6-3 shows the ways that CLM-LW can be used to address needs of varying stakeholders:

Table 6-3 Table of stakeholders, their respective interests and how CLM-LW can be used to silmulate these interests

Stakeholder/Research	**Interests**	**CLM Capability**
Local population	Wetland reduction sensitive to local water needs (grazing, fishing); with local development	Seasonal diversion of flow into wetland
Local municipality	Monitoring water quality	N/A
Government of South Sudan	Better understanding of hydrology	Outflow as function of inflow vs. current model
Government of Egypt	Wetland reduction for more downstream flow	High diversion
Nile Basin Initiative	Threshold flow beyond which there is spill to wetlands	Sensitivity analysis of area to inflow
Climate Change	Policy/No Policy	Can also include all of the above

This research will express results from different diversion schemes based on the current model of the Sudd. Specifically, results are presented

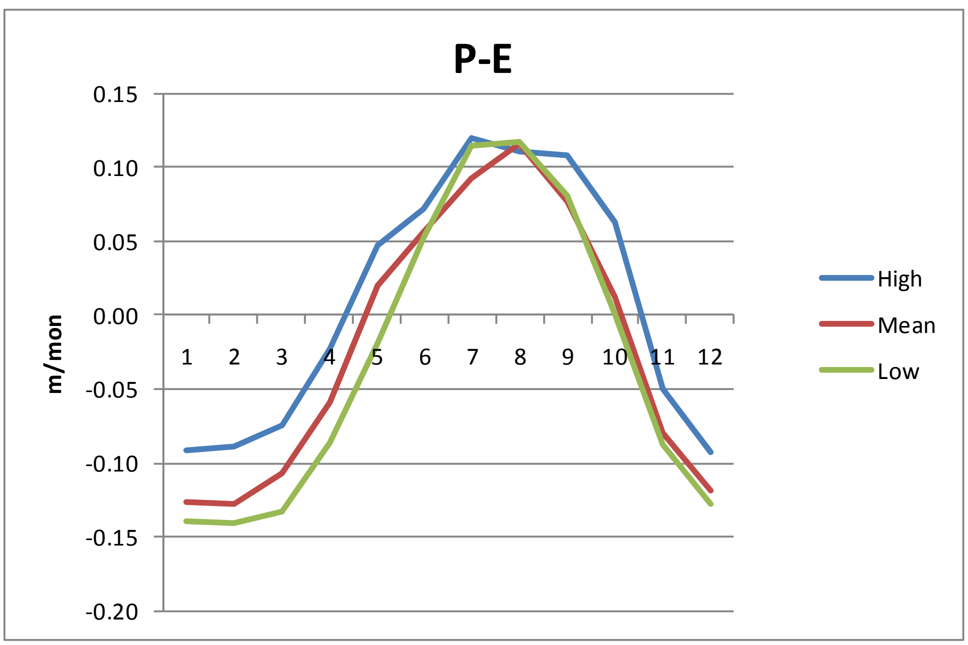
6.4.3 Comparison and Analysis of Results

CLM-LW was used so that different percentages of 1960-1990 inflow were diverted. In the analysis 2, 4, 6 … 30% of inflow was diverted. The results, described below, show how inflow, area, natural outflow, JC and flow at Malakal respond to diversion. The period of analysis was chosen to show how these parameters respond during a period of High inflow (1960-1964, or first period) as well as during periods of Low flow and Mean flow. The following graph and table show the average monthly P-E in each period, where values are given in m/mon. The average annual P-E for each of these periods is 0.10 m/yr in the High period, for Mean it is -0.25 m/yr and in the Low period, it is -0.37 m/yr.

Table 6-4 P-E values for High, Mean and Low flow periods, in m/mon

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
High	-0.09	-0.09	-0.07	-0.02	0.05	0.07	0.12	0.11	0.11	0.06	-0.05	-0.09
Mean	-0.13	-0.13	-0.11	-0.06	0.02	0.06	0.09	0.12	0.08	0.01	-0.08	-0.12
Low	-0.14	-0.14	-0.13	-0.09	-0.02	0.05	0.11	0.12	0.08	0.00	-0.09	-0.13

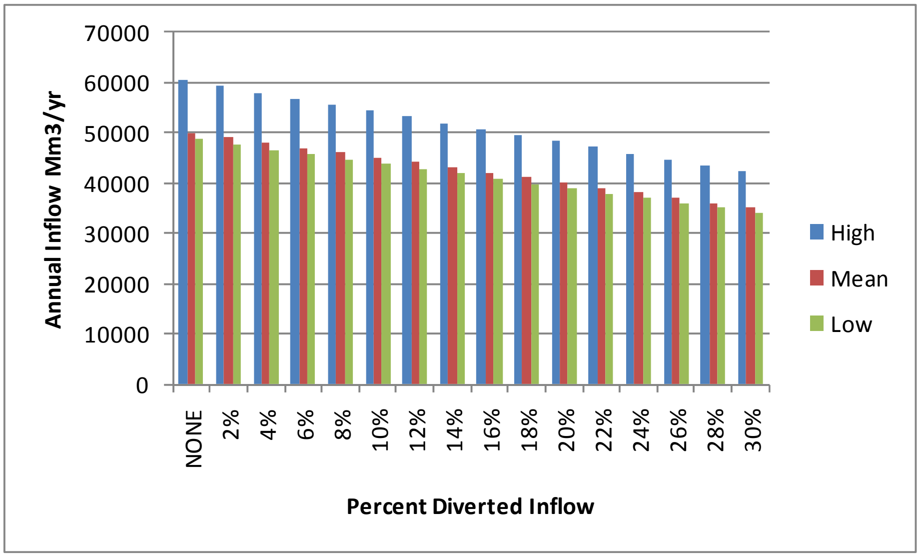
In general, the first period is characterized by higher P-E values except in August, as well as higher inflows into the Sudd as will be shown later. The three periods are used here to show the impacts to the Sudd, not only from the canal, but also as a function of climate variability.



6-6 P-E for High, Mean and Low periods

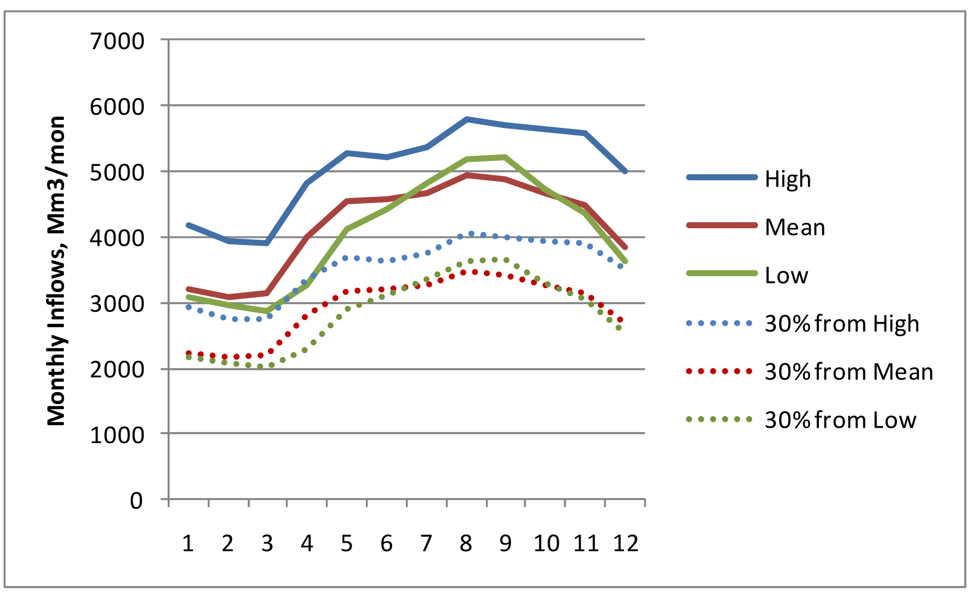
Results

In the incremental diversion scheme, diversion is reduced for in increments of 2%, from 0% to 30%. High inflows are very different from Mean and Low flows. The first graph, Figure 6-7, shows annual average inflows from the High period and that from the Low and Mean periods and how these annual flows vary for the given percentages of diversion (all subsequent flow values are given in Mm^3):



6-7 Annual flows as a result of diversion

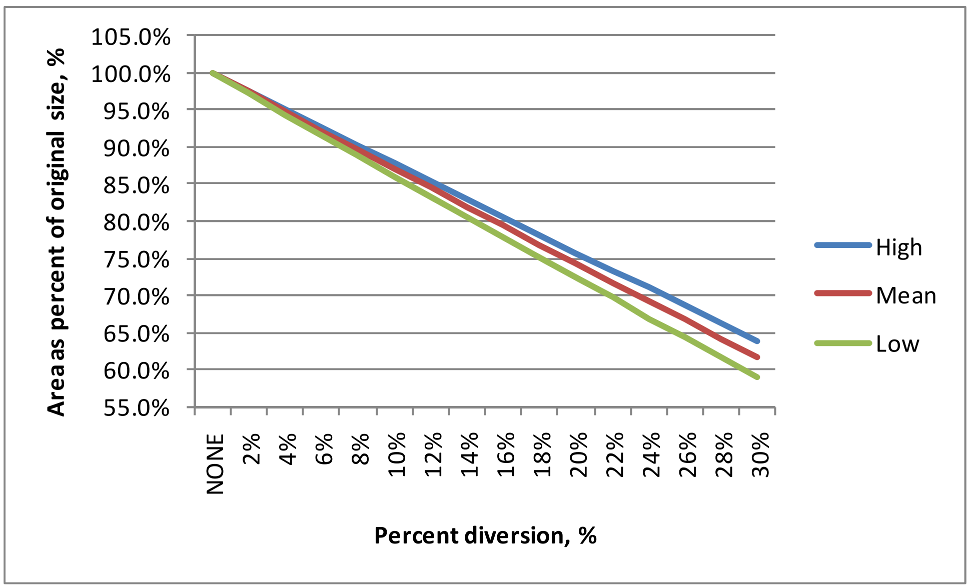
The average annual inflow for the latter period is 16% less than that of the first period, a fact that's reflected in the graph above. The monthly averages display the same thing:



6-8 Average monthly inflows for High Mean and Low flow periods, and when 30% is diverted from each

Note that inflow is diverted by 30% from High, Mean and Low flows, showing that there is a large change when water is diverted from the former period and smaller changes in the latter periods. This is important to note because, for instance, if it was decided that the ecology of the Sudd was best maintained for Mean flow levels, then the Jonglei Canal might be a good management scheme for years of higher inflows. It should also be noted that the slope of diversion for the two periods is not the same since 30% of high flows is higher than 30% of lower flows. So while they've been reduced in the same way, a specific diversion percentage is not the same for both.

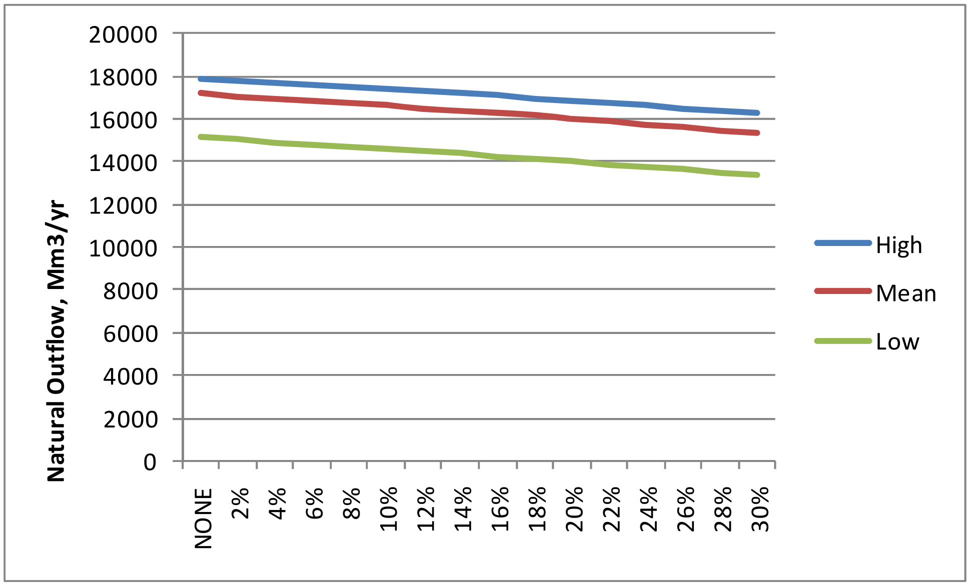
The average area for the three periods is given as a percentage of the original area (area with no diversion):



6-9 Area (as percentage of no diversion area) with respect to percent diversion in inflow

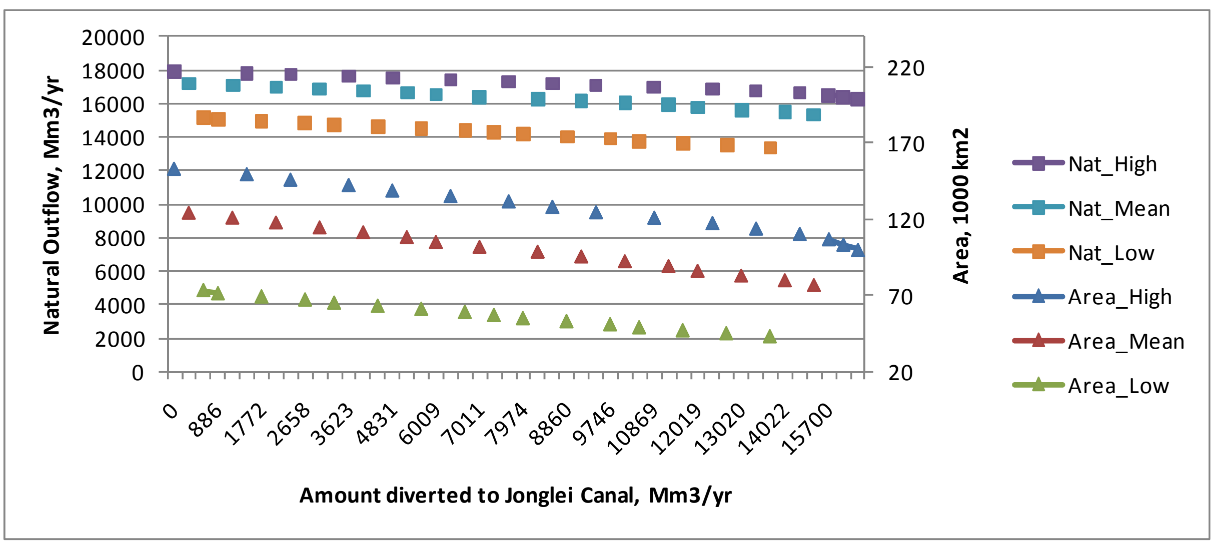
The graph in Figure 6-9 shows that reducing diversion by 16% reduces the average annual area by 19.4% for the first period, by 20.6% for the second, and 22.2% for the Low period. Area is linearly proportional to inflow; however, area is also non-linearly influenced by the natural outflow. The graph also shows that reducing inflow by 30% results in area being diminished by 36.2%, 38.3% and 41.1%, respectively.

The graphs in Figure 6-10 show how natural outflow varies as a result of diverting inflows, and how flow at Malakal increases (from non-diversion values) as a result. Recall that natural outflow refers to what the Sudd discharges as a result of its model, while flow at Malakal is a combination of this outflow and what has been diverted by the JC. The figure below shows how the annual natural outflow varies with respect to different diversion schemes. The relationship is not linear; instead, for small diversion, there is a relatively small change in natural outflow; however, as diversion schemes increase, the rate of change becomes more pronounced.



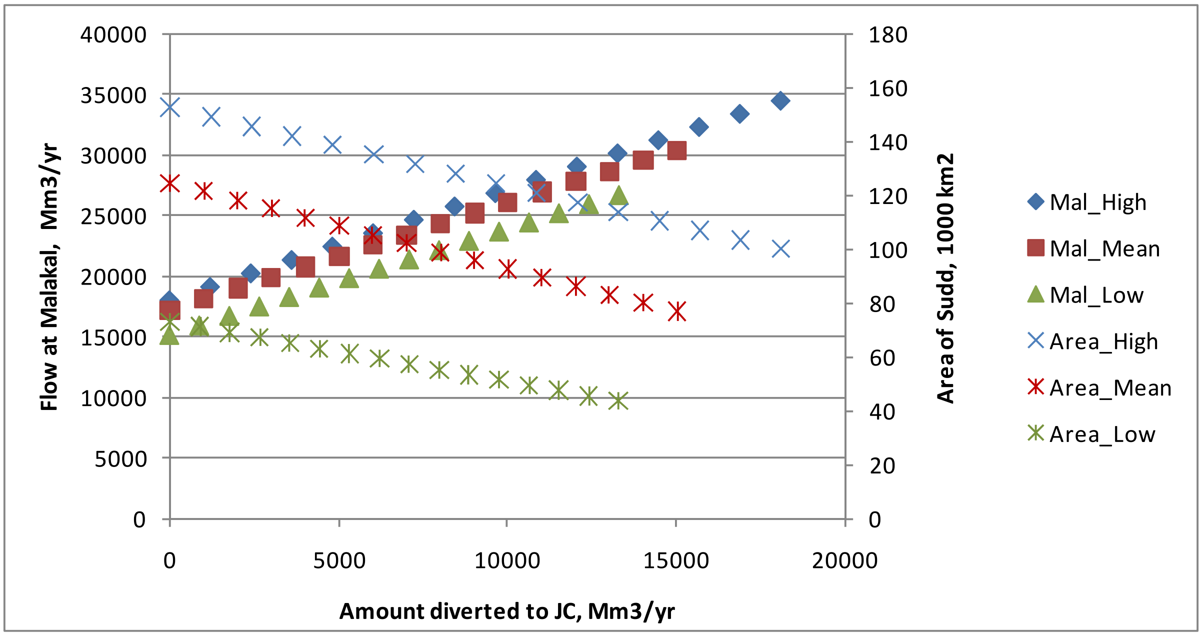
6-10 Natural outflow with respect to percent diversion

It is important to note that natural outflow from the Sudd is non-linearly dependent on area. Therefore, the relationship between how much water is diverted, resulting reduction in area and natural outflow are not linear, and are given in Figure 6-11:



6-11 Natural outflow and area as result of different diversion schemes

The last graph, in Figure 6-12, shows the amount of water diverted into the JC, given in Mm^3/yr; it also shows for these diversion schemes, the total flow at Malakal for the High period, Mean period, and Low period, and how the area changes in explicit terms in correspondence with the diversion schemes for the three periods.



6-12 How area and flow at Malakal look like for different amounts of water diverted into Jonglei Canal

Looking at only the High and Low periods, the graph shows that the Sudd's area is more resilient to inflow diversion when inflow is high to begin with and during years of relatively higher values of P-E. On the other hand, for low diversions, the two Malakal graphs increase in parallel, while for high diversion schemes, Mal_High increases at a higher rate than Mal_Low. Focusing on low diversion schemes (for instance, up to the amount proposed in the JC – 7,300 Mm^3/yr), Malakal flows increase by 37.1% for the first period, and by 41.1% of the second, corresponding to extra flows of 6,640 Mm^3/yr and 6,220 Mm^3/yr for the two periods, respectively. Area, on the other hand decreases by 16.7% and 27.9%, respectively.

Analysis

The last two graphs presented above, are key to the policy issues of the Sudd. They show that area of the Sudd is reduced non-linearly with respect to outflow from the Sudd. Because diversion schemes looked at above, and those that were recommended in the proposal of the JC, are low compared to flows at Malakal, it is difficult to spot this non-linearity based on the last graph. However, several things are clear from the analysis of High and Low periods above above:

1) The two periods display results that are clearly different, where if flows follow those in the first period, then the area is more resilient to diversion schemes than it is in the second period
2) It is less likely that flows will follow the first period since this period is generally regarded as uncharacteristic of the river system, therefore diversions stand to have a large impact on the Sudd
3) Diverting inflow from the Sudd by the proposed 7,300 Mm^3/yr will reduce the total area by almost 28%, on average. Considering that ecological services are proportional to area as was previously shown means that 28% of these ecological services (habitat for animals, and vegetation) will be reduced as well; diverting inflow by 7,300 Mm^3/yr reduces the area of mean flows by 22%
4) Considering that the Sudd geography is such that permanently flooded areas are adjacent to rivers, reducing the inflow means that river flooding will not have as much of a reach as it previously had, so dry area grazing and farming will suffer disproportionately from the reduction in area
5) On the other hand, building the JC may do more to mitigate unwanted flooding during seasons of uncharacteristically high flow

The above analysis shows just one way that CLM-LW can be used; the table given in the stakeholder analysis section shows all the other ways that CLM-LW can be used for further policy analysis.

7.0 SCIENCE AND POLICY RECOMMENDATIONS

Policy Recommendations

Based on the above analysis, the reasons for not constructing the canal can be summarized as:

1) Although many studies have been conducted on the Sudd, they do not fully describe the science, and therefore do not warrant enough reason to go forward with diversion schemes
    a. It is not clearly understood whether flooding happens once inflow reaches a threshold amount or the river floods for all flows
    b. It is unclear which has a higher impact on flooding: river spill or rainfall
    c. It is unclear whether the Sudd is a sink or source of flooded water
    d. Recharge is also another large source of uncertainty
    e. It is unclear whether the inflow/outflow model developed by Sutcliffe and Park is more representative of the Sudd, or the physical model developed here
2) Taking the above science to be representative of the wetland science, it is still recommended that the JC be dismissed
    a. Reducing the area by 22% of its current size is too large of a loss to the ecosystem
3) Based on the current threats faced by the Sudd's ecosystem, it seems that water quality and poverty alleviation are more important than construction of the Canal
4) The wetland services listed previously do not include their economic benefits, which still need to be understood. These services include water treatment, flood alleviation, and so on

The reasons for diversion can be summarized as:

1) While the benefits or drawbacks of the JC are not fully understood within South Sudan, they are fully understood for downstream stakeholders, especially Egypt
2) By increasing downstream flows, South Sudan stands to gain economic benefit from these downstream governments; the extra revenue can go a long way in reducing poverty in the region

3) Diminished water quality, and disease are already occurring in the region; reducing the size of the wetland will reduce water-borne health risks
4) Reducing the area of the Sudd will make way for development projects that can allow people of the South Sudan to move from a subsistence farming-based economy to more urbanized economies
5) The ecosystem has already changed with the presence of oil companies

Final Recommendation: *It is the final recommendation of this research that the Jonglei Canal not be built as both the scientific and economic tradeoffs are fraught with uncertainty or suggest that maintaining the Sudd is the better choice.* ***Scientifically***: the current research shows that diverting inflow up to the amount proposed for the JC reduces the area by 20%, which is characterized in this research as too severe a reduction. Sutcliffe and Park (1999), using a different model for the Sudd report that the wetland's area gets reduced from 22.3×10^3 km^2 to 17.3 22.3×10^3 km^2, or by nearly 30% (Sutcliffe and Park, 1999). ***Economically***: Although the canal's construction can be a source of income to South Sudan from downstream stakeholders, without a complete understanding of the ecosystem, and without a complete analysis of the wetland's functions, including an economic assessment of these benefits, it is impossible to tell whether benefits from construction outweigh benefits from the wetland services.

Science Recommendations

CLM-LW was built as a way to include lake and wetland hydrology into the streamflow production mechanism of CLM-RTM. Its construction included calculating wetland evaporation using the daily Modified Hargreaves, creating lake and wetland clusters, where each lake or wetland has a single discharge cell, collecting inflow and P-E for each cluster, and calculating outflow based on equations that allow for a variable storage, depth (for the lake), area (for the wetland), and outflow as a function of all other parameters. Although this model was shown to represent outflow in three lakes and three wetlands in the White Nile, three main recommendations for future work can be made:

1) Allow wetlands to be represented in CLM as partly vegetated
2) Allow the wetland variable area to be read in by CLM so that biogeophysical processes can be better represented

3) Allow CLM to read streamflow values back in from RTM, so that inflow into a cell can go back to being part of the biogeophysical processes of that cell

It is believed that these future works can improve the lake and wetland components of CLM-RTM even further.

7-1Image of the Sudd (El Moghraby, 2010)

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