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THE WATER BALANCE FOR RESERVOIRS AND ITS APPLICATION TO TROPICAL LATITUDES

Alejandro D'Urquiza-Díaz[1]
José de Anda-Sánchez[2]
E. James Nelson[3]

[1]Instituto Tecnológico y de Estudios Superiores de Occidente
Tlaquepaque, Jalisco, Mexico
[2]Centro de Investigación y Asistencia en Tecnología y Diseño del Estado de Jalisco, Guadalajara, Jalisco. Mexico
[3]Environmental Modeling Research Laboratory
Brigham Young University, Provo, Utah. USA

The hydrological balance for large water bodies, including reservoirs, requires the identification and accounting of water volumes and flows entering and leaving the water body control volume over a given period of time. These flows are varied in mechanisms and dynamics and they are highly dependent on conditions of the basin such as geology, weather, morphometry, land use, geographic location and time. A dynamic equilibrium is established between water inputs and outputs, which can be combined into a differential equation that describes reservoir water balance. Based on a thorough identification of the most likely water inputs and outputs for a reservoir, this paper reviews the methods of calculation, estimation and modeling for all such flows and volume terms involved in reservoir water balance. These methods are either deterministic, statistical or stochastic in nature, depending upon the element of the water balance. The solutions to such methods range historically from graphical to analytical to numerical to complex computer software models. This paper also analyzes the recent application and uses of modeling efforts in different basins for various types of water bodies in tropical and subtropical latitudes.

INTRODUCTION

From problem solving to decision making over management strategies, models provide a basis for representing the interconnection of various environmental phenomena in an effort to generate a tool capable of replicating observed outcomes and predicting the response of the system under different scenarios of simulation.

Since mathematical models are capable of representing the complexities of multi-varied systems such as the ones typically present in the environment, they become a useful means of understanding and studying water bodies, either natural or otherwise. Mathematical models for water bodies are often a combination of stochastic and statistical methods, deterministic functions, numerical methods and theoretical as well as semi-empirical approaches combined into engineering budget balances (Maidment, 1993).

Environmental models have a wide range of uses, especially when they are applied to surface waters. Such uses can be as varied as studying the risk of overtopping the Soyang Dam in South Korea (Kwon and Moon, 2006), replicating the evolution of dissolved oxygen in the Aguamilpa Dam in Mexico (de Victorica, 1996), or assessing the risk of extraordinary base flow conditions beyond storage capacity due to natural incidences also in the Aguamilpa Dam in Mexico (Marengo, 2006), simulating scenarios for modeling water quality under uncertainty in the Barra Bonita Dam in Brazil (Chaves and Kojiri, 2003) or even separating the effects of climate variation from anthropogenic impacts in the formation of runoff in the Krishna river in India (Bouwer et al., 2006), and even to simulate scenarios of climate change, such as modified precipitation patterns and increased temperatures (McMahon, 1993; Rasmusson et al., 1993; Alexander et al., 2008).

Models can be used to assist the decision making process regarding water resources management (Labadie, 2004; Koh et al., 2002) and basin holistic management (Puhlman et al., 2006). Nonetheless, traditional modeling has focused on water bodies in temperate regions as opposed to water bodies in tropical or sub-tropical latitudes. Due to economic, social and political factors which will not be addressed in this paper, the management of water resources is strategic for the development of any country, despite regional conditions of abundance or scarcity of water. One such example is Mexico: after an analysis of the tendencies of irrigation between 1965 and 1995 and estimating future demands for water, Barker et al. (2000) suggested that even though Mexico had enough water resources to satisfy its estimated demands until 2025, it was a matter of necessity for Mexico to increase its water storage capabilities in order to ensure future demands would be fulfilled.

For any given country, the ability to manage its water bodies is synonymous with the capacity of maintaining the availability of water in order to satisfy its current and future demands and needs, such as consumption, generation of energy and sustainable agricultural production. Though the term 'water availability' is often understood exclusively in terms of quantity of water for Government Ministries such as the Mexican Ministry of Environment and Natural Resources (Secretaría de Medio Ambiente y Recursos Naturales [SEMARNAT], 2002), the availability of water actually depends on both quality and quantity. Since availability of water is a dual term which encompasses both sufficient quantity and adequate quality, it is a matter of practice to separate its two branches, though they are in fact intertwined. One way to increase the availability of water in terms of quantity is by engaging in the construction of dams and operation of reservoirs (Barker et al., 2000). Reservoirs may expand the irrigation surfaces, thus potentially increasing the productivity of food, but the construction of dams over river paths modifies the hydraulic regimes of water bodies, thus altering the dynamics of water quantity -and quality, by extension- (de Victorica, 1984; Smithers, 2004; Fearnside, 2005; Richter and Thomas, 2007), and affecting the biotic factors of ecosystems and even generating greenhouse gases as the organic matter decomposes beneath the water level in the reservoir (Fearnside, 2005). However, reservoirs constitute water bodies intended to satisfy specific needs by storing water.

The actual water storage is a result of the balance of flows coming into and out of the reservoir. Some of these flows (direct precipitation, runoff and evaporation, for instance) are a function of meteorological variables (Schnoor, 1996; Chapra, 1997) which are highly seasonal (Oyebande et al., 1980; Bouwer et al., 2006; Chahinian and Moussa, 2007), or even cyclical due to the influence of phenomena like El Niño (Rasmusson, 1985; Rasmusson et al., 1993; Ortíz-Jiménez et al., 2005; Awulachew, 2006b). Therefore, in order to ensure that the future water storage will meet quantity demands for the reservoir, it is necessary to predict the water budgets by accounting for inflows and outflows using a proper water balance model.

REVIEW OF SOME MODELING EFFORTS APPLIED TO WATER BODIES IN TROPICAL AND SUBTROPICAL BASINS

While the characteristic weather and meteorological variables have been studied in tropical and subtropical latitudes, they have not been generalized for such latitudes (Bowden and Semazzi, 2007; Frank and Young, 2007; Lin et al., 2007; Yu et al., 2007; Alexander et al., 2008). It is important to first clarify what a tropical or subtropical latitude means.

The parallels known as the tropics (the Tropic of Cancer in the northern hemisphere, and the Tropic of Capricorn in the southern hemisphere) lie between the equator and the poles, at the exact latitudes of ±23.45°. Though the actual tropics refer to these two particular latitudes (23.45°N and 23.45°S), tropical latitudes are those comprehended between the tropics and the equator on both hemispheres of the Earth. Halfway between the equator and the poles (at latitudes of ±45°) are the imaginary frontiers which regard those latitudes between there and the poles as cold latitudes and as temperate latitudes for those between ±45° and the tropics. The term subtropical is also arbitrary, and refers to an undefined group of latitudes in the transition zone between tropical and temperate latitudes.

The amount of sunlight received over the course of a day at a specific location on the Earth surface is determined mainly by latitude and altitude (Twidell and Weir, 2002). This dependence on latitude makes daily insolation (the total energy per unit area received in one day from the sun) maximum at the equator and minimum at the poles (Twidell and Weir, 2002). Conversely, exposure to sunlight is greater the higher the altitude (i.e. elevation), as sunlight is scattered as it travels down through the atmosphere to the Earth's surface (Twidell and Weir, 2002).

Water bodies are abundant in tropical and subtropical latitudes. In an effort to understand its specific dynamics, several of these water bodies have recently undergone different modeling attempts. A summary of such efforts (by no means exhaustive) includes the following: Oyebande et al. (1980) performed the hydrological balance of the Kanji Dam over the Niger River in Nigeria, analyzing the effect of the dam with respect to evaporation and runoff flows downstream of its location. Other available studies include the modeling of Lake Abaya and Lake Chamo in Ethiopia (Awulachew, 2006a; Awulachew, 2006b), focusing on the morphometry of both lakes and the use of weather data to develop a water balance of such lakes, considering the effect of the El Niño and La Niña phenomena on those African lakes (Awulachew, 2006b). Other scientific studies include the work of Kouassi et al. (2007b) on the refinement of the hydrological balance of the hydroelectric dam of Lake Taboo in the Ivory Coast. Their paper focused on the use of empirical curves and statistical regressions for modeling precipitation and evaporation, thus accounting for meteorological variability over time. Models of the Ivory Coast have also been used to simulate the groundwater recharge of aquifers in the Not N'zi basin in Bandama (Kouassi et al., 2007a).

Latin America is also a region where modeling efforts for water bodies are increasing. Puhlmann et al. (2006) used a model to improve the management of the Paracatu Mineração River in Brazil by addressing decision making processes for mining operations in the river basin. Güntner et al. (2004) used a simplistic deterministic water balance model to simulate the water availability in large river basins in the State of Ceará of the semiarid, northeastern part of Brazil, with several thousands of reservoirs, accounting for environmental change and an increasing water demand. The work by Chaves and Kojiri (2003) in Brazil also deals with the need for optimization of the operation of a reservoir by using fuzzy stochastic programming. Other studies focus on the role of human settlements and the changes in land use over the generation of runoff in basins in Chile and in Mexico (Mendoza et al., 2002; Treviño et al., 2002; Henríquez et al., 2006) and the role of plant cover in the water balance of the La Beta and La Cubero basins in Colombia (Arroyave and Giraldo, 1997). In Mexico, the analysis of the flows and factors affecting the water balance is available for different basins such as the Cerro Prieto Dam (Yutsis et al., 2007), the San Carlos basin (Treviño et al., 2002), Lake Cuitzeo (Mendoza et al., 2002) and Lake Zapotlan (Ortiz-Jiménez et al., (2005). Other relevant hydrological modeling studies in Mexico include the calibration and validation of a model for the Laja river (Torres et al., 2005) and the modeling of the morphometry of Lake Chapala (de Anda et al., 1998) alongside an analysis of water retention times and storage deficits in the same lake (de Anda et al., 2005).

THE IMPORTANCE OF THE WATER BALANCE

All of the aforementioned studies share the application of Geographic Information Systems [GIS] and the use of historical hydrological records and meteorological data in order to calibrate and validate either empirical or pseudo-empirical models. Further, all of the models used in the aforementioned studies either focus on water quantity or quality but do not integrate the two. Thus, water balances are inherent to modeling efforts focusing on quantity in water bodies. Water balances are also the base for other complex modeling systems, such as heat budgets, thermal stratification or water quality, all of which assume the accurate prediction of stored water in a control volume over time. The amount of stored water in a reservoir (i.e. accumulation) is a function of different flows entering and leaving the water body (see Figures 1 and 2).

Despite the relative abundance of water bodies within tropical and subtropical latitudes, water balances have only recently become the prime focus of modeling. This is likely due to the combination of three factors: first, environmental modeling is still an emerging discipline; second, for most water bodies within tropical latitudes and for some in subtropical latitudes, a major challenge is the availability of the information necessary to calibrate and validate a water balance model; third, some of the software tools specialized on the modeling of specific elements of the water balance are still under ongoing development and being updated, and those in the trial or complete phases have been mostly used on water bodies in temperate latitudes (Maidment, 1993; Cunderlik and Simonovic, 2004; Knebl et al., 2005; Arredondo et al., 2007; Vivoni et al., 2007).

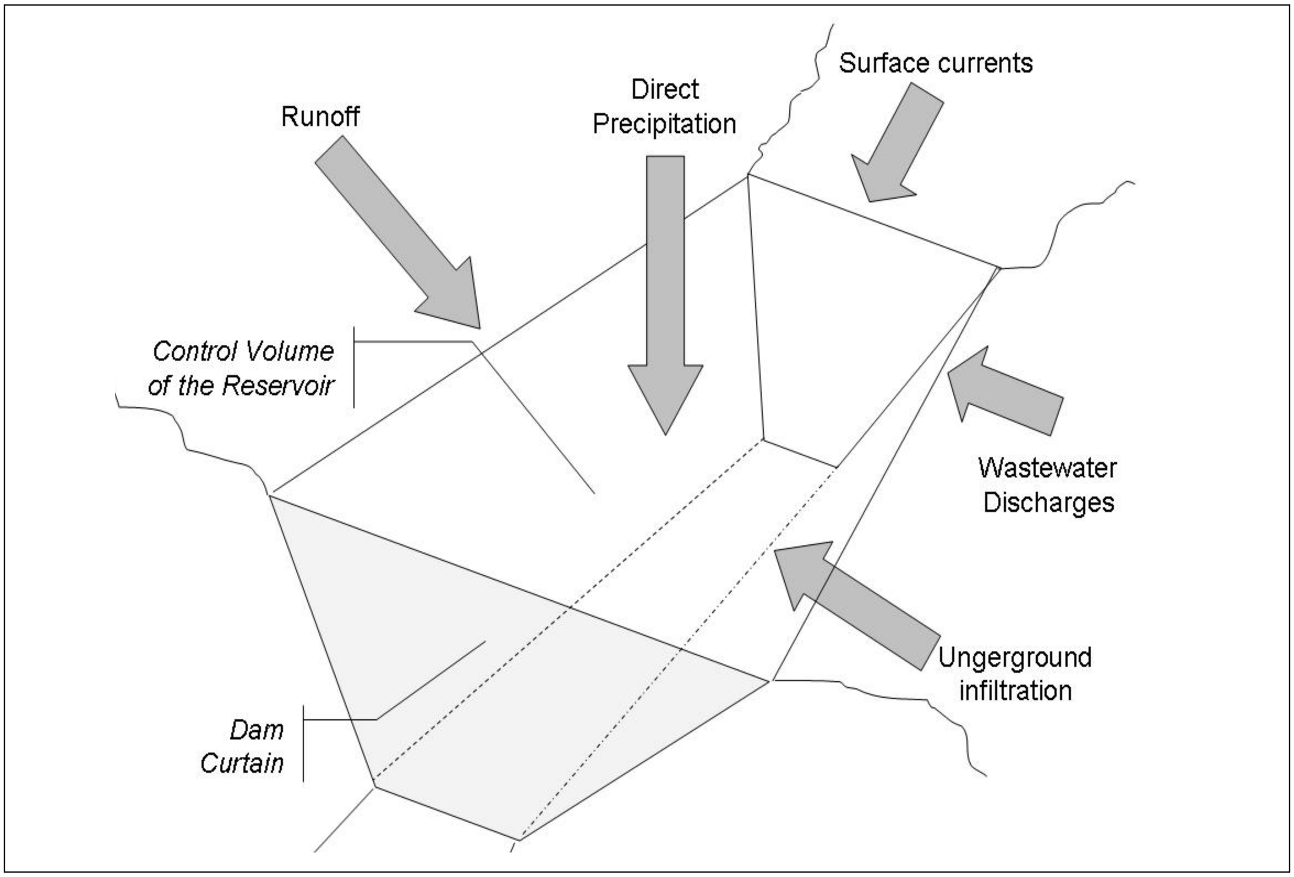

Figure 1. Typical water inputs entering a reservoir and its basin.

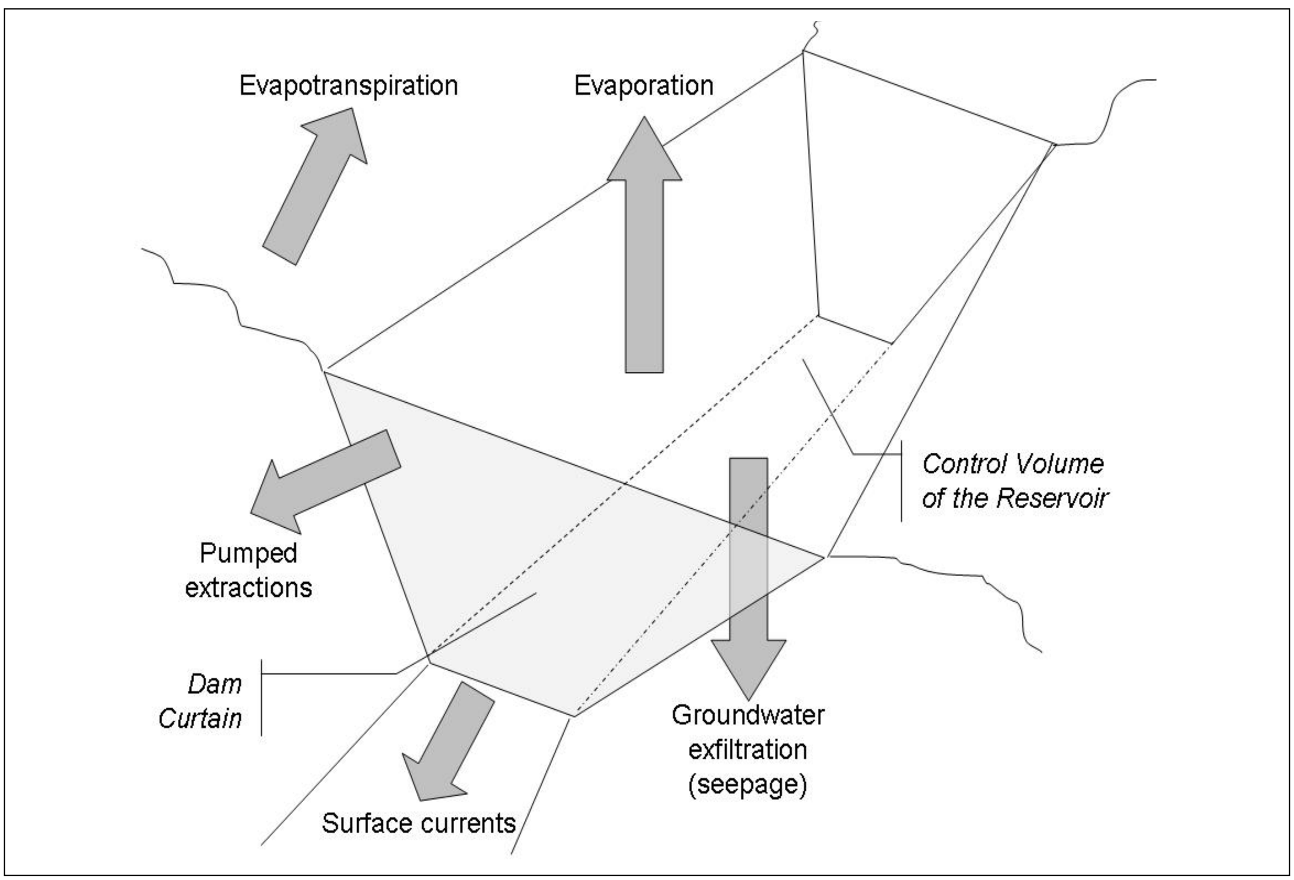

Figure 2. Typical water outputs leaving a reservoir and its basin.

ELEMENTS OF THE WATER BALANCE FOR A RESERVOIR

The hydrologic balance of any given water body serves the purpose of estimating the amount of water stored in a control volume. In general, the water balance consists in recognizing that the change in the stored volume over time (i.e. water accumulation), equals the sum of m inputs minus the sum of n outflows for any water body over a specific period of time (Sokolov and Chapman,1974; Thomann and Mueller, 1987; Chapra, 1997; Fetter, 2001; Aparicio, 2005; Arredondo et al., 2007; IAEA, 2007). This is expressed in the General Balance Equation for any water body:

$$Accumulation = \sum_m (Inputs)_m - \sum_n (Outputs)_n \tag{1}$$

where the accumulation of water is the change in stored volume in the lake or reservoir as a function of time: that is $\Delta V/\Delta t$, yet in the differential limit, this quotient can be written as dV/dt, assuming water density changes are negligible.

The water balance assumes that it is possible to identify and quantify or estimate the inputs and outputs for a given water body. Therefore, according to Sokolov and Chapman (1974), Thomann and Mueller (1987), Chapra (1997), Aparicio (2005), Arredondo et al. (2007) and IAEA (2007), the predominant inputs for a reservoir are: surface currents such as rivers or streams, direct precipitation over the reservoir surface, runoff, discharges (i.e. wastewater) and underground infiltration (see Figure 1). Likewise, outputs are in the form of surface currents such as rivers, pumped extractions for consumption, evaporation, evapotranspiration and groundwater exfiltration, or leakage (see Figure 2). In mathematical form, the aforementioned flows and fluxes can be expressed in the following differential ordinary equation (Chapra, 1997):

$$\frac{dV}{dt} = \sum_i Q_{r,i} + Q_p + Q_{roff} + Q_d + Q_{\inf} - \sum_o Q_{r,o} - Q_{ext} - Q_{evap} - Q_{evaptrnsp} - Q_{exf} \tag{2}$$

In Equation 2, Q signifies volumetric flow, and its various subscripts have the following meaning: r refers to surface flows (i.e. rivers or streams), and the subscripts i and o are used to distinguish between inflows and outflows. Also, p stands for direct precipitation; *roff* corresponds to flows running off from the land surface adjacent to the reservoir; d is used for discharges; *inf* refers to infiltration currents; *ext* denotes pumped extractions; *evap* is used for evaporation; *evaptrnsp* corresponds to evapotranspiration and *exf* stands for exfiltration. Thus, Equation 2 is a representation of the temporary distribution of water in the reservoir. Despite the variety of terms in Equation 2, a broader approach can be used to roughly estimate the availability of water. For instance, the Mexican Ministry of Environment and Natural Resources considers in the legislation piece known as NOM-011-CNA-2000 that the availability of water, in other words the 'accumulation' term in Equation 2, can be approximated in terms of the generation of runoff as a function of precipitation, evaporation and seepage (SEMARNAT, 2002). It should be noted that the text of NOM-011-CNA-2000 acknowledges that at the time when such piece of legislation was passed in Mexico, there were no other similar pieces of legislation around water balance methods in other nations of the world (SEMARNAT, 2002).

Sokolov and Chapman (1974), Thomann and Mueller (1987), Chapra (1997), Aparicio (2005), Arredondo et al. (2007) and the IAEA (2007) all present conventional methods of general application for the calculation or estimation of the aforementioned volumetric flows given by Equation 2. However, for the case of water bodies with limited information available, as is the case of most reservoirs, especially so in tropical latitudes, it is a challenge to adequately express all of the terms in the hydrological balance. Efforts to do so often result in the combination of data coming from statistical analyses, calculations, other models and frequently from overlapping (yet incomplete) data bases from different entities (Güntner et al., 2004).

It should be noted, however, that even though hydrological processes such as those terms of Equation 2 evolve on a continuous time scale, the records kept in hydrological data bases are defined in a discrete time scale as such records result from measurements and samplings. Therefore, most hydrologic series in such data bases contain data on yearly, seasonal, quarterly, bimonthly, monthly, weekly, daily or even hourly time intervals (Salas, 1993). In order to adequately combine the terms of Equation 2, it is recommended that the time scale of all data be on the same time scale. Unfortunately, this is not always the case, and time-series analysis are often necessary, as it helps to generate synthetic hydrologic records and forecast hydrologic events, as well as to fill in missing data and even extend hydrological records (Salas, 1993).

WATER INPUTS FOR A RESERVOIR

According to this review of the State-of-the-Art of hydrologic balance for reservoirs, as per Equation 2 the following are the most common types of inflows entering a reservoir and their calculation or estimation methods (see Figure 1):

a) Surface currents, such as rivers and streams

In this case, it is necessary to identify all tributary inflows to the reservoir. The goal is to estimate the volumetric flow rate of all such tributaries. Where there are no hydrometric information available, point measurements of depth water velocity can be used to estimate cross sectional areas and flow rates (Manning, 1891; Gupta, 1989; Chapra, 1997; Aparicio, 2005; IAEA, 2007). Surface velocity can also be measured with hydraulic structures known as flumes, such as the Venturi or Parshall flumes (Chow, 1994). These flumes are specially shaped open channel flow sections imposing a restriction in the channel cross-sectional area (converging the flow to a throat section and then a diverging section), and even varying the physical slope of the channel. This results in an increased surface velocity and a change in the water level in the throat section, which is measured in order to calculate the flow rate of the surface current (Chow, 1994; Grant, 1995). Though surface flow rates can also be measured with weirs (Chow, 1994; Munson et al., 1994; Naudascher, 2000), flumes have the advantage that they can measure higher flow rates than comparable sized weirs, and operate with a considerably smaller head loss than a weir. Flumes can also operate without accumulation of sediments, as the higher velocity in the throat section reduces the deposit of solids. However, flumes are more expensive than weirs, and can not be used in combination with a weir or sluice gate upstream (Chow, 1994; Grant, 1995).

Where flow measurements are unattainable (for instance, because of budget constraints), it is also possible to use runoff models to estimate the tributary inflows to the reservoir (Sokolov and Chapman, 1974; Fetter, 2001; Cunderlik and Simonovic 2004; Kouassi et al., 2007a).

b) Direct precipitation over the reservoir

The estimation of the direct precipitation over a reservoir requires the use of information collected in meteorological monitoring stations (Smith, 1993; Schnoor, 1996; Aparicio, 2005; Bouwer. et al., 2006), as well as the statistical validation of data series in order to determine whether the data fit any given probability distribution (Gumbel, 1941; Chow, 1951; Jenkinson, 1955; Smith, 1987; Smith, 1993; Breña and Breña, 2005; Kouassi et al., 2007b). Where there are several meteorological monitoring stations in the basin, for each station, the statistically calibrated data sets (typically with at least 20 years of information on daily precipitation) need to be weighted against the corresponding representative portions of the basins drainage area. These weights are determined in accordance to the generation of Thiessen Polygons typically derived using a GIS (National Technical Information Service [NTIS], 1996; McGhee, 1999; Fetter, 2001; SEMARNAT, 2002; Treviño et al., 2002).

Radar measurements of rainfall are also convenient, as radar is capable of covering an extensive area with high spatial and temporal resolution. Though radar precipitation estimates are also subject to different possible errors, radar can provide data with a spatial resolution as small as $1km^2$, and time intervals as short as 5min (Smith, 1993).

It is also important to analyze the data for cyclical or seasonal trends (Smith, 1993; Breña and Breña, 2005), in order to acknowledge whether data are influenced by natural phenomena such as El Niño (Rasmusson, 1985; Bowden and Semazzi, 2007; Alexander et al., 2008), which affects the dynamics of flooding caused by extraordinary storm events and atypical annual precipitation in different tropical and subtropical latitudes (Rasmusson et al., 1993; Knebl et al., 2005; Awulachew, 2006b; Marengo, 2006). The El Niño Southern Oscillation [ENSO] cycle begins with an anomalous warming of the upper ocean layers near the Pacific coast in South America which results in an oscillation in surface pressure between this geographical location and the west Pacific-Indian Ocean (Rasmusson et al., 1993). This oscillation is associated with yearly climate variation patterns: as the ocean- atmosphere interaction in the tropical Pacific Ocean develops, the pattern of surface winds shifts changing the heat exchange dynamics between oceanic layers, which result in changes in seasonal temperatures and precipitation patterns within tropical and subtropical latitudes (Rasmusson, 1985; Rasmusson et al., 1993). Depending on the phase of the oscillation, the ENSO cycle consists of two consecutive yearly phases: one in which the sea water surface warms and enhances convective rainfall, and then the complementary phase the next year when the sea water cools down and precipitation diminishes (Rasmusson et al., 1993).

c) Surface runoff

The generation of runoff is related to the amount of precipitation falling over the drainage basins directly adjacent to the reservoir (except for that which falls directly over the reservoir). According to the review of scientific literature, there are several available methods which use different tools and strategies to model the flows of surface runoff into a water body. The first significant contribution to the calculation of runoff was done by Mulvaney (1851), who described the concept of time of concentration (i.e. the time which water takes after precipitating over the land to accumulate on a given spot). Then, the widely used method for estimating runoff was that of the United States Soil Conservation Service [US SCS] (US SCS, 1972; Kent, 1973; Sokolov and Chapman, 1974; US SCS, 1986; Pilgrim and Cordey, 1993; SEMARNAT, 2002; Aparicio, 2005). In practice, according to Kent (1973), NTIS (1996) and McGhee (1999), this method can be limited as it only provides an estimation of the maximum expected runoff flow for small hydrological basins (i.e. basin surface area under 2000 acres, or 809 ha. This method consists of the application of permeability factors to different land surfaces considering soil and land use (including vegetative coverage). The method weighs the products of the latter with mean coefficients of rain intensity, and is valid for areas under annual precipitation between 350 to 2150mm (NTIS, 1996; McGhee, 1999; Fetter, 2001; SEMARNAT, 2002). This method is therefore useful in the design of sewerage structure and water discharge, but it lacks the necessary sensitivity to use it on water balances for large basins, as the method is only valid for a single storm event and not over longer periods generally simulated for a water balance.

Thus, several research efforts have leaned towards the development of stochastic models from meteorological data over large basins, such as the Probability Distributed Model [PDM] which relates runoff to rainfall (Moore, 2007; Kay et al., 2007), or fitting runoff data to specific probability distributions (Oyebande et al., 1980; Kouassi et al., 2007a), as well as time-series analysis (Weber and Stewart, 2004). There are also recent efforts to identify the spatial-temporal variation of runoff in the catchment area of a basin by modeling runoff generation as the result of various overlapping mechanisms (such as the water saturation in soil, groundwater seepage and the descent of gravity flows from elevated portions of the basin) which act independently (Pilgrim et al., 1990; Vivoni et al., 2007). However, since these models require statistical methods, their calibration depends on the particular criteria used for error control (Chahinian and Moussa, 2007).

Other than meteorologic variables, the generation of runoff is also affected by soil permeability. Therefore any GIS used to model surface runoff should incorporate theme layers with soil type information, vegetative coverage and land use (Arroyave and Giraldo, 1997; Mendoza et al., 2002; Treviño et al., 2002; Henríquez et al., 2006). Furthermore, remote sensing can provide a useful means to assessing the allocation and extent of different variables such as vegetal coverage and apparent surface geology (Liang, 2007). Likewise, the level of detail and spatial resolution in Digital Elevation Models [DEM] can introduce errors in the estimation of runoff flow rates, hence Endreny and Wood (2001) have incorporated these errors in statistical uncertainty analyses for runoff estimation.

It is noteworthy to point out that there are different software packages specialized in the estimation of runoff, such as the Watershed Modeling System [WMS] (National Water Research Institute [NWRI],1996), the Hydrologic Engineering Center's Hydrologic Modeling System [HEC-HMS] (Knebl et al., 2005) and the Soil and Water Analysis Tool [SWAT] (Torres et al., 2005), STREAM (Bouwer et al., 2006) and the Triangulated-irregular-network based Real-time Integrated Basin Simulator [tRIBS] (Vivoni et al. 2007), all of which have been used to calibrate runoff models in watersheds.

The WMS software allows for the import of DEMs. WMS uses DEMs to delineate watershed boundaries that define the important unit used in hydrologic runoff models. WMS has the ability to perform simulations of the water balance with an emphasis on runoff generation using interfaces to the HEC-HMS and other hydrologic simulation software. WMS has the ability to model water quality in 2D through an interface to CE–QUAL-W2 (NWRI, 1996). Both WMS and HEC-HMS are versatile tools which can be used over large extensions of territory with considerable topographic variability (NWRI, 1996; Cunderlik and Simonovic, 2004; Knebl et al., 2005).

By itself, the HEC-HMS software simulates seepage losses through a decision tree defined by the user in terms of a particular basin. Through a GIS extension called HEC-GeoHMS, it is possible to delineate secondary basins within the main basin to simulate runoff generation (Knebl et al., 2005).

SWAT is a software package developed by the US Department of Agriculture, which estimates runoff by following a method created by the US SCS (1972). The objective of SWAT is to assist the user in the decision making process around variables such as hydrology, climate, sedimentation, soil temperature, nutrients, pesticides crop growth and crop variety in order to improve the yields and sustainability of agriculture (Torres et al., 2005).

STREAM is a GIS for modeling the hydrological balance in dynamic water bodies such as rivers and streams. This software estimates runoff from temperature, precipitation and soil characteristics (Bouwer et al., 2006).

Finally, tRIBS is a software which uses Triangulated Irregular Networks [TIN] to perform water balances in control volumes assigned to each triangular element of the network. TINs consist of a set of triangles created from DEMs: the DEMs have different points which are arranged as the triangles' vertices. Each triangle is assigned a single specific elevation value based on the linear interpolation of the elevations of the vertices, thus forming triangular planes of equal elevation. This allows for an advanced degree of variety in the soil parameters which influence the generation of runoff (Vivoni et al. 2007).

d) Wastewater discharges into the reservoir

Where there may be found any direct discharges of wastewater (either municipal or industrial), it is necessary to have data in terms of measured discharge flow rates from sewage and storm drainage networks entering the reservoir (Chow, 1994; NTIS, 1996; McGhee, 1999; Naudascher, 2000; Aparicio, 2005).

e) Groundwater seepage inflows

Inflow seepage refers to the groundwater entering a water body due to the presence of underwater springs, as well as from the geology and soil types in the basin and in the bathymetry of the water body (Fetter, 2001). These flows are rather difficult to estimate, and are often combined with outflow seepage (i.e. water flowing out of the water body into the underground) into a net seepage flow (Horton, 1933; Chapra, 1997; Aparicio, 2005; IAEA, 2007; Yutsis et al., 2007).

WATER OUTPUTS FROM A RESERVOIR

Similar to inflows, the following are the most common types of outflows from a reservoir –see Equation 2- and their calculation or estimation methods according to this review of the State-of-the-Art of the hydrological balance for reservoirs (see Figure 2):

a) Surface currents leaving a reservoir

Since dams are usually built over the natural path of a river, reservoirs are exoreic, which means that at least one flow (i.e. river) leaves the basin of the reservoir. Therefore, it is necessary to identify and account for the water flows discharged or bypassed from the dam curtain over a given time frame. These flowrates can be measured using discharge data from weirs and sluice gates (Chow, 1994; Munson et al., 1994; Chapra, 1997; Naudascher, 2000; Aparicio, 2005).

b) Pumped extractions for consumption

If water is extracted from a reservoir, it is necessary to have access to extraction discharge data over a given time frame. These data are best portrayed in flow charts (and/or empirical regressions, if possible) to represent extractions over time (Sokolov and Chapman, 1974; Munson et al., 1994; Chapra, 1997).

c) Evaporation

Evaporation flux from the surface of reservoir can be determined either by means of statistical forecasting analysis of the meteorological information in monitoring stations close to the reservoir, or by measuring evaporation in floating pans over the water surface in the reservoir itself (Shuttleworth, 1993; Shuttleworth et al., 1988). In either case, the statistical validation of information is necessary (Breña and Breña, 2005; Kouassi et al., 2007b), as well as the calibration of data by use of empirical quotients (Shuttleworth, 1993; Chapra, 1997). Calibration is often needed because direct measurements generally overestimate actual real evaporation (Sokolov and Chapman, 1974). To compensate for this overestimation, the actual measurements are compared to theoretical values of evaporation, thus obtaining a mean efficiency factor.

The calibration of measured data comes from the comparison of such measurements against expected evaporation according to an energy balance (i.e. heat budget) over the water body. Assuming that the reservoir is a Continuously Stirred Tank Reactor [CSTR] with i inflow surface currents and o outflow surface currents, the heat budget can be written as (Thomann and Mueller, 1987; Shuttleworth, 1993; Chapra, 1997; IAEA, 2007; Ortíz-Jiménez and de Anda, 2007):

$$V\rho_T C_{p,T}\frac{dT}{dt} = \sum_i \left(Q_r \rho_T C_{p,T} T\right)_i - \rho_T C_{p,T} T \sum_o \left(Q_r\right)_o + A_S \bar{H}_{Total} \qquad (3)$$

where $\bar{H}$ was used to represent heat fluxes (heat flows per unit of surface area) of the reservoir:

$$\bar{H}_{Total} \equiv \bar{H}_{solar} + \bar{H}_{atm} - \bar{H}_{WR} - \bar{H}_{C} - \bar{H}_{evap} \qquad (4)$$

In Equations 3 and 4, T is the water temperature, t is time, V is the control volume, r_T is water density as a function of water temperature, $C_{p,T}$ is the heat capacity of water at constant pressure at a given water temperature, Q is used for flow rates, and A_S is the surface area of the water body. As for the suffixes in the right hand member of Equation 4, these stand for solar shortwave radiation, atmospheric radiation due to water vapor, longwave radiation from the water surface, the combined effects of conduction and convection over the reservoir surface, and the combined net effects of evaporation and condensation over the water surface, respectively.

If the reservoir is thermally stratified, and therefore an epilimnion and hypolimnion are distinguishable by a thermocline, the heat budget is represented by the simultaneous Equations 5 and 6, which assume that no water currents enter or leave the reservoir at the hypolimnion (Thomann and Mueller, 1987; Chapra, 1997):

$$V_e \rho_{T_e} C_{p,T_e}\frac{dT_e}{dt} = \sum_i \left(Q_r \rho_T C_{p,T} T\right)_i - \rho_{T_e} C_{p,T_e} T_e \sum_o \left(Q_r\right)_o$$

$$+ A_S \bar{H}_{Total} + v_\tau A_\tau \left(\rho_h C_{p_h} T_h - \rho_e C_{p_e} T_e\right) \qquad (5)$$

$$V_h \rho_{T_h} C_{p,T_h}\frac{dT_h}{dt} = v_\tau A_\tau \left(\rho_{T_e} C_{p,T_e} T_e - \rho_{T_h} C_{p,T_h} T_h\right) - H_L \qquad (6)$$

In Equations 5 and 6, the subscript e stands for epilimnion and the subscript h stands for hypolimnion. H_L is the flow of heat losses in the hypolimnion due to seepage and potential heat losses as the water contained therein is in contact with the walls and floor of the reservoir.

Therefore, the estimation of the flow of evaporation from the surface of the reservoir is obtained by solving for the heat flux term of evaporation in Equation 4, which is paired with either

Equation 3 or with Equation 5 depending on whether the water body is thermally stratified. Thus, if the heat flux of evaporation is calculated, then, it can be further used to determine the mass flow of evaporated water from the surface of the lake. This mass flow accounts for the expected evaporation of water, and is calibrated against measured data.

Since water density and the heat capacity of water at constant pressure are properties that depend on water temperature, these parameters should be modeled implicitly within Equations 3, 5 and 6 in terms of water temperature itself (Yaws, 1999). Furthermore, some of the heat fluxes within Equation 4 are strongly dependent on wind velocity over the reservoir surface. However, care should be exerted, as wind velocity is often registered within meteorological stations in anemometers at 10m (about 32ft) above the ground (Twidell and Weir, 2002), but mathematical expressions of the terms in Equation 4 use wind velocity at 7m (about 23ft) above the water surface level (Thomann and Mueller, 1987; Chapra, 1997). Wind velocity often is represented by an exponential profile with respect to ground level, so it can vary rapidly with elevation. Expressions to correct wind velocity measurements from meteorological stations to another required elevation are available in Twidell and Weir (2002).

It should be noted that this heat balance strongly depends on the incoming solar radiation over the water body over a whole insolation day (Thomann and Mueller, 1987; Chapra, 1997). The solar radiation flux is a function of geographic latitude and elevation of the water body and the position and apparent movement of the sun (Twidell and Weir, 2002). Therefore, the instant value of the solar radiation flux changes not only with the day of the year, but with the time of the day as well. This presents a problem, for which Ortíz-Jiménez and de Anda (2007) offered a first approach solution by modeling the total solar radiation flux (i.e. the accumulated solar radiation flux over a whole day) using fixed data from Allen et al. (1998) in terms of mean energy flows and average number of insolation hours at the 15^{th} day of every month for a specific latitude. However, there are mathematical models which allow for better calculation of total daily insolation by using mathematical functions describing instant solar radiation, and integrating them over any whole day of the year for a given latitude and elevation (Twidell and Weir, 2002).

Therefore, in order to solve Equation 4 for the heat flux of evaporation, the critical variables are water temperature, relative humidity, wind velocity, air temperature, surface area of the reservoir, the amount of water stored in the control volume and location (i.e. latitude and elevation). These are the variables that ought to be measured whereas the rest of the variables can be modeled or expressed in terms of the critical ones (Thomann and Mueller, 1987; Chapra, 1997; Twidell and Weir, 2002). If the heat flux of evaporation has been estimated, then the theoretical mass flow of evaporation can be calculated simply using the latent heat of vaporization of water. This mass flow of evaporation is compared to the actual measurement in the pans, thus obtaining the mean efficiency factor of the pan (a positive number less or equal to one). Measurements are often overestimations of the theoretical values because of different effect, such as the added heat reflected or emitted by the pan itself (Sokolov and Chapman, 1974).

d) Evapotranspiration and consumptive use

Evapotranspiration refers to the evaporation of water carried out by plants in the basin or even over the reservoir surface. This evaporation is made through the stomas of plants distributed throughout its foils. The term 'consumptive use' refers to the amount of water from a basin used by agricultural activities and therefore lost to the atmosphere in the form of evapotranspiration. According to Aparicio (2005), the useful volume of a reservoir for agriculture depends on the demands of consumptive use of water. Since the combined area of the foils of a plant is larger than the projection area of the plant over the basin or the reservoir, and since the evapotranspiration can happen virtually any time of the day whereas evaporation is only significant during hours with solar irradiation, the evapotranspiration loss is usually larger than the corresponding evaporation loss (Fetter, 2001).

Evapotranspiration is difficult to estimate, and at times, it is even neglected and accepted as a source of error in the approximation of the water balance (SEMARNAT, 2002). However, there are several methods to estimate evapotranspiration from a basin. Traditionally, evapotranspiration is estimated with the Thornthwaite Method (Thornthwaite, 1948), which can be solved graphically (Palmer and Havens, 1958) or analytically (Fetter, 2001; Aparicio, 2005). Since the Thornthwaite Method uses monthly averages of air temperature, it only provides mean estimations of monthly evapotranspiration volumes. For more detailed estimations, there are empirical equations derived from mass transfer considerations as well as solar radiation and air temperature (Xu and Singh, 2002). Evapotranspiration has also been modeled from statistical methods using meteorological data in tropical basins (Awulachew, 2006b) as well as the use of software such as the General Purpose Simulation System [GPSS] (Ortiz-Jiménez et al., 2005).

e) Groundwater seepage outflows

As stated previously, inflow and outflow seepage are usually combined into a single net seepage flow. This net flow of groundwater seepage is difficult to estimate, and is therefore usually determined from the hydrologic balance, solving for the net seepage flow assuming that is possible to either measure, calculate or estimate all other elements in Equation 2, though this implies that all unaccounted variations and errors be also included in this term (Sokolov and Chapman, 1974; Yutsis et al., 2007). However, the net flow of groundwater seepage can also be estimated through means of empirical methods with associated errors (Fetter, 2001; Aparicio, 2005). Some methods of approximation consist of estimating the overall amount of groundwater using a very general balance in terms of extraction permits for water usage vs. infiltration (SEMARNAT, 2002). Another method uses tracing isotopes which are put into the reservoir and then detected in wells placed in zones where the presence of groundwater flow is assumed. Then the groundwater flow is estimated by means of a mass balance (IAEA, 2007). Likewise, there are specialized software packages for modeling groundwater flow, such as Visual Modflow, Aqtesolv and Flownet (Fetter, 2001).

According to Fetter (2001) and Götzinger et al. (2006), Visual Modflow is a 3D model which uses finite differences to simulate the recharge, evapotranspitation and constant density and temperature flow in confined and unconfined aquifers. The Aqtesolv software is specialized in analyzing groundwater flow with data from deep wells. On the other hand, the Flownet software is a finite differences model which simulates stationary flow through vertical cuts in the soil and rock layers in order to represent a potential network of paths which could be used by water to flow from the surface to the underground (Fetter, 2001).

THE MORPHOMETRIC MODEL FOR A RESERVOIR

The geometry of a water body has profound effects over its hydraulic performance as well as its water quality. The geometry of a water body determines the amount of stored water as a function of depth. However, since the geometry of most water bodies, including reservoirs, is irregular, such functions are nonlinear. A means to represent the variation in geometry as function of depth requires tailoring a specific morphometric model for a given water body.

A morphometric model (also known as bathymetric model) of a reservoir or lake is a set of mathematical expressions which describe the relationship between the fundamental physical dimensions of such water bodies: maximum depth d, mean depth d_{med}, surface area A_S, and total stored water volume V. Note that all of these dimensions are a function of the elevation of the water level in the reservoir or lake. Just as the water balance for a water body represents the allocation of water over time, the morphometric model represents the allocation of water over physical space for a water body.

A morphometric model is constructed using the information of a bathymetric study: data of cross-sectional areas of bathymetric level curves at different depths (or elevations) of the reservoir or lake. First, these data are combined by means of a parametric function describing surface area as a function of depth or elevation. Then, the stored volume between each contour is estimated by different means, often numerical as opposed to analytical. The overall accumulated storage volume is calculated by adding the stored volume between level curves from the bottom of the reservoir or lake to the top. This allows for yet another parametric curve describing overall accumulated storage volume as a function of depth or elevation. These sets of parametric curves are known as hypsographic curves (Chapra, 1997; de Anda et al., 1998; Ortíz-Jiménez et al., 2005; Awulachew, 2006a). The optimal number of contours to use in the model depends on the maximum depth of the water body, as well as the difference between the cross-sectional areas at the surface and the bottom of the dam (Hakanson,1981).

Initial attempts to describe the morphology of lakes (or dams) were to assume its geometry as that of an inverted elliptical cone (Neumann, 1959) or to use an index to account for the irregularity of its shape (Ryder, 1982). However, the use of parametric curves as described above is more typical, in the form polynomial curves as a function of depth or elevation. An alternative to this traditional approach was developed by de Anda, et al. (1998), who used a model in which the quotient of overall accumulated storage volume to surface area is considered to be directly proportional to the maximum depth elevated to a certain power

$$\frac{V}{A_S} = \kappa d^{\mu} \tag{7}$$

In Equation (7), the quotient of V/A_S is also known as the mean depth of the water body. Thus, data sets from a bathymetric study (surface areas and depths) combined with accumulated storage volume can be used in a linear form of Equation 7 in order to determine the regression parameters κ and μ for a water body:

$$\ln\left(\frac{V}{A_s}\right) = \ln\kappa + \mu\ln d \tag{8}$$

The usefulness of the morphometric volume described in the previous equations is that one single variable (i.e. maximum depth) can be used to calculate all of the other fundamental dimensions of the water body: mean depth d_{med}, surface area A_S, and total stored water volume V. Furthermore, as the surface level elevation Z_S is usually registered frequently in most reservoirs and some lakes, the surface level elevation can easily be transformed into maximum depth, provided that the constant elevation of the bottom Z_0 of the reservoir or lake is known:

$$d \equiv Z_S - Z_0 \tag{9}$$

It should be stressed that a model is an approximate representation of reality. Therefore, the morphometric model has an associated error which is largely due to the method used to calculate the stored volumes between each of the contours (Chapra, 1997; de Anda et al., 1998; Awulachew, 2006a; Arredondo et al., 2007). These errors are often the result of using approximate numerical integration methods over the data of the bathymetric study (Chapra and Canale, 2003), including the product of the average of the cross-sectional areas of adjacent contours times the distance between them which in fact is equal to integration by the trapezoidal method (Chapra, 1997; Torres-Orozco, 2007). However, studies such as that of Endreny and Wood (2001) suggest that the errors in topographic and bathymetric models can propagate and result in significant errors in the calculation of other elements of the water balance. Therefore, efforts to improve the integration methods and thus reduce the associated error to morphometric models could improve the calculations of stored water in a reservoir or lake when using such models in a water balance.

Another source of error is the impending sedimentation in reservoirs, which reduces over time the effective volume of water stored corresponding to any given water level in the reservoir. Surface currents entering the reservoir transport materials through advection (Shen and Julien, 1993; Chow, 1994; Hemond and Fechner, 1994; Chapra, 1997), but as these currents enter the reservoir, the hydraulic regime changes and as the currents' velocity and patterns is modified in the reservoir, advection is no longer the predominant transport mechanism, as sedimentation allows for solids to settle and deposit at the bottom of the reservoir (Chapra, 1997). Assuming that solids accumulate in the bottom in a somewhat uniform fashion as sedimentation occurs over the whole surface area of the reservoir, which contributes with clay, sand and silt settling to the bottom (Shen and Julien, 1993; Schnoor, 1996; Thibodeaux, 1996; Chapra, 1997), then the actual elevation of the inferior limit of the water volume in the reservoir will increase over time as solids accumulate. The morphometric model described in Equation (7) can be used to calculate the overall storage volume in the reservoir. If the volume of sediments accumulating over time can be calculated in the reservoir (Shen and Julien, 1993; Chapra, 1997), then it can be subtracted from the overall storage volume to yield the actual volume of stored water in the reservoir.

ANALYSIS OF RELEVANT CONTRIBUTIONS TO HYDROLOGICAL BALANCES OVER TIME

Though numerous, the references cited in this paper are not comprehensive as they are not the entirety of the published modeling efforts concerning one or more elements of the hydrologic balance around the world between the years 1850 and 2008. However, from the classical references to the specific studies discussed herein, the general progression and trends in hydrologic modeling around water balances and morphometry has been identified. Therefore, the references cited in this work are to be considered as a representative sample (though not in the statistical sense) of the efforts in hydrologic modeling for the considered time frame.

In reality, most of the references cited in this paper are not intended to advance on specific aspects of the water balance, but either their innovation and/or impacts have been such that they became relevant to the field of hydrologic modeling. Some references made contributions to specific portions of the hydrologic balance, whereas some others made impact throughout several of such areas (see Tables 1, 2 and 3).

Within the references cited in this article, Table 4 indicates that Pumped extractions and Morphometry were the least popular fields (i.e. fields with fewer publications) than other areas of the hydrologic balance, such as Surface Runoff, Direct Precipitation and Water Storage, which have the largest number of studies.

Three different general models of solution (Maidment, 1993; Schnoor, 1996; Chapra, 1997) were identified in the cited references in this review:

· Deterministic Models: These models are straightforward, as they consist of mathematically defined functions that return specific outputs describing the response of the system under particular input variables. These models are purely theoretical or semi-empirical.

· Statistical Models: These models relate data sets of inputs and observed outputs in order to predict the most likely responses of the system to different variations in the same. Since these models are generated by data, they are semi-empirical or empirical.

· Stochastic Models: These models use probability distributions to represent the behavior of the system (at times, even under uncertainty) when it is exposed to different variables.

For those models described above, the specific solution methods were classified as qualitative, graphical, analytical or numerical and in the event where special software was used, it was noted as a special type of solution method.

Table 5 portrays the breakdown of types of models and solutions employed in the cited references between 1850 and 2008. Cells containing numbers in Table 5 indicate periods of time where the corresponding modeling efforts were identified and the number of publications are depicted. The figures on Table 5 are not mutually exclusive, as most of the cited references included more than one type of solution and/or model in their respective analyses. Besides, solutions are hardly pure as the solution of one model could require some steps to fall under one category and other steps under other category. If the references considered on Table 5 are indeed representative of the hydrological modeling efforts around the world, then it can be noted that even though deterministic models are dominant, statistical models have been used since the early 20th Century, while stochastic models have been used since the mid 20th Century. However, both statistical and stochastic models have been used more frequently since the 1980s and even more so since 2000 (see Figure 3).

Both Table 5 and Figure 3 suggest that the progression of model types in hydrologic modeling still relies heavily on deterministic approaches, yet these are often combined with statistical and or stochastic models as not all of the elements of the water balance have been satisfactorily represented with pure deterministic functions (such as surface runoff generation and precipitation, for instance). The combination of deterministic, statistical and stochastic approaches results in solutions which tend more to the numerical and use software while still keeping analytical solutions in the toolkit. This shift from analytical solutions to numerical solutions is understandable as hydrologic modeling deals with dynamic and complex systems. Table 5 also shows that even though qualitative and graphical solutions are still in use, they are now rare and rather limited.

DISCUSSION

Even though most of the tropical and subtropical watersheds in the cited references have been subject to different types of modeling efforts, no general methodologies have been developed to address tropical watersheds in a distinct manner from watersheds in temperate regions. Overall, the broad modeling scheme seems to be the same for both kinds of watersheds, but there are

Table 1. Chronology of relevant contributions within cited references to the water accumulation terms of the hydrological balance (figures are not mutually exclusive).

Reference	Accumulation		Reference	Accumulation	
	Morphometry	Storage		Morphometry	Storage
Horton (1933).		X	Aparicio (2005).		X
Neumann (1959)	X		de Anda et al. (2005).		X
Sokolov & Chapman (1974).		X	Fearnside (2005).		X
Hakanson (1981)	X		Knebl et al. (2005).		X
Ryder (1982)	X		Ortíz-Jiménez et al. (2005).		X
Thomann & Mueller (1987).		X	Torres et al. (2005).		X
Maidment (1993).		X	Awulachew (2006a).	X	
McMahon (1993)		X	Awulachew (2006b).		X
Schnoor (1996).		X	Götzinger et al. (2006).		X
Arroyave & Giraldo (1997).		X	Kwon & Moon (2006).		X
Chapra (1997).	X	X	Marengo (2006).		X
de Anda et al. (1998).	X		Puhlmann et al. (2006).		X
Endreny & Wood (2001).	X		Arredondo et. al. (2007)	X	X
Koh et al. (2002).		X	IAEA (2007).		X
SEMARNAT (2002)		X	Kouassi et al. (2007b).		X
Chaves & Kojiri (2003).		X	Richter & Thomas (2007).		X
Güntner et al. (2004).		X	Torres-Orozco (2007)	X	
Labadie (2004).		X	Yutsis et al. (2007).		X
			Total	9	29

Table 2. Chronology of relevant contributions within cited references to the water input terms of the hydrological balance (figures are not mutually exclusive).

Reference	Inputs				Reference	Inputs			
	Surface Currents	Direct Precipitation	Surface Runoff	Discharges		Surface Currents	Direct Precipitation	Surface Runoff	Discharges
Mulvaney (1851).		X	X		Chapra (1997).	X	X	X	X
Manning (1891).	X				McGhee (1999).		X	X	X
Gumber (1941)			X		Yaws (1999).				
Thornthwaite (1948).			X		Naudascher (2000).	X			X
Chow (1951).		X			Endreny & Wood (2001).			X	
Jenkinson (1955).		X			Fetter (2001).	X	X	X	
Palmer & Havens (1958).			X		Koh et al. (2002).	X			
US SCS (1972).			X		Mendoza et al. (2002).			X	
Sokolov & Chapman (1974).	X	X	X	X	SEMARNAT (2002)		X	X	
Oyebande et al. (1980).			X		Treviño et al. (2002).		X	X	
Rasmunsson (1985).		X			Cunderlik & Simonovic (2004).	X		X	
US SCS (1986).			X		Weber & Stewart (2004).		X	X	
Smith (1987).		X			Aparicio (2005).	X	X	X	
Thomann & Mueller (1987).	X	X	X	X	Breña & Breña (2005).		X		
Shuttlewoth et al. (1988).					Knebl et al. (2005).	X	X	X	
Gupta (1989).	X			X	Torres et al. (2005).	X		X	
Pilgrim et al. (1990).			X		Awulachew (2006b).		X		
Pilgrim & Corday (1993).			X		Bouwer et al. (2006).		X	X	
Rasmunsson et al. (1993).		X			Henríquez et al. (2006).			X	
Salas (1993).		X			Marengo (2006).	X	X		
Shuttlewoth (1993).		X			Bowden & Semazzi (2007).		X		

Table 2 (continued). Chronology of relevant contributions within cited references to the water input terms of the hydrological balance (figures are not mutually exclusive).

Smith (1993).		X			Chahinian & Moussa (2007).			X	
Chow (1994).	X			X	IAEA (2007).	X	X		
Munson et al. (1994).	X			X	Kay et al. (2007).			X	
Grant (1995).	X				Kouassi. et al. (2007a).	X		X	
NTIS (1996).		X	X	X	Kouassi et al. (2007b).		X		
NWRI (1996).			X		Moore (2007).			X	
Schnoor (1996).	X	X			Vivoni et al. (2007).			X	
Arroyave & Giraldo (1997).		X	X		Alexander et al. (2008).		X		
					Total	19	30	33	9

specific phenomena which occur in tropical and subtropical reservoirs and lakes that have not been fully addressed in the particular models of the specific elements of the water balance, such as:

· Localized climate and weather variability, trends and cycles, as influenced by larger phenomena such as El Niño (Rasmusson, 1985; Rasmusson et al., 1993; Knebl et al., 2005; Ortíz-Jiménez et al., 2005; Awulachew, 2006b; Marengo, 2006).

· Different evaporation patterns due to warmer temperatures and higher humidity (Thomann and Mueller, 1987; Shuttleworth, 1993; Chapra, 1997; IAEA, 2007; Kouassi et al., 2007b; Ortíz-Jiménez and de Anda, 2007).

· Different exposure to sunlight during day hours throughout the year (Twidell and Weir, 2002).

· Thermal stratification in deep reservoirs that may not turn over during the winter, as is often the case in temperate regions, resulting in all-year long thermal stratification (Schnoor, 1996; Thibodeaux, 1996; Chapra, 1997).

CONCLUSIONS

Hydrologic modeling is a vast field which combines science and engineering methodologies which result in complex models. The hydrologic balance of a reservoir or lake describes the temporal allocation of water passing through the water body. A comprehensive water balance for a reservoir includes different elements such as overall accumulated storage volume, inflow surface flows, direct precipitation, surface runoff generation, wastewater discharges over the water body, outflow surface flows, evaporation, evapotranspiration, pumped extractions and sluice gate discharges from dam curtains and net groundwater seepage. All of these elements are modeled separately, though relations between them must be identified. These individual models result in expressions of these elements as functions of time, which are then combined into one expression of the form of Equation 2, which is solved numerically to account for storage volume variation over time.

Table 3. Chronology of relevant contributions within cited references to the water output terms of the hydrological balance (figures are not mutually exclusive).

Reference	Outputs				
	Surface Currents	Extractions	Evaporation	Evapo-transpiration	Net Goundwater Seepage
Horton (1933).					X
Thornthwaite (1948).				X	
Palmer & Havens (1958).				X	
Kent (1973)				X	
Sokolov & Chapman (1974).	X	X	X	X	X
Oyebande et al. (1980).			X		
Thomann & Mueller (1987).	X		X	X	X
Shuttlewoth et al. (1988).			X		
Gupta (1989).	X				
Shuttlewoth (1993).			X		
Chow (1994).	X				
Munson et al. (1994).	X	X			
Grant (1995).	X				
Schnoor (1996).	X		X		X
Chapra (1997).	X	X	X	X	X
Allen et al. (1998).				X	
Yaws (1999).			X		
Naudascher (2000).	X				
Fetter (2001).				X	X
SEMARNAT (2002)					X
Twidell & Weir (2002).			X		
Xu & Singh (2002).				X	
Aparicio (2005).			X	X	X
Breña & Breña (2005).			X		
Ortíz-Jiménez et al. (2005).			X	X	
Awulachew (2006b).				X	
Götzinger et al. (2006).					X
IAEA (2007).	X		X		X
Kouassi et al. (2007b).			X		
Ortíz-Jiménez & de Anda (2007).			X		
Yutsis et al. (2007).					X
Total	10	3	15	12	11

The morphometric model of a reservoir or lake is a set of mathematical expressions which describe the variation of the fundamental physical dimensions of the water body (i.e. maximum depth, mean depth, surface area and storage volume) over elevation. Therefore, the morphometric model of a reservoir or lake describes the spatial allocation of water. This model requires the combination of statistical methods to generate parametric curves which are integrated numerically in order to yield storage volumes. The associated errors to the numerical methods used for such purpose can lead to under and over estimations of storage volumes; these errors can propagate when combining the morphometric model to the hydrologic balance equation, thus resulting in errors in the estimation of other elements in the water balance.

Table 4. Number of overall relevant contributions within cited references to the different terms of the hydrological balance, between 1850 and 2008 (figures are not mutually exclusive).

Accumulation	Morphometry	9
	Storage	29
Inputs	Surface Currents	19
	Direct Precipitation	30
	Surface Runoff	33
	Discharges	9
Outputs	Surface Currents	10
	Extractions	3
	Evaporation	15
	Evapo-transpiration	12
	Net Goundwater Seepage	11

Table 5. Number of articles within cited references using different types of solutions, aggregated by sort of model employed, between 1850 and 2008 (figures are not mutually exclusive).

Solution Types		Deterministic Models (theoretical or semiempirical)					Statistical Models (semiempirical or empirical)					Stochastic Models (probabilistic)				
Period		Qualitative	Graphic	Analytical	Numerical	Software	Qualitative	Graphic	Analytical	Numerical	Software	Qualitative	Graphic	Analytical	Numerical	Software
1850	1900	2	2	2												
1900	1950	2	1					1	1							
1950	1955								1							
1955	1960	1	2	1					1					1		
1960	1965															
1965	1970															
1970	1975	2	2	1												
1975	1980															
1980	1985	1		2					1							
1985	1990	1	2	4	1				2					1		
1990	1995	1	2	7	2				8					3	1	
1995	2000	1	1	8	3	1			3	1	1					
2000	2005	1	1	8	3	2			5	1	1			5	2	
2005	2008	4	1	11	4	7			10	2	2			7	1	
Total		16	14	44	13	10	0	1	32	4	4	0	0	17	4	0
		97					41					21				

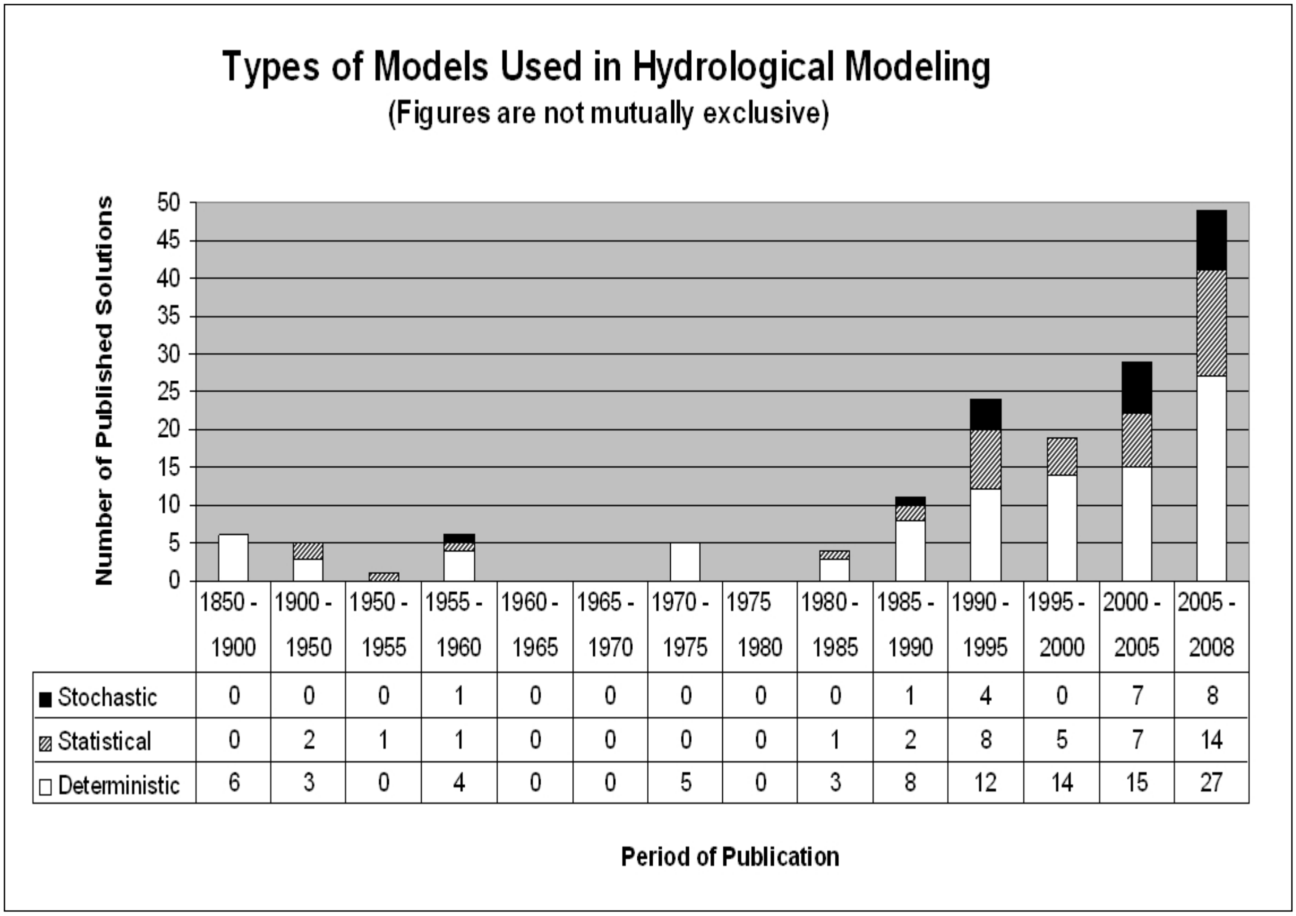

Figure 3. Number of solutions used in hydrological modeling efforts between 1850 and 2008, per general type of model.

The use of more refined modeling techniques for the different elements of the water balance often results in the combination of analytical and numerical solutions as well as the use of specialized software addressing deterministic, statistical and stochastic approaches. Furthermore, numerical methods are required to solve the hydrological balance equation and the morphometric model.

Finally, the general models used for watersheds in temperate regions prove useful in the simulation of tropical and subtropical reservoirs and lakes. However, special adjustments should be considered to account for variations and trends in climatology, weather, evaporation flows, daily solar insolation and year-round stratification.

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NOTATION

Table 8 includes all symbols used to represent variables and parameters in the equations of this paper.

Table 8. Notation of variables.

Symbol	Common Units	Meaning
A_S	m^2	Surface area of the water body.
A_τ	m^2	Mean surface area of the thermocline.
$C_{p,T}$	J/[kg°C]	Heat capacity of water at constant pressure at a given water temperature.
d	m	Maximum depth of the water body.
d_{med}	m	Mean depth of the water body.
e	---	Subscript used to represent the epilimnion.
$\bar{H}_{atm}$	J/[m^2d]	Heat flux of the longwave radiation from the atmosphere (mostly due to its moisture content).
$\bar{H}_C$	J/[m^2d]	Heat flux of the combined effects of conduction and convection due to the action of wind over the surface of the water body.
$\bar{H}_{evap}$	J/[m^2d]	Heat flux due to water evaporation from the surface of the water body.
H_L	J/d	Flow of heat losses from the hypolimnion.
$\bar{H}_{solar}$	J/[m^2d]	Heat flux of the daily direct solar shortwave radiation (i.e. insolation) over the surface of the water body.
$\bar{H}_{WR}$	J/[m^2d]	Heat flux of the longwave radiation from the surface of the water body.
$\bar{H}_{Total}$	J/[m^2d]	Heat flux resulting from the summation effects or heat transfer over the surface of the water body.
h	---	Subscript used to represent the hypolimnion.
i	---	Subscript used to represent inflows.
κ	---	Proportional coefficient of the morphometric model (regression parameter).
μ	---	Power coefficient of the morphometric model (regression parameter).
v_τ	m/d	Coefficient of heat transfer velocity through the thermocline.
o	---	Subscript used to represent outflows.
Q	m^3/d	Volumetric flow (i.e. flowrate).
Q_d	m^3/d	Volumetric flow of discharges to the water body.
Q_{evap}	m^3/d	Evaporation volumetric flow.
$Q_{evaptrnsp}$	m^3/d	Evapotranspiration volumetric flow.
$\mathrm{Q_{exf}}$	m^3/d	Volumetric flow of exfiltration currents from the water body.
Q_{ext}	m^3/d	Pumped extractions volumetric flow.
Q_{inf}	m^3/d	Volumetric flow of infiltration currents to the water body.
Q_p	m^3/d	Volumetric flow of direct precipitation over the watr body surface.
Q_r	m^3/d	Volumetric flow of surface currents.
Q_{roff}	m^3/d	Volumetric flow of surface runoff.
ρ_T	kg/m^3	Water density as a function of water temperature.
T	°C	Water temperature.

Table 8 (continued). Notation of variables.

T_e	°C	Temperature of water in the epilimnion.
T_h	°C	Temperature of water in the hypolimnion.
t	d	Time.
V	m^3	Storage volume of the water body.
V_e	m^3	Volume of water in the epilimnion.
V_h	m^3	Volume of water in the hypolimnion.
Z_S	m	Elevation of the surface of the water body (usually with respect to sea level).
Z_0	m	Elevation of the bottom of the water body (usually with respect to sea level).

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ADDRESS FOR CORESPONDENCE
Dr. Jose de Anda
CIATEJ, A.C.
Normalistas 800
CP 44270 Guadalajara, Jalisco
Mexico

Email: janda@cencar.udg.mx