On the Contribution of Victoria Nile River Discharge to the Hydrological Performance of East Africa's Lake Victoria

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ABSTRACT
This paper presents an analytical re-appraisal of Lake Victoria's water balance, against a background of persistent, worldwide claims in the media that the sharp decline of the Lake's water level observed between 2003 and the end of 2006 was primarily the consequence of excessive and unscrupulous abstractions of water by operators of Owen Falls Dam Power Stations at Jinja, Uganda, allegedly in sheer contravention of the so-called "agreed curve" that was adopted purportedly to uphold the hydrological health, and hence the natural water levels, of the Lake. An equation that facilitates quantification of the contribution of Victoria Nile to the depletion of the waters of Lake Victoria during times of falling water levels is derived. An analogy is established between the derived equation and the equation of state of perfect gases of thermodynamics that provides a framework for treatment of the two sets of variables in the two equations in similar ways. With aid of the equation, evaluations of the contributions of the agreed curve releases and over-abstractions, as components of the overall contribution of Victoria Nile to declines of water levels of Lake Victoria, are undertaken for the hydraulic data statements of December 2005 - the worst month in terms of the recent Lake level fall. The results reveal that the "famous" 55% responsibility level for the declining Lake levels observed then and attributed to over-abstraction in the various media claims could only have arisen out of a flawed prescription of what the 55% actually measured. It is shown thereafter that even with as much as 55% contravention of the agreed curve, the overall contribution of Victoria Nile to the declining Lake water levels could not have exceeded 15%, except if the Lake water level happened to fall at rates of 3 millimeters or less per day during the observation period. In such a case, the paper argues, there would hardly have been so much outcry and accusations as propagated in the media. Finally, the paper questions the efficacy of the agreed curve to uphold the "natural" hydrological health of Lake Victoria, other than to simply guarantee water supply for irrigation requirements of riparian Countries downstream.

Keywords: Agreed Curve, Lake Victoria, Fluctuation, Over-Abstraction, Riparian Countries, Victoria Nile, White Nile.

1. INTRODUCTION

Lake Victoria, the largest lake in the African Lake Plateau and the second largest freshwater body in the world, is a very prominent geographical feature in Africa. Lying at 1,134 meters above sea level, with the northern edge touching the Equator in Eastern Africa, its 3,400 kilometer long rugged shoreline and surface area of nearly 68,800 square kilometers are shared between the three Countries of Uganda, Kenya and Tanzania. It has a catchment basin, estimated at 184,000 square kilometers, that stretches into the Countries of Burundi, Rwanda and the Democratic Republic of Congo (See Figure 1). It is thus a trans-boundary resource. With such a spread, it can be a potential source of harmony when handled rationally, or dispute if handled irrationally. As the source of the White Nile, a major contributor to the main Nile River that flows through the Sudan into Egypt and ultimately empties into the Mediterranean Sea, it is also clearly the origin of an international resource, for whatever happens to it inevitably translates into effects on the other Countries in the Nile Basin (Klohn and Andjelic, 2004).

The estimated average depth of 40 meters and a maximum depth of 84 meters give it an estimated volume of 290,000 cubic kilometers of water, which, by world standards, makes it a shallow lake. Yet it is the lifeline of the fisheries industries in the three East African Countries, the source of virtually all of the hydropower in Uganda, as well as the source of domestic and industrial water supplies in all the big cities and towns surrounding it. It also supports a horticulture industry along its shores and plays a strategic role as a key marine transport link between the three East African Countries (EAC Secretariat, 2006). For these and other climate-related reasons, over a century now, right from the time when it was established to be the source of the White Nile in the nineteenth century, Lake Victoria has been the subject of numerous hydrological surveys and other environment-related investigations (Hurst and Phillips, 1938).

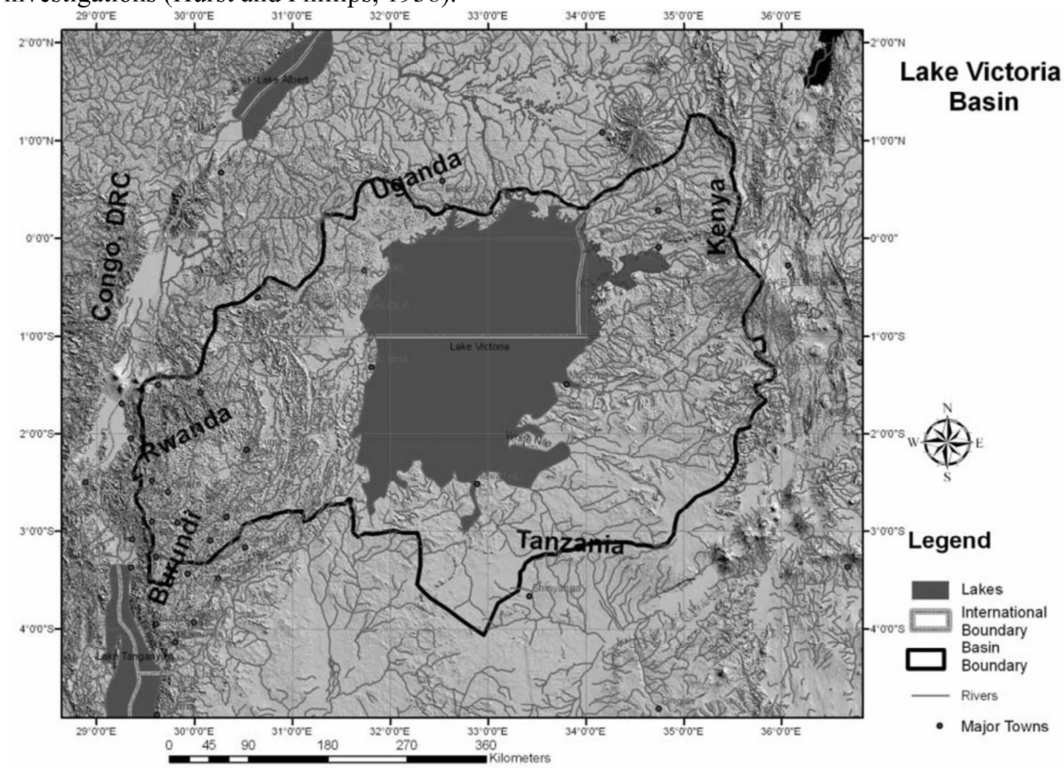

Figure 1: Map of Lake Victoria Water Basin

In the second half of the twentieth century, its water balance became the subject of intense and sustained appraisals, following the sudden 2.5 meter dramatic rise in its water level between October 1959 and May 1964 (de Baulney and Baker, 1970; WMO, 1974, 1982; Kite, 1981a, 1981b; Piper, Plinston and Sutcliffe, 1986; IHA, 1993; Sene and Plinston, 1994; Nicholson, Kim and Ba, 1997; Yin and Nicholson, 1998; Nicholson, Kim and Ba, 2000). Recently, when its water level suffered this time an alarmingly sharp decline of nearly 1.5 meters (Figure 2), between 2001 and the end of 2006, (**http://www.fas.usda.gov/pecad/highlights/2005/09/uganda_26sep2005/**), a new torrent of investigations into the water balance and assessment of the role of Victoria Nile discharges again set in (Kull, 2006a; Kull, 2006b; Mubiru, 2006; Sutcliffe and Petersen, 2007).

None of these new investigations and appraisals, unfortunately, has been able to answer the fundamental question of what underlies the Lake's erratic fluctuations, traceable over both historic and geologic time (Yin and Nicholson, 1998). Indeed, for the case of the 2.5-meter unexpected dramatic rise of the early 1960s that was preceded by unusually heavy rains over the East and Central African Regions, none has conclusively established the cause of the unusually heavy rains.

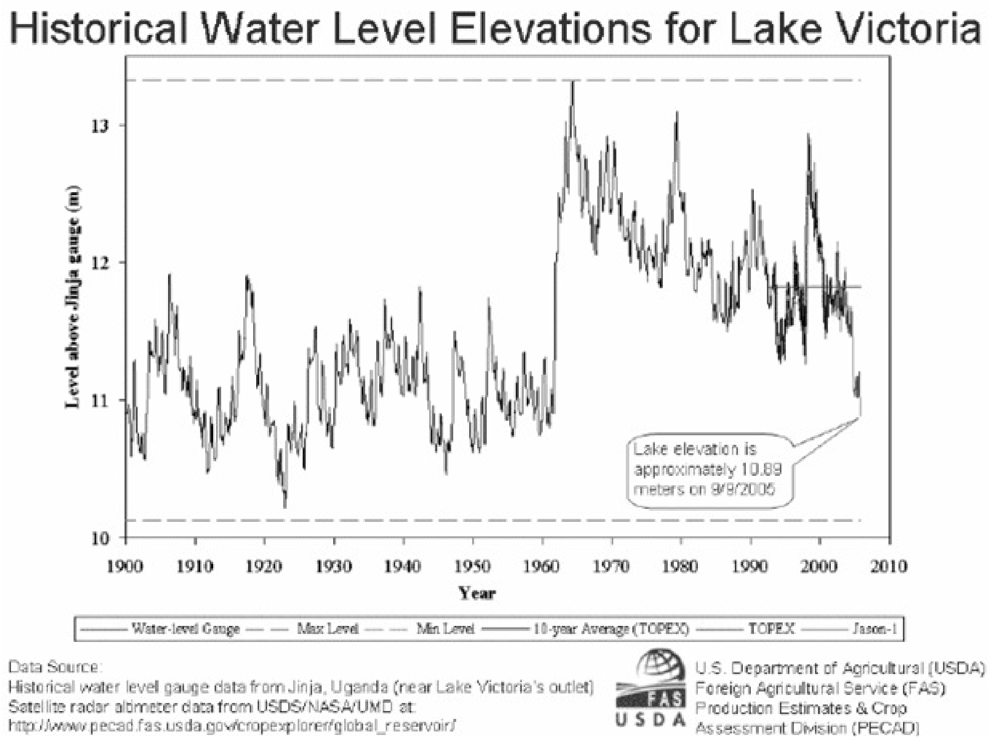

Figure 2: Historical Water Levels of Lake Victoria

As for the recent case of sharp decline of the Lake's level, which apparently was also manifested by the water levels of all the other Great Lakes in the Eastern African Rift Valley, namely, Turkana, Tanganyika, Rukwa, (Figure 3), none of the reported investigations has fared any better in explaining what these lakes keep responding to. The intense unending debate on the cause(s) of the unpredictable fluctuations of the Lake's water level is therefore little wonder.

From the hydrological perspective, it is instructive to observe that the dramatic rise of the 1960s occurred barely five years after the completion of the construction of Owen Falls Dam and the commissioning of the power station therein in 1954. Likewise the recent sharp drop of nearly 1.5 meters between 2001 and the end of 2006 occurred barely five years after the commissioning of the Owen Falls Power Station Extension Project in 2000. Could such coincidences be sufficient to suspect the involvement of the human hand? Shalash (1980), Acres International (1990a, 1990b, 1991), Jennifer (2006), Onek (2004, 2005), Reynolds (2005), Kull (2006a, 2006b), and many others certainly think so, even when the same declines were registered in respect of the other Great Lakes in the Eastern African Rift Valley, as depicted in Figure 3. With no involvement of human hand operations suspected in the declines of the water levels of the latter lakes, whatsoever, would it not be fair to treat this as a case of sheer selectiveness and subjectivity? How else can one explain a situation where, on one hand, an observed sharp decline in the case of Lake Victoria is attributed principally to reckless over-abstractions of water by some unmindful operators of a hydropower complex, and on the other, do not reach the same conclusions in respect of the same events registered with regard to the other Great Lakes in the same region with tectonic origins, presumably because these others do not have power stations at their outlets to over-abstract the water?

Against this background of relentless questions, this paper undertakes an analytical re-examination of the water balance of Lake Victoria, with a primary focus on the quantification of the contribution of Victoria Nile (the only significant outflow from the Lake) to the decline of the Lake water levels, such as the case observed between 2001 and the end of 2006.

In this re-examination, nowhere shall the author invoke the "famous" proclamation by Hurst and Phillips (1938) that they found "*over a period of 27 years runoff from the basin and outflow over the Ripon Falls were roughly equal and therefore evaporation from the surface of the lake was approximately equal to the rainfall*", for it is noted that while the Hurst and Phillips (1938) finding was indeed possible and true for that particular period of investigation from 1905 to 1932, as the Lake levels were approximately the same at the start and end of the period (see Figure 9) it certainly cannot be expected to hold true for all times, as common sense would dictate.

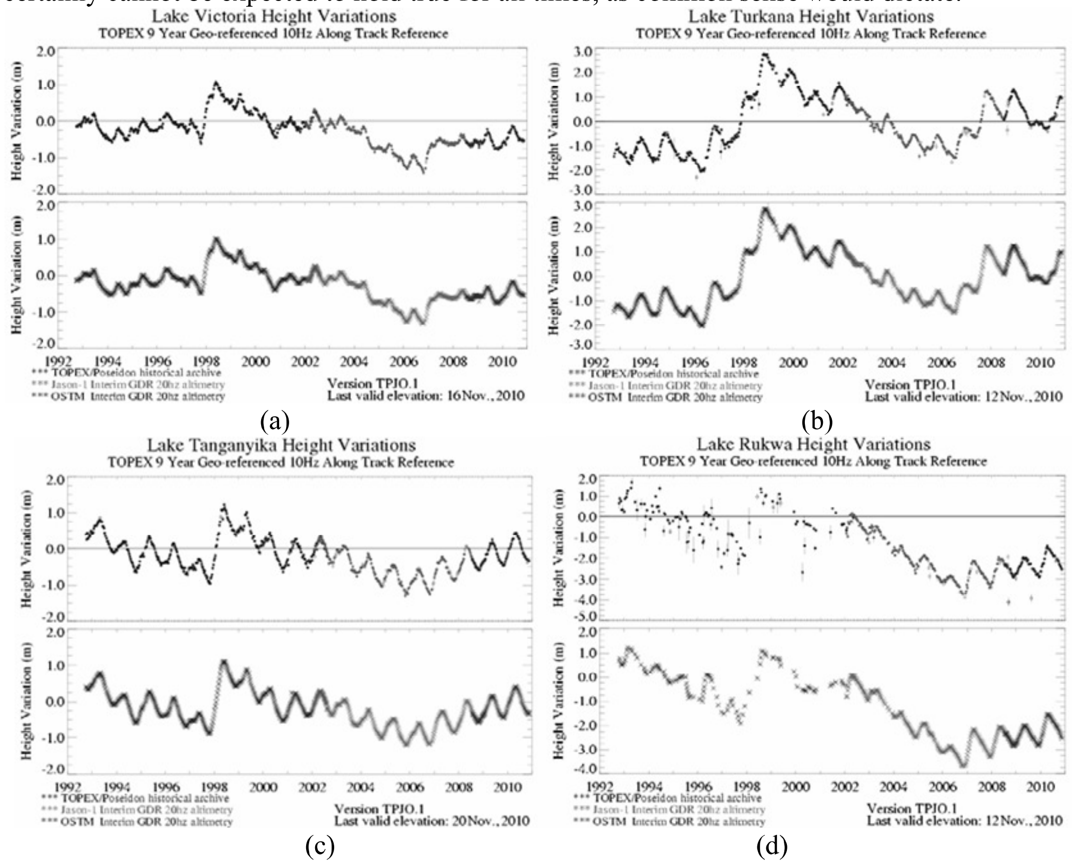

Figure 3: Fluctuations of Levels of the Great Lakes in Africa's Eastern Rift Valley

2. LAKE VICTORIA'S WATER BALANCE

Hydrologists invoke the law of conservation of mass to account for waters entering and leaving closed water basin systems over a prescribed duration of time. Generically, the water budget for any closed water basin system is encapsulated by the statement

$$\pm\text{Net Change in Basin Storage} = \text{Total Water Inflow} - \text{Total Water Outflow} \quad (1)$$

The $\pm$sign incorporates the possibility that the "Net Change" can be an increase or a decrease. The challenge for the hydrologist then is to identify and quantify the components or factors that constitute the terms "Total Inflow" and the "Total Outflow". Once done, the hydrologist must then follow with studies of the processes that drive the dynamics of these factors. These studies require, as a minimum, substantial knowledge of the geography and topography of the basin, and can constitute a formidable task.

For Lake Victoria basin, much of the task of identification of the components in the two terms was performed and accomplished in the latter part of the last century in the course of investigations into what caused the dramatic 2.5 meter rise between October 1959 and May 1964.

These studies identified two major factors in the “Total Inflow”, namely the direct rainfall on the Lake’s surface and the combined river tributary inflows and land surface runoffs. They also established that the principal factors in the “Total Outflow” are the evaporation off the large surface and the Victoria Nile outflow across Ripon Falls at Jinja. No significant magnitudes of the usual underground flows were established by any of the studies.
From these findings, a consensus evolved and prevails today that the water balance of Lake Victoria may be expressed symbolically as:

$$\pm\Delta S_{LV} = P_{LV} + Q_{CD} - E_{LV} - Q_{VN} \tag{2}$$

where, for a specified duration of time, ΔS_{LV} is a positive entity denoting the net change in the Lake’s storage, P_{LV} denotes the rainfall received directly over the Lake’s surface, Q_{CD} denotes the catchment discharge given by the sum of river tributary inflows and land surface runoffs, E_{LV} represents the evaporation off the Lake’s surface and Q_{VN} is the outflow from the Lake in form of Victoria Nile, which is eventually released through the turbines of the hydro-electric power station complex at Owen Falls Dam. This is thus the fundamental equation that any investigator into the hydrological health of the Lake must start from and work with**.** Figure 4 provides a schematic of this water balance, with Victoria Nile flow separated into Victoria Nile discharge as per the agreed curve, Q_{VNAC}, and Victoria Nile over-abstraction, Q_{VNOA}, to facilitate subsequent analyses and derivations.

The challenge in the application of this equation in any analysis lies in the fact that not all the variables are either directly measurable or can be estimated with sufficient accuracy. While the net change in the Lake’s storage and the outflow from the Lake in form of Victoria Nile are indeed directly measurable, direct rainfall, evaporation and catchment discharges can only be estimated. This state of affairs, unfortunately, has often forced many hydrologists and other analysts to invoke the assumption of equality between direct rainfall and evaporation on the strength of the above-referenced proclamation by Hurst and Phillips (1938). But such an assumption clearly amounts to ignoring the role of meteorological factors in the dynamics of the changes in the storage of the Lake. No wonder then that it has led to some of the outrageous conclusions to date. The approach taken here therefore will depart from those practices that assume equality between rainfall over the lake and evaporation off its surface for the reason that it must necessarily take into account the influence of meteorological factors in the dynamics of the net change in the Lake’s storage.

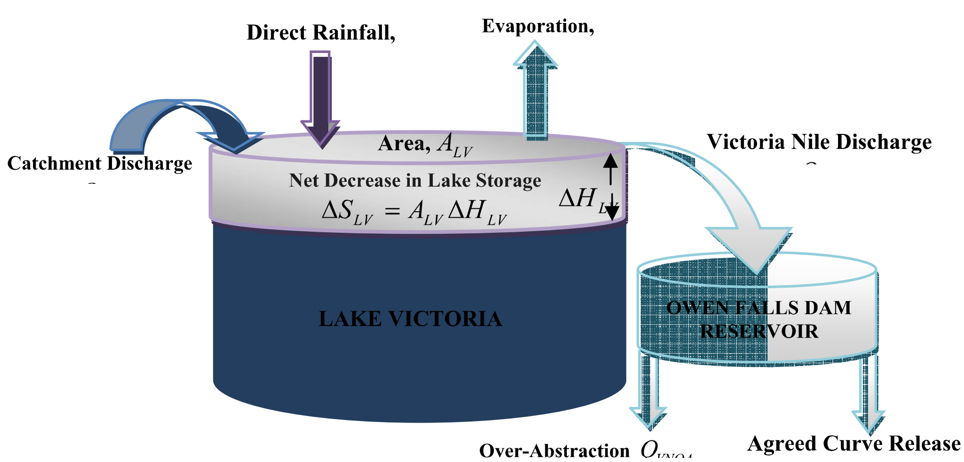

Figure 4: A Schematic of Lake Victoria Water Balance for Declining Water Levels

3. EQUATION OF STATE FOR DECREASING NET LAKE STORAGE

From the generic form (2), taking the minus sign to account for decreasing net storage, it follows that the applicable form of Lake Victoria's water balance equation for periods of decreasing net lake storage (declining water level) is given by the expression

$$\Delta S_{LV} = E_{LV} - P_{LV} - Q_{CD} + Q_{VN} \tag{3}$$

The rainfall P_{LV}, the catchment discharge Q_{CD} and the evaporation E_{LV}, as noted previously, are inherently difficult to estimate accurately and thus constitute three unknown variables in the equation. Such an equation, *Linear Algebra* tells us, cannot be solved uniquely. The number of unknown variables must therefore be reduced. For this purpose the entity introduced is

$$\Delta E_{LV} = E_{LV} - P_{LV} - Q_{CD}, \tag{4}$$

which, when positive, prescribes the net evaporation over the "Total Water Inflow" (sum of the direct rainfall over the lake surface and catchment discharges). With this entity, the water balance then becomes

$$\Delta S_{LV} = \Delta E_{LV} + Q_{VN} \tag{5}$$

and has only one entity, ΔE_{LV}, that is difficult to estimate accurately. A vitally significant import of this equation is that whenever a net decline in Lake Victoria's water level is observed, this must be attributed to two main factors, namely, the excess evaporation over the combined direct rainfall on the Lake surface and catchment discharges, representing meteorological factors, and the Victoria Nile outflow, representing the part influenced by operations of humans. Evidently, the sum of the contributions of the meteorological and human operation factors to the depletion of the waters of Lake Victoria over a prescribed duration of time, expressed in percentages, is

$$100 = 100\left(\Delta E_{LV} / \Delta S_{LV}\right) + 100\left(Q_{VN} / \Delta S_{LV}\right). \tag{6}$$

Clearly, therefore, the percentage contribution of Victoria Nile River discharge to the net decrease in Lake Storage over a specified duration of time and denoted by C_{VN}, is measured by

$$C_{VN} = 100\left(Q_{VN} / \Delta S_{LV}\right), \tag{7}$$

and from net evaporation, denoted by C_{NE}, is measured by

$$C_{NE} = 100\left(\Delta E_{LV} / \Delta S_{LV}\right). \tag{8}$$

In the applications of equations (7) and (8), the pertinent interval of time must be spelt out. As water releases through the turbines at Owen Falls Power Station are measured daily and the Lake levels at the Jinja pier are also monitored on daily basis, the day is certainly the appropriate candidate and is therefore taken.

Accordingly, if A_{LV} denotes the surface area of the Lake in square kilometers and ΔH_{LV} denotes the rate of net fall in Lake level in millimeters per day, then

$$\Delta S_{LV} = A_{LV} \Delta H_{LV} \times 10^{-3} \tag{9}$$

is the net decrease in Lake storage in cubic meters per day. The portion of this volume that will have been discharged via Victoria Nile on the specific day is

$$Q_{VN} = 60 \times 60 \times 24 \times R_{VN} = 864 \times 10^2 R_{VN} \tag{10}$$

where R_{VN} denotes the mean rate of water release through the turbines in cubic meters per sec on a specific day. Consequently, equation (7) yields the expression

$$C_{VN} = \frac{864 \times 10^4 R_{VN}}{A_{LV} \Delta H_{LV} \times 10^{-3}} = \frac{864 \times 10^7}{A_{LV}} \times \frac{R_{VN}}{\Delta H_{LV}}, \tag{11}$$

as the measure of the percentage contribution of Victoria Nile River discharge to the net daily rate of fall of Lake water level. As for the contribution of the net evaporation, which cannot be determine directly by means of equation (8) because as ΔE_{LV} still remains a difficult entity to estimate accurately, the following fact is inoked:

$$C_{VN} + C_{NE} = 100. \tag{12}$$

This relationship, together with equation (11), then gives the percentage contribution of the net evaporation to the fall in Lake level as

$$C_{NE} = 100 - C_{VN} = 100\left(1 - \frac{864 \times 10^5}{A_{LV}} \frac{R_{VN}}{\Delta H_{LV}}\right), \tag{13}$$

Equations (11) and (13), respectively, thus provide us with the desired tools for quantification of the impacts of human operations and meteorological factors on the hydrological health and performance of Lake Victoria.

4. ANALOGY WITH THE PERFECT GAS EQUATION OF STATE

To appreciate the vivacity and useful of relationships (11) and (13) in the debate about the role of human operations in the depletion of the waters of Lake Victoria, the equation of the state of the perfect gas (Nelkon and Parker, 1977) is important. The equation states that for a given mass of a perfect gas, the Pressure P, the Volume V, and the Temperature T are related through the expression:

$$PV = RT, \tag{14}$$

in which R denotes the Universal constant that varies from one perfect gas to another. Further, it is learnt then that this is a relationship that constrains the behavior of the perfect gas. To date, this law has been so restraining that no perfect gas is known to have violated it. With this knowledge, equation (11) is referred to, to move the entity ΔH_{LV}, the daily rate of the net decline of Lake water level in millimeters, from the denominator of the right hand side to the numerator of the left hand side, so as to write

$$C_{VN} \Delta H_{LV} = \left(864 \times 10^7\right) R_{VN} / A_{LV} \tag{15}$$

At once it is observed that the two equations are now analogous, with C_{VN} the analogy of the Pressure P, ΔH_{LV} the analogy of the Volume V, and R_{VN} the analogy of the Temperature T. In this sense, the quantity $\left(864 \times 10^7\right) / A_{LV}$, which is symbolized by Λ_{LV}, can be viewed as the analogy of the Universal Gas Constant R and call it Net Lake Storage Decrease Constant. It is then noted that just as the Universal Gas Constant varies from one perfect gas to another, so does the Net Lake Storage Decrease Constant vary with the surface area of the Lake.

With introduction of the Net Lake Storage Drop Constant equation (11) is re-written in the more generic form

$$C_{VN}\Delta H_{LV} = \Lambda_{LV} R_{VN}. \tag{16}$$

Armed with the strength of this perfect gas analogy, the behavior of the Net Lake Storage Decrease can be likened to that of a perfect gas and investigate the dynamics of the variables C_{VN}, ΔH_{LV} and R_{VN} within the framework for the investigation of the dynamics of the perfect gas variables P, V and T, in thermodynamics. Thus the analogue of the $P-V-T$ surface for the perfect gas can be generated in the form of a $C_{VN}-\Delta H_{VN}-R_{VN}$ surface, which is depicted in Figure 5. From this $C_{VN}-\Delta H_{LV}-R_{VN}$ surface, it is evident that at a fixed rate of water release R_{VN}, the percentage contribution C_{VN} of Victoria Nile to the depletion of the waters of the Lake varies inversely with the daily rate of net fall of Lake level ΔH_{LV}, much like the pressure P of a perfect gas varies with the volume V at a constant temperature T. This variation generates a $C_{VN}-\Delta H_{LV}$ curve, much like the $P-V$ curve for a perfect gas. As the rate of water release R_{VN} is increased, the $C_{VN}-\Delta H_{LV}$ curve shifts to the right (to "higher curves"), just like for increasing temperatures, the $P-V$ curve shifts to the right on the $P-V-T$ surface.

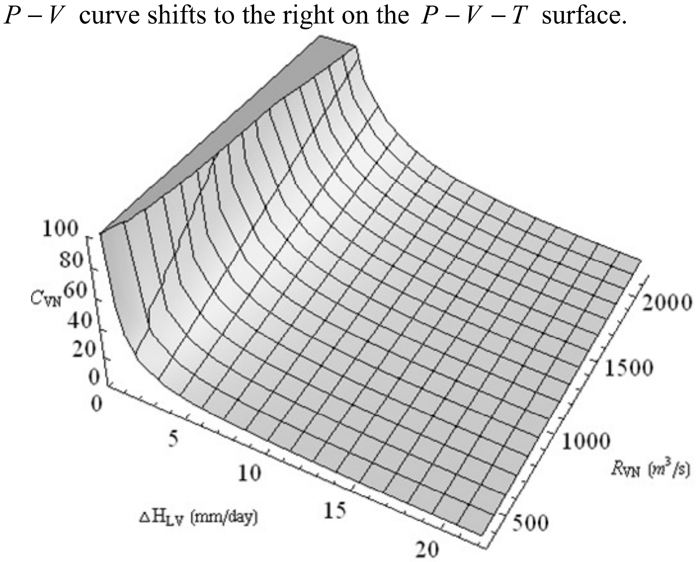

Figure 5: The $C_{VN}-\Delta H_{LV}-R_{VN}$ Surface for Net Lake Storage Drop

Noting that increasing the percentage contribution of Victoria Nile to the depletion of the waters of Lake Victoria C_{VN} means decreasing the percentage contribution of net evaporation C_{VE}, as can easily be inferred from expression (13), it can be seen that for any fixed daily rate of water release R_{VN} through the turbines, this results in a reduction of the daily rate of fall of the Lake level ΔH_{LV} and is therefore good for the hydrological health of the Lake.

As for the dependence of the percentage contribution on the daily rate of water releases, it is observed in Figure 5 that for a fixed daily rate of net fall of Lake Level ΔH_{LV}, the percentage contribution C_{VN} of Victoria Nile to the depletion of the waters of Lake Victoria increases proportionately with increasing daily rate of water release R_{VN} through the turbines. This, of course, implies decreasing net evaporation contribution C_{VE}, as can easily be inferred from expression (12). And yet decreasing net evaporation contribution C_{VE} means decreasing net evaporation ΔE_{LV} and, in turn, requires increased "Total Inflow", as may be discerned from expression (4). It must therefore be concluded that an increase in the percentage contribution of Victoria Nile to the depletion of the waters of the Lake for a fixed daily rate of net fall of Lake Level happens when there is a decrease in net evaporation and, consequently, an increase in the "Total Inflow" into the Lake. Such is clearly a condition that upholds the hydrological health of the Lake and enhances power production.

From the $C_{VN} - \Delta H_{LV} - R_{VN}$ surface again, it can be seen that for a fixed percentage contribution C_{VN} of Victoria Nile to the depletion of Lake Victoria, the daily rate of net fall of Lake Level rises proportionally with rising rates of water releases through the turbines. As sustenance of a constant percentage contribution of Victoria Nile to the depletion of the waters of the Lake for increasing rates of water releases through the turbines comes at a cost of increasing daily rate of net fall of Lake level. This can only be possible if in place is a mechanism of maintaining net evaporation constant which does not augur well for the hydrologic health of the Lake, although it portends well for power production.

Similar considerations and analyses as the foregoing can be undertaken for the percentage contribution of net evaporation to the depletion of the waters of Lake Victoria on the basis of equation (13). The resulting $C_{NE} - \Delta H_{LV} - R_{VN}$ surface is shown in Figure 6.

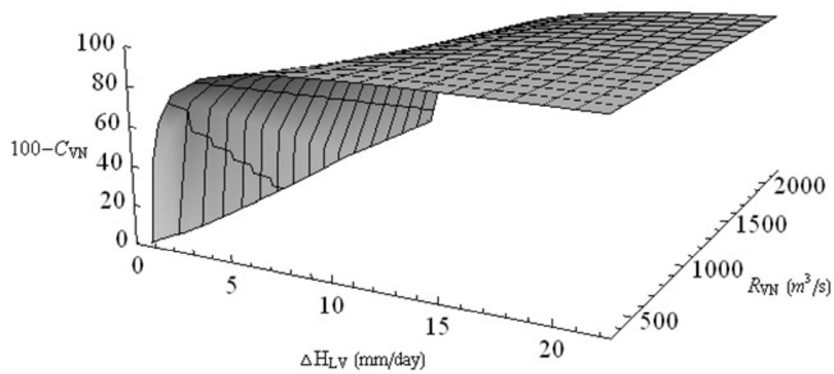

Figure 6: The $C_{NE} - \Delta H_{LV} - R_{VN}$ Surface for Net Lake Storage Drop

At once it is noted from the $C_{NE} - \Delta H_{LV} - R_{VN}$ surface that this time the percentage contribution of net evaporation to the depletion of waters of Lake Victoria C_{VE} rises asymptotically with increasing daily rate of net Lake level fall. As this rise must satisfy relationship (13), it follows that C_{VN} correspondingly decreases asymptotically.

For a fixed daily rate of net Lake level fall ΔH_{LV}, the percentage contribution of net evaporation to the depletion of waters of Lake Victoria C_{VE} decreases with increasing daily rates of water releases through the turbines, as is easily discerned from expression (13). The percentage contribution of Victoria Nile to the depletion of Lake Victoria C_{VN} of course then correspondingly rises under such circumstances.

Considered jointly, the two percentage contributions are clearly of complementary nature for the closed water basin system that Lake Victoria is. Figure 6 depicts these complementarities in the form of joint $C_{NE} - \Delta H_{LV} - R_{VN}$ and $C_{VN} - \Delta H_{LV} - R_{VN}$ surfaces.

From the foregoing analyses, therefore, it follows that increasing the rate of water releases through the turbines does not necessarily lead to increased percentage contribution of Victoria Nile to the depletion of the waters of Lake Victoria, unless the daily rate of net fall of Lake level remains constant or decreases. In both cases the hydrological the health of the Lake is either upheld or enhanced. In the next section, the efficacy of the so-called "agreed curve" to uphold the hydrological health and performance Lake Victoria is examined.

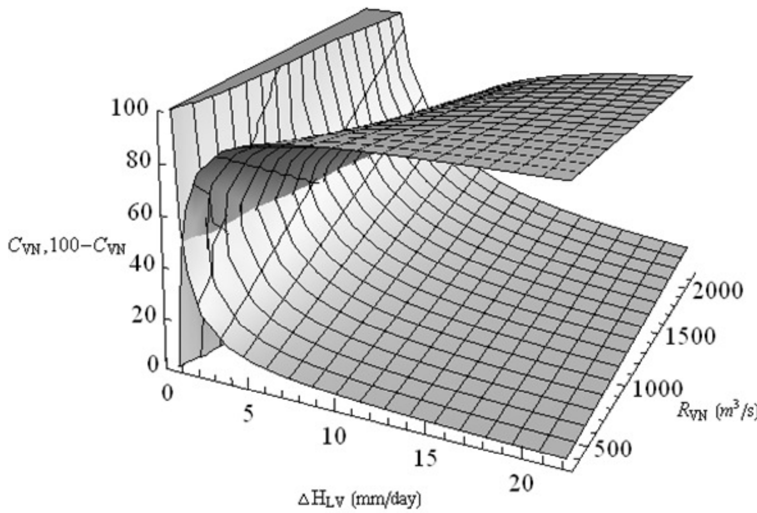

Figure 7: Joint $C_{NE} - \Delta H_{LV} - R_{VN}$ and $C_{NE} - \Delta H_{LV} - R_{VN}$ Surfaces

5. AGREED CURVE EFFICACY TO UPHOLD THE HYDROLOGICAL HEALTH OF LAKE VICTORIA

On its way to provide power for Uganda and support the irrigation schemes in the Sudan and Egypt, Victoria Nile sets off as an out pour from Lake Victoria across a spot called Ripon Falls, three kilometers upstream of the Owen Falls Dam in the Eastern Uganda City of Jinja. And being the only river that flows out of the Lake, the flow regime of Victoria Nile has been and is a subject of utmost and critical importance for both the hydrological health and the performance of the Lake, for it is the only factor in the water balance equation of the Lake that can effectively be controlled or manipulated by human operations.

Until the completion of the construction of Owen Falls Dam and the commissioning of the first units of the initial power station (now Nalubaale) therein in 1954, it was generally perceived in hydrological circles that the terrain at Ripon Falls served as a "natural" regulator of the Lake's outflow, and hence moderator of the fluctuations of its level. This notion presumably followed from the perception that evaporation off the Lake's surface, estimated variously by numerous hydrological studies to account for nearly 80% of its water loss, is a major meteorological factor that may be considered to be generally stable all year round along the Equator.

With the commissioning of the hydropower station, the Lake was considered to have been effectively turned into a huge natural reservoir and the regulation of its outflow thus henceforth passed into the control of human beings. The regulation was, nevertheless, to be executed in accordance with a water discharge policy, popularly known as the "Agreed Curve" (Figure 8), with a view to addressing the concerns and interests of the riparian Countries downstream.

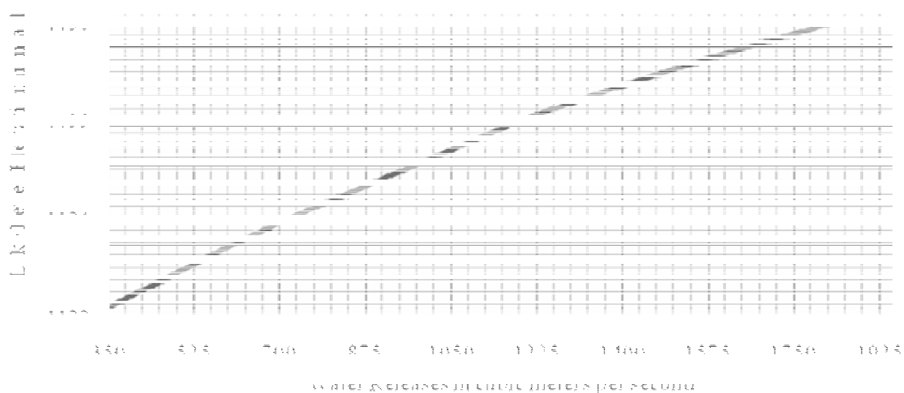

Figure 8: Agreed Curve for Lake Victoria

This agreed curve policy, which depicts the stage-discharge relationship for the Lake on the basis of measurements of the Lake's water level and Victoria Nile's flows predating 1948, (Kite, 1981a; Kite, 1981b; Gibb and Partners, Kennedy and Donkins, 1948; Acres International, 1990; Acres International, 1991; Maj and Izama, 2006), was designed, according to the authors of the policy, to ensure that water releases through the power station and its sluice gates would neither unduly drain the waters of the Lake nor cause undue rise in Lake water levels that would result in flooding.

It specified the volume of water in millions of cubic meters to be released daily through the hydropower station and its sluice gates as a function of the Lake's level obtaining on the particular day. Available records of measurements indicate that water releases in conformity with the Agreed Curve "appear to have sustained" the Lake's natural level up to 1960 (see Figure 9). Thereafter an anomalous behavior set in.

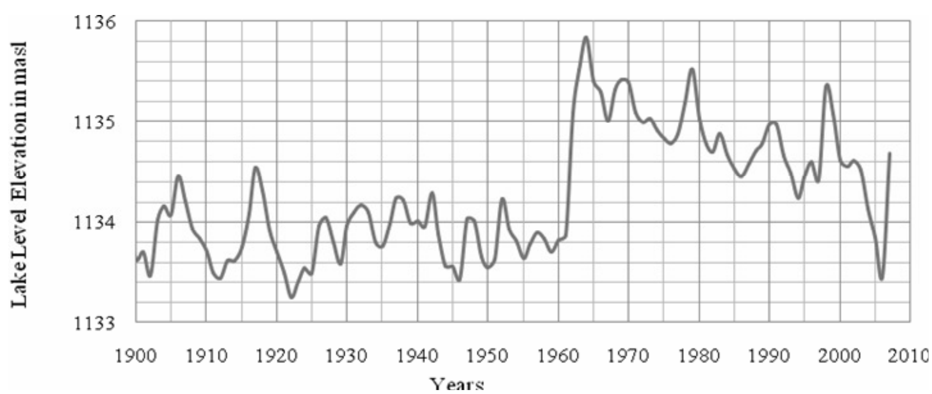

Figure 9: Fluctuations of Lake Victoria Water Levels

Indeed, in spite of continued conformity with the agreed curve after the commissioning of Owen Falls Power Station (OFPS), available records nevertheless show that between 1961 and 1964 the Lake's water level rose dramatically and unexpectedly by almost 2.5 meters for still unexplained reasons. Conjectures about the cause of this sudden rise in the Lake's water levels soon set in, with many attributing the rise and its sustenance to possible under-releases arising from poor adherence to the agreed curve policy. The numerous investigations launched into the actual cause or causes of the rise to date can hardly be said to have yielded any finally conclusive answer, other than to indicate that there was an unusually excessive rainfall over the entire east and central African region during the period. But what caused this unusually excessive rainfall to date remains unclear – a matter that meteorologists perhaps still have to address (Acres International, 1990; Acres International, 1991).

Recently, with yet another anomalous behaviour in the Lake's water levels exhibited between 2001 and the end of 2006 in the form of an estimated sharp decline of 1.1 meters below the 10-year average level of 1134.7 meters above sea level referenced to Mombasa (**http://www.fas.usda.gov/pecad/highlights/2005/09/uganda_26sep2005/**), once more there re-emerged a flurry of accusations of non-compliance with the agreed curve against Uganda (Adam, 2006). Of particular note and interest in this paper is an extremely incriminating report, generated on behalf of the International Rivers Network and authored by one Daniel Kull, based in Nairobi, Kenya, initially claiming to be a United Nations' Staff and then subsequently an "independent hydrologic engineer", and released on 9th February 2006. In the report, purportedly based on some hydrological modeling, Kull (2006a, 2006b) emphatically asserted that:

1. The Owen Falls Power Station Project, undertaken to provide a stop-gap bridging solution to address Uganda's power deficit anticipated then, had instead created a second "dam" in parallel (rather than in series) to an existing one at the site and that this is what exacerbated the discharge intensity of water from Lake Victoria, beyond the "natural" or "agreed curve" levels, through over-abstraction,
2. The design of the Owen Falls Power Station Extension Project used erroneous hydrological data and that this led to an over-dimensioned power station and hence to over-abstraction of water from the Lake,
3. The operations of the Owen Falls Power Station complex were 55% responsible for the observed drop of the Lake's level and the long-running drought experienced in the region contributed only 45%.
4. The obtaining hydrology of Victoria Nile, the observed past 100-year data and non-adherence to the "agreed curve" could hardly support the construction of the next power station at Bujagali, some 8 kilometers downstream of Owen Falls Power Station.

In what follows, the author focuses on the third assertion as part of the overall process of determination of the contribution of Victoria Nile to the depletion of the waters of Lake Victoria in times of declining water levels. In what follows, the contribution of noncompliance with the agreed curve to the declining Lake water levels is established and thereafter the efficacy of the agreed curve to actually uphold the hydrological health of Lake Victoria is examined.

Referring to the water balance schematic (Figure 4), it is noted that the daily Victoria Nile flow, Q_{VN}, may generically be split into two components, namely: the flow according to the agreed curve, Q_{VNAC}, and the flow as a result of over-abstractions, Q_{VNOA} such that

$$Q_{VN} = Q_{VNAC} + Q_{VNOA} \tag{17}$$

Further, by letting R_{VNAC} and R_{VNOA}, respectively, denote the mean daily rates of water discharge through the turbines in accordance with and in noncompliance of the agreed curve, the daily Victoria Nile flow can be recast as:

$$Q_{VN} = 86400 R_{VNAC} + 86400 R_{VNOA} \tag{18}$$

With this statement, the overall percentage contribution of the Victoria Nile to the falling water levels of Lake Victoria, as stated in equation (7), can be re-expressed alternatively as

$$C_{VN} = 8640000\left(R_{VNAC}/\Delta S_{LV}\right) + 8640000\left(R_{VNOA}/\Delta S_{LV}\right) \tag{19}$$

By setting

$$C_{VNAC} = 8640000\left(R_{VNAC}/\Delta S_{LV}\right) \text{ and } C_{VNOA} = 8640000\left(R_{VNOA}/\Delta S_{LV}\right) \quad (20)$$

the percentage contribution of Victoria Nile can then be expressed as

$$C_{VN} = C_{VNAC} + C_{VNOA}, \quad (21)$$

with C_{VNAC} measuring the percentage contribution due to compliance with the agreed curve and C_{VNOA} measuring the percentage contribution arising out of noncompliance with the agreed curve. Finally, upon substituting expression (9) in equations (20), it is found that

$$C_{VNAC} = \frac{27}{215}\frac{R_{VNAC}}{\Delta H_{LV}} \text{ and } C_{VNOA} = \frac{27}{215}\frac{R_{VNOA}}{\Delta H_{LV}} \quad (22)$$

are the respective percentage contributions to the declining Lake water levels due to compliance and noncompliance. With these equations, it can then be tested whether or not the assertion in the Daniel Kull Report (2006a) that over-abstraction was to the tune of 55% responsible for the sharp fall in water levels was valid.

For this purpose the data for December 2005 is used and is depicted in Table 1, which was probably the worst month in terms of over-abstraction in the era of operations of Owen Falls Power Station by Eskom Uganda Limited. These data are from the Company's weekly hydraulic reports submitted mandatorily to Uganda's Directorate of Water Development, the Country's lead water agency.

It is, first of all, instructive to note from the outset that in Table 1, there were days, such as the 5th and the 11th December, when the Lake water level declined by as much as 20 millimeters per day. For a Lake surface area of 68,800 square kilometers, this meant the disappearance of 1,376 million cubic meters, and yet the volume of water that was discharged through the power station at the rate of 973 cubic meters per second, inclusive of over-abstraction, was only about 84 million cubic meters and constituted roughly 6%. Likewise, on 20th December when the Lake level declined by 10 millimeters and water was released at the rate of 1168 cubic meters per second, with an over-abstraction of 56%, the portion of that water lost from the Lake that passed through the power station was only about 101 million cubic meters, or roughly 15%. This really should have immediately raised everyone's eyebrows that something else, very strange, other than Victoria Nile flow through the power stations, or specifically over-abstraction for that matter, was surely the culprit here.

Scanning through the last column of Table 1 then, it can be seen that the days from 12th to 24th and from 27th to 31st of December were undoubtedly times of excessive over-abstractions, constituting on some days as much as 56% of the Owen Falls Power Station discharge. This percentage is indeed very close to that quoted by Daniel Kull. The mean discharge rates on those days were around 1150 cubic meters, again not very far from what he quotes in his report. But as just noted previously, the volume of discharged through the power stations could not have exceeded 15% of the total volume of water lost from the Lake. So why is there this discrepancy? What is the problem and where does it lie?

The flaw clearly lies in the incorrect prescription of what this 56% measures. Whereas in his analysis, Daniel Kull (2006a) takes this percentage as the proportion by which over-abstraction contributed to the then observed falling water levels, the correct prescription should have been that it was a measure of the component of over-abstraction in the volumes of what water discharged through Owen Falls Power Station on those days.

For correct estimations of the contributions of compliance and with the agreed curve noncompliance to the then declining Lake water levels, equations (22) should have been employed. In this way, considering the discharges of 20th December 2005, the contribution from compliance with the agreed curve should have been

$$C_{VNAC} = \frac{27}{215} \times \frac{509}{\Delta H_{LV}} \approx \frac{64}{\Delta H_{LV}}\% \tag{23}$$

and that due to noncompliance should have been

$$C_{VNOA} = \frac{27}{215} \times \frac{659}{\Delta H_{LV}} \approx \frac{83}{\Delta H_{LV}}\% \tag{24}$$

Since the Lake level fell by 10 millimeters that day, it means that the estimated contribution from compliance should have been 6.4% and that from noncompliance should have been 8.3%. Together these should have given the percentage contribution of Victoria Nile to the declining Lake water level as

$$C_{VN} = 6.4 + 8.3 = 14.7\%$$

In general, with percentage contribution equations (23) and (24), it is then a simple matter to compute the contributions of the agreed curve water releases and over-abstractions through the Owen Falls Power Stations (OFPS) on any day.

Table 1: Owen Falls Power Station (OFPS) Daily Hydraulic Statements for December 2005

Date	Lake Level Elevation (masl)	Agreed curve discharge (cumecs)	Nalubaale Discharge (cumecs)	Kiira Discharge (cumecs)	OFPS discharge (cumecs)	OFPS Over-abstraction (cumecs)	% of agreed curve discharge	% of over-abstraction discharge
1-Dec	10.75	532	402	571	973	441	55	45
2-Dec	10.74	529	408	580	988	459	54	46
3-Dec	10.75	532	358	602	960	428	55	45
4-Dec	10.75	532	404	546	950	418	56	44
5-Dec	10.76	536	401	530	931	395	58	42
6-Dec	10.74	529	395	578	973	443	54	46
7-Dec	10.74	529	414	574	988	458	54	46
8-Dec	10.74	529	402	554	956	427	55	45
9-Dec	10.74	529	405	561	967	437	55	45
10-Dec	10.73	525	401	500	902	377	58	42
11-Dec	10.74	529	595	430	1025	496	52	48
12-Dec	10.72	521	588	484	1072	551	49	51
13-Dec	10.72	521	588	516	1104	583	47	53
14-Dec	10.71	517	583	548	1131	614	46	54
15-Dec	10.71	517	606	561	1167	650	44	56
16-Dec	10.70	513	591	556	1147	634	45	55
17-Dec	10.70	513	594	482	1076	563	48	52
18-Dec	10.69	509	595	509	1104	595	46	54
19-Dec	10.69	509	567	539	1106	597	46	54
20-Dec	10.69	509	596	572	1168	659	44	56
21-Dec	10.68	505	605	543	1148	643	44	56
22-Dec	10.68	505	594	553	1147	642	44	56
23-Dec	10.67	501	412	692	1104	603	45	55
24-Dec	10.66	497	436	587	1023	526	49	51
25-Dec	10.66	497	409	522	931	434	53	47
26-Dec	10.66	497	402	525	927	430	54	46
27-Dec	10.66	497	454	580	1035	538	48	52
28-Dec	10.66	497	460	624	1083	586	46	54
29-Dec	10.65	493	452	656	1108	615	45	55
30-Dec	10.64	490	409	640	1050	560	47	53
31-Dec	10.64	490	435	631	1067	577	46	54

Alternatively, graphs can be drawn of percentage contributions versus daily rates of net fall of Lake levels for prescribed rates of water releases through the power station, as in Figure 10, and then read off the percentage contributions.

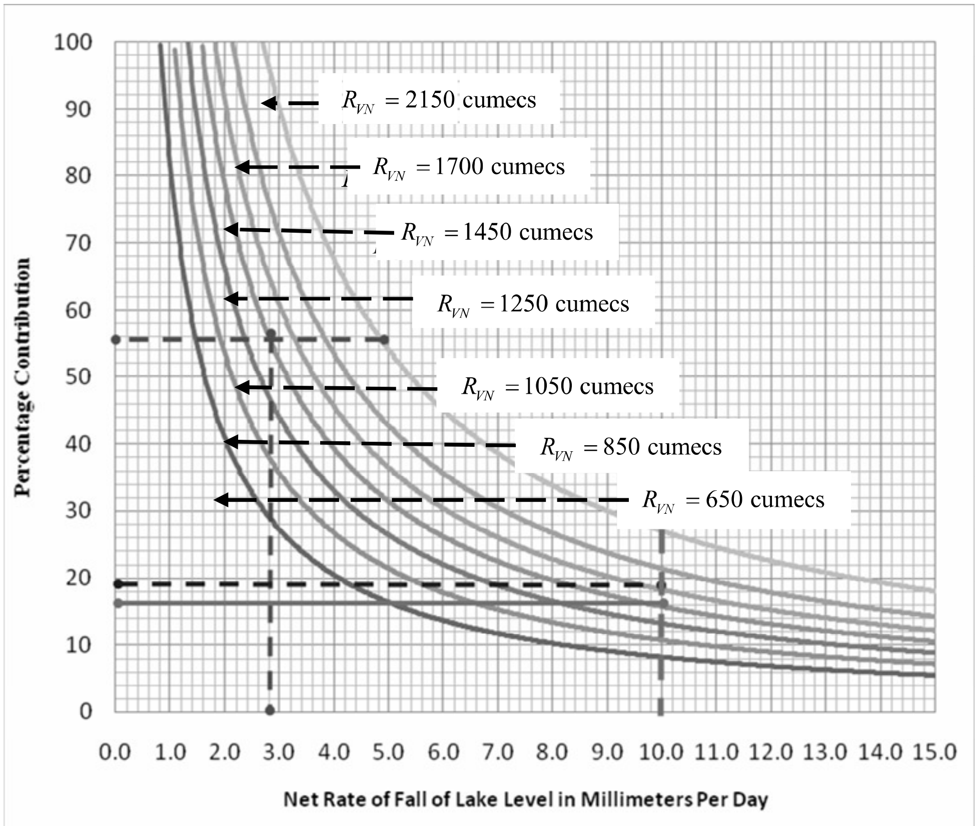

Figure 10: Percentage Contributions of Victoria Nile to Falling Water Levels of Lake Victoria

6. CONCLUSION

In this paper an equation is derived that links the percentage contribution of the only river outflow of Lake Victoria, the Victoria Nile, in the depletion of the waters of the Lake to the daily rate of net drop in the Lake's water level and the daily rate of water releases through the turbines at Owen Falls Power Station at Jinja, Uganda. It has been shown that the equation is analogous with the equation of state of the perfect gas of thermodynamics. This has allowed the techniques for analyses of the dynamics of perfect gases to be applied to the dynamics of Lake Victoria's net decrease of storage in times of falling water levels.

The derived equation has facilitated quantification of the percentage contributions of human operations and meteorological/hydrological factors to the falling water levels of Lake Victoria, observed between 2003 and the end of 2006. The results show that the worldwide media claim that human operations at the hydropower station complex was 55% responsible for the observed depletion of the waters of the Lake at the time was false and was a product of a flawed prescription of what that percentage measured. The true percentage contribution of human operations is found not to have exceeded 15% for the maximum water release rate at that time of 1250 cubic meters per second. The meteorological and hydrological factors were found to contribute in the region of 80 to 85%.

The equation has also helped to ascertain that, contrary to what common sense might want to make us believe, increasing the percentage contribution of Victoria Nile to the depletion of the waters of Lake Victoria during periods of falling Lake levels actually promotes sustenance of the hydrological health of the Lake, for it leads to decreases in daily rate of net fall of Lake level.

Finally, the equation has facilitated a re-appraisal of the presumed function of the so-called "agreed curve" water release policy in upholding the hydrological health of Lake Victoria. The result reveals that the agreed curve hardly promotes the hydrological health of Lake Victoria, but is useful only in guaranteeing that specified outflows of the Lake are available at specified Lake water level elevations for irrigation requirements of downstream riparian Countries. Adherence to the agreed curve has no impact on the net evaporation, which is mainly influenced by meteorological factors (rainfall and evaporation) that are way beyond the control of human operations. The only effective contribution to the sustenance of the hydrological health of Lake Victoria and others can only be through undertaking those human activities that will lead to more rainfall and less evaporation.

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