Rising Water Levels at Lake Enriquillo, Dominican Republic:

Advice on Potential Causes and Pathways Forward

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Purpose

This short report summarizes the results of a five-day mission (September 26-30, 2011) by a four-person, multidisciplinary, bilingual team to the Dominican Republic (Santo Domingo and Lake Enriquillo). The mission was undertaken in response to a request from the Instituto Nacional de Recursos Hidráulicos (INDRHI), an agency of the Government of the Dominican Republic charged with wise use and preservation of water resources, to the Institute for Water Resources, U.S. Army Corps of Engineers. A 2011 agreement links the two institutions and their respective UNESCO "category 2" centers, the Centre for the Sustainable Management of Water Resources in the Caribbean Island States (CEHICA) and the International Center for Integrated Water Resources Management (ICIWaRM).

The purpose of mission was:

- To provide feedback to INDRHI with respect to the many hypotheses proposed to account for the rising surface elevation of Lake Enriquillo in the southwestern part of the country, and
- To provide general advice concerning future pathways to prevent, adapt to, or mitigate this rise.

Basis for Conclusions and Recommendations

The team was organized and deployed within about one month's time. This limited the time available to research the problems of the region in advance. Likewise, it was asked to provide its results verbally at the end of the mission and in written format soon afterwards. This report should not be considered an original research effort, and has not been extensively peer reviewed. Its conclusions and recommendations are those of the authors and do not represent official policy of the U.S. government. With this understanding and for readability, references have also been minimized in this report.

The primary foundations for the conclusions and recommendations in this report were:

- Existing reports written by INDRHI or available through its professional staff (e.g. INDRHI, 2011);
- An extensive one-day briefing and orientation by INDRHI on all aspects of the problems and hydrometeorological information relevant to the rise of Lake Enriquillo, especially between 2006 and 2011;
- Direct observations during a very effective two-day field expedition to the lake and surrounding area, organized by INDRHI;
- Raw data kindly made available to us by INDRHI staff;
- Extensive discussions with INDRHI scientific, engineering and field staff;
- Other publically available information; and
- Best professional judgment.

Some limited external research was done by Dr. Enfield prior to the mission, in particular regarding the historical time series of precipitation over the Dominican Republic and its relationship to tropical cyclone activity and a leading climatic index called the Atlantic Multidecadal Oscillation.

Geography and Geology

Lake Enriquillo is located in the southwestern Dominican Republic, along the border with Haiti (Figure 1). It is situated in a closed basin, below sea level, with a salinity that historically has been on the order of two to three times that of seawater. The valley in which it is located was an ancient marine channel; subsequently, deltaic sediments from the Yaque del Sur River to the east and a series of smaller rivers to the west have isolated the lake from Neiba Bay and Lake Azuei, respectively. The lake covers an area varying from 200-300 km², and has three islands, the largest of which is Isla Cabritos. It receives rainfall runoff from both the Neiba Mountains to the north and the Bahoruco Mountains to the south (both ranges composed primarily of limestones) as well as rain that falls directly on the lake.

The Enriquillo-Plantain Garden fault zone extends along the valley and movement along a segment of this fault in Haiti was responsible for the devastating 2010 earthquake there. The Haiti earthquake occurred after most of the lake rise that concerns the USACE mission. The last major event along this fault in south-central Dominican Republic may have been in 1751 (Mann et al., 2008).

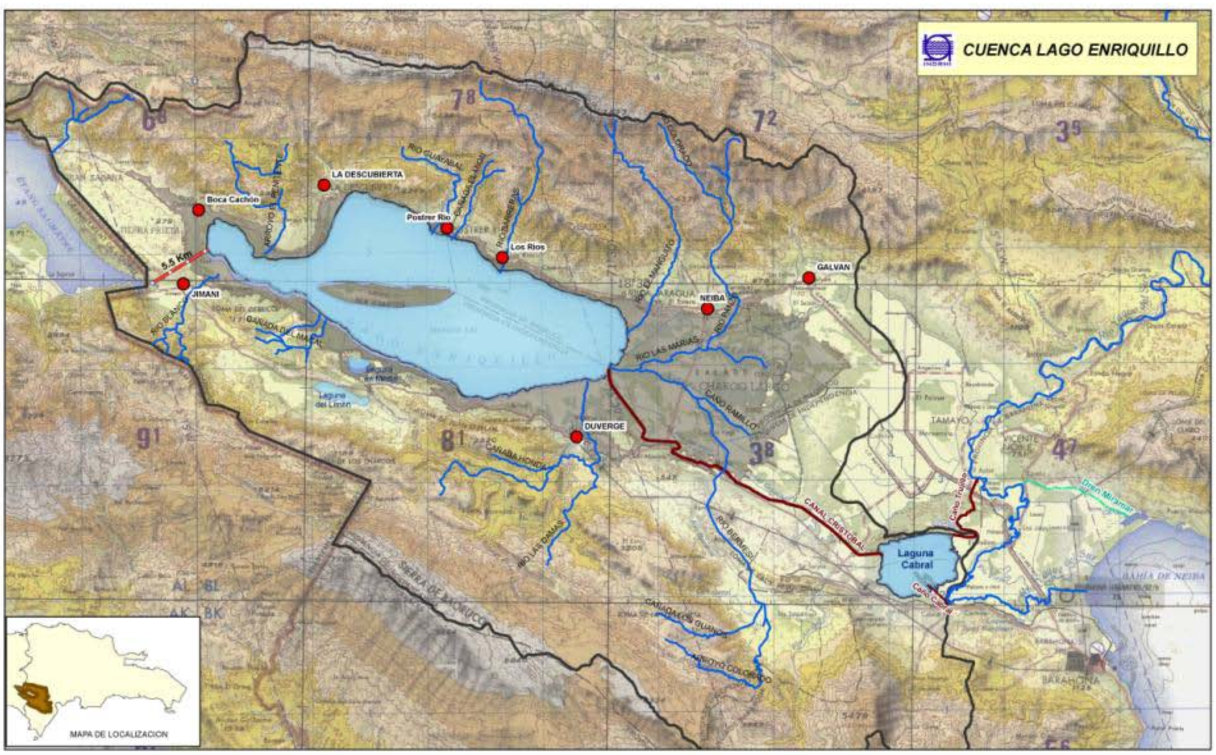

Figure 1. Lake Enriquillo Basin. Note Lake Azuei in Haiti to the west, the Neiba and Bahoruco Mountains to the north and south respectively, alluvium from the Yaque del Sur River isolating the lake from Neiba Bay to the east, Isla Cabritos in the western part of the lake, and local springs and streams supplying fresh water to the lake from all sides. Source: INDRHI.

The road passing through the town of Jimaní, just west of the lake, connects the Dominican Republic to Haiti, which is an important trading partner for the country. Thus, lake-level rise has implications beyond local transportation, agriculture, housing and water-supply damage to regional trade and commerce. There are also effects on ecology and tourism; the lake and its islands are on the Ramsar List of Wetlands of international Importance for its biodiversity, supporting three threatened species of reptiles and five of birds. It is also a UNESCO Biosphere Reserve.

Climatic History

The natural climate variability of Hispaniola includes the seasonal-to-interannual variations due to El Niño — La Niña (ENSO), and multidecadal climate shifts due to slow variations in North Atlantic sea surface temperatures (SST) and the correlated fluctuations in tropical cyclone activity. The multidecadal variability is termed the AMO — the Atlantic Multidecadal Oscillation (Enfield et al. 2001). This is a documented climate phenomenon known to affect Caribbean rainfall in general and rainfall associated with changes in tropical cyclone (TC) frequency, in particular (Goldenberg et al. 2001). Prior to 1970 and after 1995 the AMO was in warm phases with increased TC activity and increased likelihood of TC hits on or near Hispaniola. From 1970 to about 1995, the North Atlantic was cooler and TC activity was relatively low.

Starting in 2004 Atlantic TC activity increased sharply and a series of TCs affected Hispaniola from 2005 to 2009. Figure 2 shows how the tropical North Atlantic SST was above average and Hispaniola rainfall rose steadily after 1995 to a maximum in 2005-2008. More significant perhaps is the rather remarkable increase in the number of days — starting in 2003 — in which the center of tropical cyclones passed within 300 km of Hispaniola, potentially producing copious rainfall. This phenomenon figures prominently in our analysis below.

Hydrology and Water Budget

Throughout geologic time and apparently historically, the lake appears to have risen and fallen with climatic cycles and local precipitation. However, there is very little reliable information on lake levels during the 20th century. Such information as exists indicates that the lake was much larger in the 1890s and also at much higher levels, approximately at present mean sea level, possibly because that decade had a great deal of tropical cyclone activity and human impacts such as water management and extensive agriculture were virtually non-existent. However, we cannot discard the possibility that in the late 19th century the lake may have received an important contribution from the Yaque del Sur River, as appears to have occurred after 2007. Following that period the lake levels went down to values of generally slightly more than 40 m below sea level. We assume that variations occurred due to natural climate variability, although not to an extent that would have had the kind of impact we have seen in the last 5-6 years.

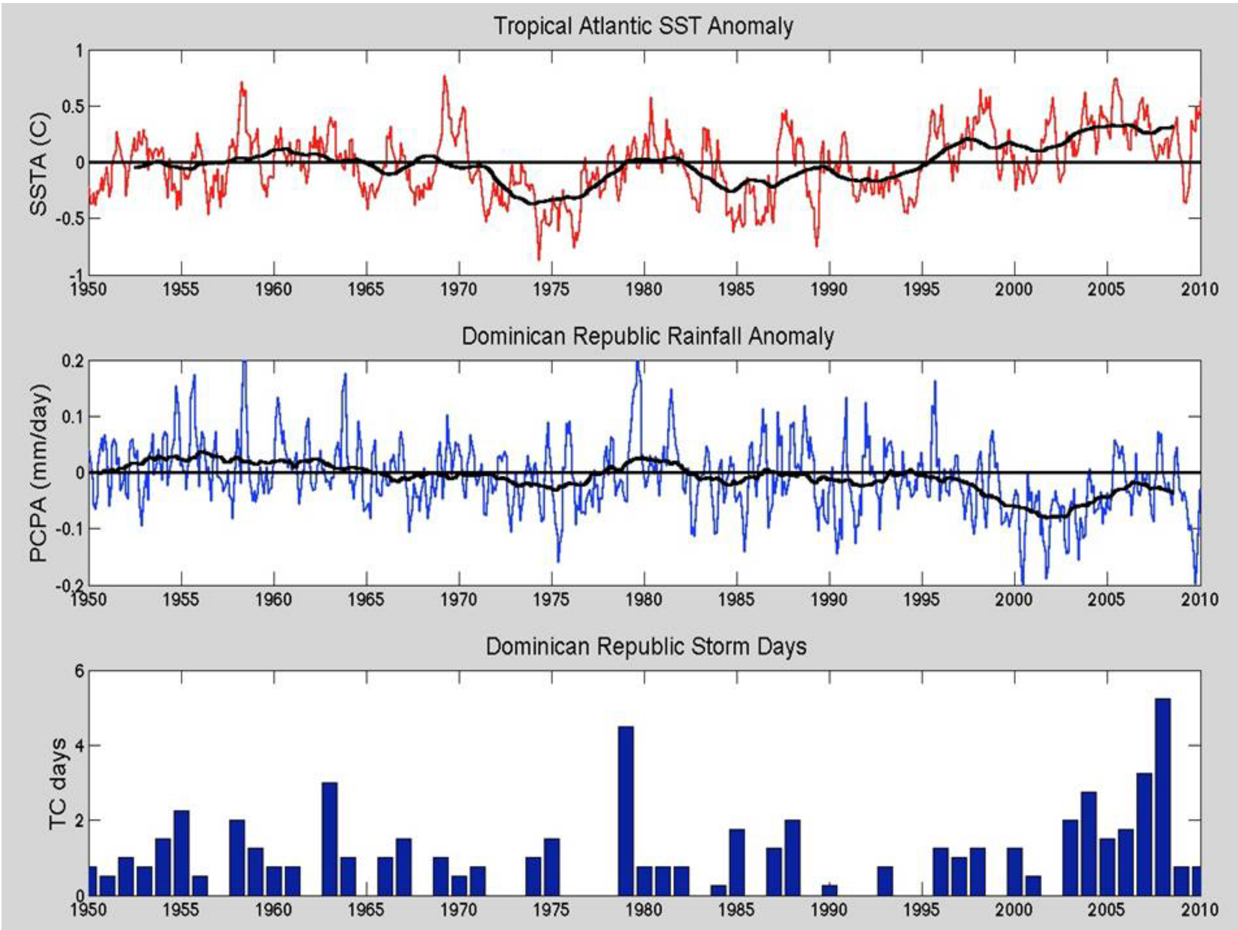

Figure 2. From top to bottom: (1) monthly averaged SST over the tropical North Atlantic, (2) reanalyzed precipitation at a grid point over Hispaniola, and (3) the yearly totals of storm days estimated by the times when tropical cyclones passed within 300 km of the island. These are times when significant amounts of rainfall could have affected the Enriquillo and Yaque del Sur watersheds. Data sources: Top: NOAA Extended Reconstructed Sea Surface Temperature v3b; Middle: NOAA's Precipitation Reconstruction Dataset; Bottom: NOAA HURDAT 'best track' data set.

In the 1950s, water control structures (dams, canals) were built, agriculture developed rapidly and largely anecdotal evidence suggests that lake levels continued to be fairly stable and low until about 2005. The explanation for this is uncertain, due in no small part to scarcity of data, but it is likely a combination of:

- Upstream and downstream water control structures on the Yaque del Sur River,
- Consumptive water use of the irrigated agriculture that some of these structures fed,
- Somewhat lower than average precipitation, and/or
- A self-regulating balance between inflows and evaporation, where higher inflows lead to a greater surface area for evaporation, in turn leading toward a return to lower lake levels.

However, around 2005-2006, lake levels began rising, and have continued to do so through September 2011. This recent rise is the focus of much of this report.

Evaluation of Lake Level Rise Hypotheses

Given the serious impact of the increasing lake levels, the issue has attracted much attention nationally and even internationally. Climate change, recent storm activity, increased groundwater flow from Lake Azuei (with or without the influence of the 2010 earthquake), increased sedimentation and other factors have been hypothesized. None of these hypotheses, to our knowledge, has been quantitatively examined. In fact, a detailed, quantitative analysis is not possible at present—due in no small part to poor constraints on the changes in lake volume and area over time. In general, this report takes a *semi*-quantitative water balance approach, along with observations, theory, minor original research and best professional judgment, to examining the likely relative contributions of these various hypothesized causes. Each major hypothesis is discussed below, generally in the order of perceived reasonableness.

The Semi-Quantitative Water Balance Approach

The observed increase in lake area during the last decade is from about 200 km^2 to 300 km^2, a 50% increase. INDRHI estimates that the lake has risen by about 6 m since the benchmark year 2000, although the lake levels did not significantly increase until after 2005. Simple multiplication (6 m x ~250 km^2) puts the corresponding increase in lake volume at about 1.5×10^9 m^3, depending on bathymetry.

As noted earlier, natural historical fluctuations in precipitation and other parameters in the Lake Enriquillo basin generally have not produced such lake level variations. To see why this might be true, we first assume that evaporation from the lake remains approximately constant at about 2000 mm per year. In reality, it does vary somewhat from year to year due to small variations of temperature and wind. Salinity changes probably would only have a minor effect on evaporation, perhaps a few percent (estimated from Panin and Brezgunov, 2007). Thus, the historically stable lake level and area would have been maintained by an average combined precipitation and watershed runoff (ground and surface) of the same amount. The mean and standard deviation of annual precipitation amounts for seven rainfall stations around the lake (data from ONAMET) have been computed as 913 mm and 251 mm, respectively.

We make the first-order assumption that inflow contributions to the lake have about the same variation (~25%) as the precipitation. Thus, the typical year-to-year variation in the water input to the lake is on the order of 25% of the mean annual evaporation of 2000 mm (i.e. 500 mm), since evaporation equals lake inflows when lake levels are stable. The corresponding variation in lake volume would accordingly be about 0.5 m x 2×10^8 m^2 (0.5 m * area of the lake) or simply, a volume of 10^8 m^3. Furthermore, increases in the evaporative surface of the lake due to increased volume create a negative feedback where increased evaporation compensates increases in lake inflows. Using the same ratios for change of area/change in volume as above, a volume increase of $10^8 m^3$ would increase the lake surface by roughly 8×10^6 m^2 (800 Ha). Thus, these new 800 Ha of lake would annually evaporate an additional 2m x

8000000 m^2 (i.e. 1.6 x 10^7 m^3), in a negative feedback that over several years would tend to naturally balance increased inflows with increased evaporative area. In a similar manner, in dry periods with below average rainfall the lake may slightly reduce its size, leading to lower evaporative losses (due to reduced area), thus balancing reduced inflows.

Overall, this line of reasoning suggests that the typical natural variation in lake volume explainable historically from meteorological records is about an order of magnitude lower than the variation observed since 2005. That is the equivalent of year-to-year variations in lake level of the order of one-half meter, which explains why lake levels have remained stable until recently and have not had a measurable historical impact on the population and farming around the lake. We therefore conclude that some other explanation is probably required to understand the extraordinary recent increase in lake levels and areas.

We will now address individually a number of hypothesized explanations for the extraordinary recent history of Lake Enriquillo. These hypotheses have been summarized in INDRHI (2011). It is important to note that quantitative data are insufficient to definitively evaluate most of these hypotheses; hence, for the most part we can do little more than discuss the likelihood that each, in turn, is reasonable.

Increased precipitation combined with structural failure

Figure 3 shows how the lake's surface area (estimated from LandSat imagery) started to increase in 2005 when Hurricane Rita and tropical storm (TS) Alpha passed close to Hispaniola. In August 2006, there were two back-to-back storms, Chris and Ernesto. In 2007 two storms — Noel and Olga — passed directly over the island, in late October and early December, respectively. During this period, rising flood stages of the Yaque del Sur River caused the Trujillo dike to fail. Almost all of the water from the Yaque del Sur, which normally drained southeastward into Neiba Bay (Figure 1), began to flow westward into the Enriquillo watershed, partially through the Trujillo Canal and partially uncontrolled across the eastern Enriquillo flood plain. In 2008, TS Fay caused more flooding through the broken water control infrastructure. The lake stabilized from then to 2011. From May through July of 2011, however, multiples of normal rainfall levels fell on both watersheds and by September 2011 the lake had risen another half meter. The Trujillo Canal structure had been rebuilt in April 2011, but considerable volumes of water were observed by the authors leaking through the structure, toward the Cabral Lagoon. The Yaque del Sur River was also reported to be overflowing the road on the eastern side of the Cabral Lagoon, and flowing into the lagoon during periods of high flows, the last one of which was less than two weeks prior to the authors' visit.

The correlation of the overall increase in lake level with recent tropical storms and hurricanes suggests a likely causal relationship of the latter on the former. However, the historically subdued response of the lake to earlier (albeit less extreme) fluctuations in number of storm days (established primarily anecdotally given the paucity of historical lake-level data) supports the conclusion that the failure of the Trujillo Canal structure has played an important role in providing the volumes of water on the order of magnitude that may account for the severe rise during the 2000s.

This hypothesis can be supported semi-quantitatively for the recent period of July 20 to September 28, for there is a well documented lake level rise of 50 cm, or 0.5 m. Given INDRHI's estimate of lake area for that time period of about 320 km^2, or 3.2×10^8 m^2, this corresponds to a volume increase of about 1.6×10^8 m^3. During the same time, there has been continuous flow through a structure on the Cristobal Canal, carrying water originating from the Yaque del Sur River via the Trujillo Canal and the Cabral Lagoon, to Lake Enriquillo. Field estimates of this flow by the study team and INDRHI personnel were on the order of 15 to 20 m^3/s. 15-20 m^3/s x 86,400 s/day x ~70 days is about $0.9\text{-}1.2 \times 10^8$ m^3 during the same time period. INDRHI field personnel suggested that for some of that time period, there were additional, uncontrolled flows around the structure, so the total volume may have been higher.

We conclude that for the best documented period of time for lake level rise, flows into the lake originating from the Yaque del Sur watershed were on the same order of magnitude as the lake volume increase calculated for this period. This suggests that while some of the other potential inputs discussed below may have contributed in some way to the lake level change, the majority of the rise can be accounted for by inputs from the Yaque del Sur watershed.

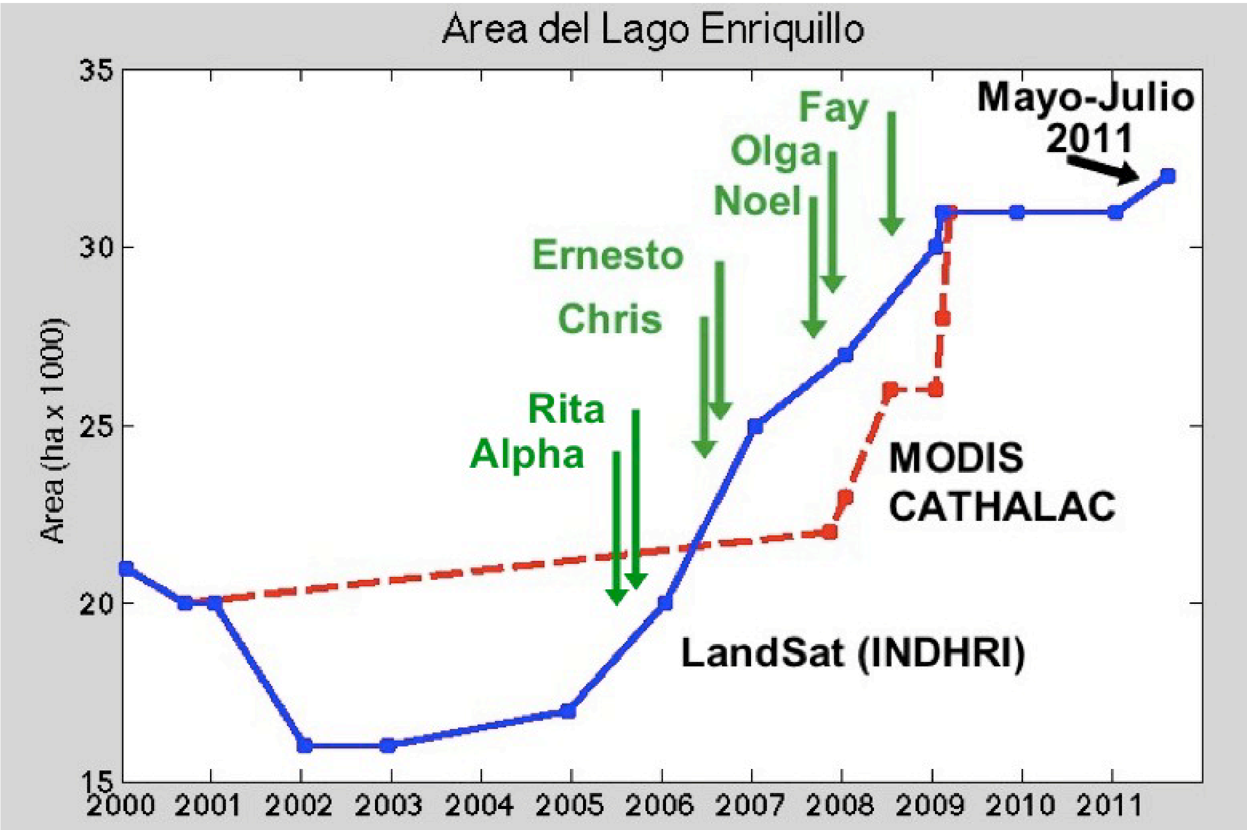

Figure 3. Blue line: surface area of Lake Enriquillo, estimated from LandSat imagery by INDRHI. Red line: area estimates made from MODIS imagery by CATHALAC. Green arrows indicate months in which the named storms passed within 300 km of Hispaniola. The historical average area is thought to be near the 2001 value (20,000 hectares).

Potential role of anthropogenically-induced climate change in recent precipitation increases

The increased Hispaniola rainfall in recent years might be viewed as either the result of natural climatic variation, or perhaps as CO_2-induced climate change, based on the expectation that a warmer atmosphere will hold more water vapor with the potential for greater rainfall amounts. In the former case, there is no reason to expect that the current trend is anything but cyclical; in the latter, it would be viewed as the beginning of a permanent upward trend.

Climate change impacts are currently very difficult to detect, even with very sophisticated statistical tools, because they are very difficult to separate from the natural variability of meteorological processes. In other words, it is a problem of very low signal-to-noise ratio, especially in the Caribbean region. Even if it is certainly true that climate models predict an increase in precipitation on a planetary scale, the projected geographical distribution of the changes in precipitation is far from uniform. Projections based on global climate model simulations done for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007) consistently show that the Intra-Americas Sea (Caribbean + Gulf of Mexico) will be receiving either similar amounts of precipitation or considerably *less* precipitation by the end of the 21st century, depending on the IPCC scenario considered (Figure 4).

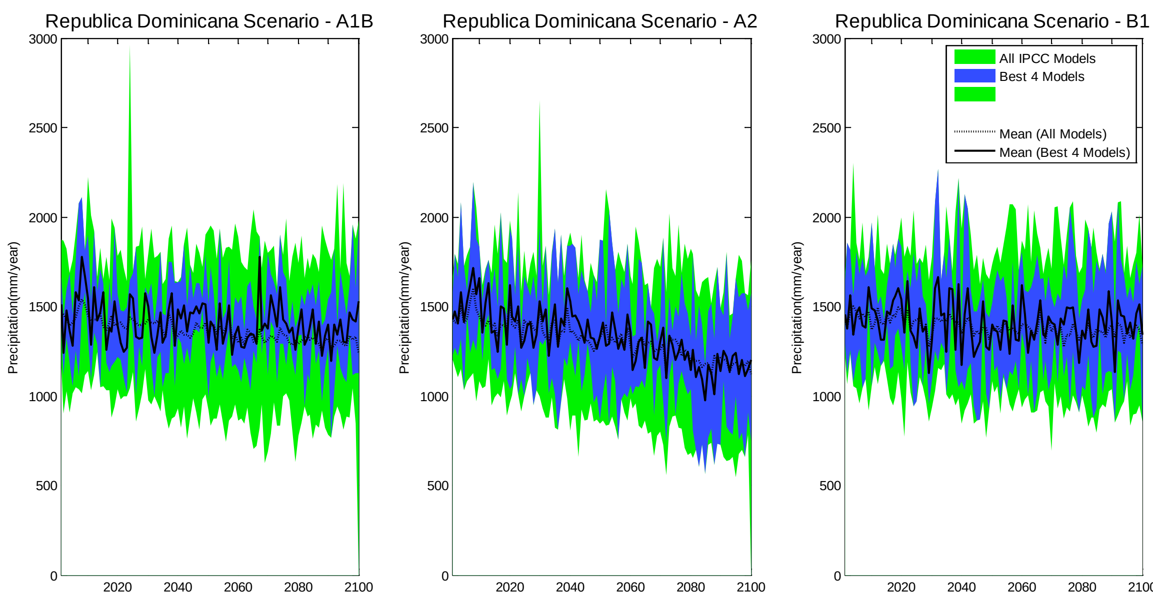

Figure 4. Precipitation projections for the Dominican Republic corresponding to the three main IPCC emission scenarios - A1B, A2, B1 - which represent different rates and timing of future global CO_2 emissions (IPCC 2007). Data is from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. Using a tool developed at the Department of Hydrology of The University of Arizona, a reliability ensemble average (REA) was performed to determine which models best simulate the historical observations (methodology of Georgi and Mearns, 2002, as modified by Dominguez et al., 2009). All model results were bias-corrected as per Wood et al. (2002). The area in green shows the spread of projections from all models (mean is dotted line), while the area in blue shows the spread of the projections from only the four best models (whose mean is the solid line), based on the REA analysis over the island of La Hispaniola.

This is because (1) the increased precipitation does not occur uniformly, rather that there is more (wetter) at middle-to-high latitudes but less (drier) in the tropics and subtropics generally; and (2) the models also project a decrease in the total number of tropical cyclones in the Atlantic basin, which produce significant amounts of rain in the Caribbean.

In the case of Hispaniola, neither the reanalyzed gridded rainfall data (Figure 2) nor the station data afforded to us by ONAMET from stations around the lake shows a long-term upward trend in Hispaniola rainfall in the 20th century. We only find shorter term variations undoubtedly due to natural causes, which, as we have just shown, cannot explain the observed increase in lake level. Even the recent period of storm activity (2005-2009) has not exceeded that of periods before 1970 when the North Atlantic (AMO) was also warm, and the rainfall, though greater than normal recently, has not exceeded historical norms. Hence, based both on IPCC projections and on observed data records we see little evidence that climate change has been a major driver of past lake level increases. Regardless, it will be several decades at least before it will be possible to distinguish any climate change rainfall impact from the stronger natural variability at the shorter time scales.

Increased flow from local streams and springs

If precipitation has remained within its historical range of natural variability, it is reasonable to assume that flows from local streams and springs have also remained within their historical values. The recent warm phase of the Atlantic Multidecadal Oscillation and the associated wetter climate for the Caribbean region discussed above for the period 2006-2011 may have led to potential above-average spring and stream flows. In the case of the springs, variations in flow can show a time lag inherent to groundwater storage and travel time. However, the limited data available does not show a consistent or significant change in spring flows around the lake.

Spring flow measurements have been done manually, thus data records are understandably discontinuous, in the form of one measurement day per month, with the bulk of the measurements in the late 80's and early 90's with some very isolated measures in later years. Comparisons with recent flow measurements in September 2011 are sparse and inconclusive. The last flow measurement (on September 14, 2011) at *Rio Las Damas* (southeast of the lake) was $2.4 m^3/s$ while the average of previous Septembers in the historic record, corresponding to eight different years, is $0.6 m^3/s$ (almost a 400% increase). The last flow measurement (on September 14, 2011) at *Cachon Pocilga* (northeast of the lake) was $0.1 m^3/s$ while the average of two previous September flows is $0.06 m^3/s$ (a 170% increase). On the other hand, recent measurements (September 14, 2011) at *Canal las Marias* (east of the lake), *Cachon La Zurza* (southeast) and *Cachon Caoba* (northwest) show $1.4 m^3/s$, $0.07 m^3/s$ and $0.03 m^3/s$ indicating decreases to 60%, 25% and 15% of the averaged historic September measurements.

It can be observed that spring and stream flow measurements in geographically close locations can show diverging trends. Whether this is due to observation points having different contributing areas with different rainfall events over the recent past, or due to different travel times of water through the ground, is unknown.

Given the limitations of single-day measurements to capture the seasonal behavior of springs and stream flows, and the limited data available, more observations are needed in order to better characterize the variability of flow in springs and streams. In any case, existing observations do not seem to be outside their historic range of natural variability and do not provide evidence that such flows would have contributed significantly to the lake level increase.

Subsurface Flow from Lake Azuei

The higher elevation of the brackish Lake Azuei—consistently above sea level whereas Lake Enriquillo has generally been tens of meters below sea level—as well as its lower salinity argues that there is likely to be some finite subsurface flow from the former to the latter. However, a number of lines of evidence suggest that this is unlikely to be a major component of the water budget of Lake Enriquillo, and not a major component of the recent rise in its surface elevation. These lines of evidence include:

1. Flow in shallow aquifers would almost certainly discharge in the topographically lower parts of the Tierra Prieta region, such as Boca Cachon or the lower Rio Blanco basin. We know of no evidence of consistently brackish springs in either area.
2. A limited number of wells sampled in the area show no evidence of mixing with brackish water.
3. Topography in the alluvial fan/delta that separate the two lakes is considerable, and qualitatively evaluated is likely to have a hydraulic divide in the subsurface between the two.
4. Significant flow from Lake Azuei to Lake Enriquillo via deep aquifers is even more unlikely. Sediments underlying Lake Enriquillo are generally much finer grained than the fans and deltas ringing it; this generally has the effect of focusing groundwater flow upward into the coarser sediments along the margins of a water body. Line of evidence #1 above would therefore apply to this flow as well. Also, the high salinity of Lake Enriquillo would force the less saline (i.e. less dense) groundwater from Lake Azuei (if any) to surface in springs around Lake Enriquillo.
5. Since 2005, indications are that the rise in surface elevation of Lake Enriquillo has been greater than that of Lake Azuei. This would have had the effect of decreasing the hydraulic gradient, or driving force, and, therefore, groundwater flow toward Lake Enriquillo from Lake Azuei.

Overall, this conclusion could be tested by careful observations of the salinity and discharge of springs and seeps along the western edge of Lake Enriquillo, and better mapping of the water table of the region that separates the two lakes to confirm whether there is a hydraulic divide in the shallow subsurface.

Increased Flow from Lake Azuei due to Recent Seismicity

Some data suggest that the increase of permeability due to fault zones is much larger in limestones (the dominant rock type in the Lake Enriquillo area) than in sandstone-shale sequences (e.g., Reyer et al., 2011). Given the presence of the Enriquillo-Plantain Garden fault zone along the valley, and its association with the 2010 Haiti earthquake, it has been suggested that movement along the fault in 2010 may have greatly increased permeability of the sedimentary units it passes through in the Enriquillo region.

According to the US Geological Survey, the estimated Modified Mercalli Intensity for the area around Lake Enriquillo was about 4, or "light" perceived shaking (http://earthquake.usgs.gov/earthquakes/eqarchives/poster/2010/20100112.pdf). This suggests that 2010 changes in the directional permeability of the rock units west of the lake would have been minor. In addition, the steepest increases in the lake level occurred from 2005-2009—preceeding the earthquake. Thus, it seems unlikely that earthquake-related phenomena have been major contributors to the recent lake-level rise. Longer-term, fault-related high-permeability zones are certainly possible, but would already be accounted for in the discussion in earlier sections of this report.

We note, however, that the 2010 earthquake post-dates 90% of the recent lake rise and thus cannot explain the observed changes in any case. We have no information about the seismicity immediately before or after 2005, but it seems likely that it could not have exceeded the Mercalli #4 intensity estimated for the Enriquillo region during the Haiti earthquake, and probably was less than that. Hence, we believe that increased flow from Lake Azuei due to recent seismic activity is not likely to be a significant contributor to lake level rise in Lake Enriquillo.

Increased Volume of Sedimentation from the Yaque del Sur River and other Streams

Despite rapid progress in landscape dynamics in recent decades, geomorphologists are unable to predict sediment transport rates in streams with better than order-of-magnitude accuracy (Jerolmack, 2011). Average erosion rates are equally difficult to estimate, but are typically in the range of several cm to several 10s of cm per 1000 years over a range of climates and slopes. Limestone removal rates are on the same order of magnitude, and data from Jamaica are about 8-10 cm per 1000 years (Bloom, 2004).

An absolute maximum volume of deposition of sediment in the last 100 years into Lake Enriquillo can be estimated using the above removal rates and assuming that all of the mass removed from the Enriquillo and Yaque del Sur catchments was sediment (not dissolved) and it all was deposited in the lake. Using a combined catchment area of about 8000 km^2 compared to a lake surface area of about 200 km^2 (a 40:1 ratio), 10 cm per 1000 years x 40 = 400 cm per 1000 years or 40 cm per 100 years. This is over an order of magnitude lower than the estimated lake level rise of 6 m in the past decade alone. It thus seems unlikely that sedimentation has played a major role in lake level rise.

Other less quantitative lines of evidence are consistent with this conclusion. For example, no major new delta lobes are visible from the air either east or west of the lake. Second, while Yaque del Sur water definitively has ended up in the lake, INDRHI field personnel are convinced by field evidence that much of the associated sediment was trapped in the Cabral Lagoon, which intercepts water passing from the Trujillo Canal toward the Cristobal Canal, and has silted up significantly.

A planned bathymetric survey of the lake will help to further test this hypothesis, in addition to providing information useful for other purposes such as habitat evaluation. Detailed analysis of local sediment deposition rates using radiometric dating techniques could also be useful to improve these estimates.

Near-Term Mitigation

We can conclude from the foregoing that most of the hypothesized contributors to recent lake level rise do not seem adequate to explain a large proportion of this phenomenon. Even the recent increase in precipitation in the Enriquillo and Yaque del Sur watersheds alone would seem unlikely to have directly caused a large percentage of the rise. However, recent storm events functioning as a severe weather trigger for the destruction of the Trujillo water control structure, and for the subsequent diversion of water from the neighboring Yaque del Sur watershed into the Enriquillo basin, appear capable of having produced a rise of the correct order of magnitude. Whether it is responsible for 50 percent or 90 percent of the inputs into the lake, an important conclusion from the above analysis is that *as long as flow from the Yaque del Sur River continues to find its way into Lake Enriquillo through the damaged Trujillo dike, lake levels will likely continue to rise*.

One approach is to make repairs to this and other damaged or sedimented infrastructure and adapt as necessary to any potential rises in lake level. The lake will probably remain vulnerable to major rainfall events. Another approach is to consider additional structural solutions. One conceptual idea—which is by no means the only option—is discussed in the following paragraphs.

INDRHI is well underway implementing the Monte Grande Project which includes irrigation and flood control improvements in the lower flood plain (east of the lake) and the construction of a new reservoir that would regulate close to 75 percent of one of the largest watersheds in the Dominican Republic with close to 5,000 square kilometers of contributing area. Extraordinary flood events, up to 4000 cubic meters per second (cms), could potentially occur below the dam even after completion of the multipurpose Monte Grande Reservoir with a storage capacity of up to 250 million cubic meters of water. However, construction of this reservoir and improvements to soil conservation practices would greatly reduce the significant sediment load, as observed during our visit, of the Yaque del Sur River.

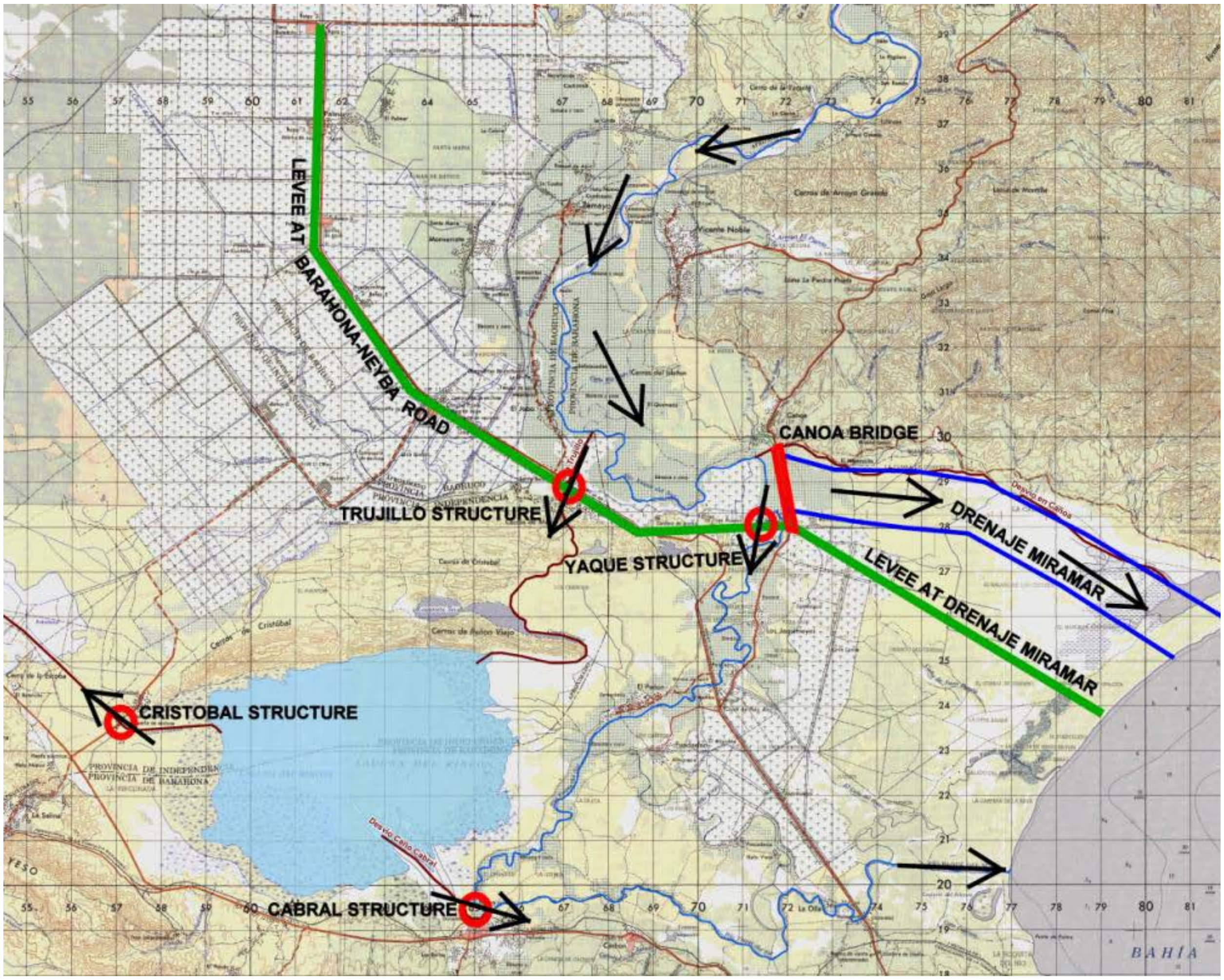

Figure 5. Conceptual ideas for potential improvements to effectively manage the water distribution and prevent overflows from the Yaque del Sur River into the Lake Enriquillo watershed.

Figure 5 depicts conceptual ideas for potential improvements to effectively manage the water distribution and prevent overflows from the Yaque del Sur River into the Lake Enriquillo watershed. These conceptual ideas generally agree with previous studies and opinions from experts at INDRHI to effectively divide both watersheds and prevent uncontrolled flows from the Yaque del Sur River into the Enriquillo watershed. These conceptual measures could facilitate the management of freshwater for the following purposes:

- Provide sufficient irrigation for agricultural lands in the lower flood plain.
- Control water inflows through the Trujillo Canal into Cabral Lagoon.
- Control Cabral Lagoon water levels and overflows through the Cristobal Canal into Lake Enriquillo.
- Protect all populated areas from an extraordinary flood event.
- Protect most agricultural areas from an extraordinary flood event.

The proposed conceptual measures will require additional planning, engineering, environmental and implementation studies to assure feasibility, acceptable hydraulic performance, minimization of potential impacts to the environment, stability and safety of the proposed measures. In order of importance, these conceptual flood control and water management measures are the following:

- **Consider moving the Trujillo Canal Dike and Flow Control Structure away from the Yaque del Sur River (somewhere near Neyba-Barahona road).**

  Originally, this structure was located about 200 meters south from the river. In 2007, the original structure failed due to flanking of dike caused by floods from Hurricane Noel. The failure resulted in about 4 years of uncontrolled flows from the Yaque del Sur River into Cabral Lagoon through the Trujillo Canal and into Lake Enriquillo through the Cristobal Canal. Both canals were severely eroded and an undetermined but substantial amount of sediments were deposited in Cabral Lagoon and Lake Enriquillo. The existing control structure at the Trujillo Canal was recently reconstructed right at a river meander and it already suffered severe damage due to flanking and erosion of its west abutment. Debris racks should be provided at structure inlets and prevent obstruction and/or damage to gates. The Trujillo Canal cross section upstream and downstream of the new structure should be stabilized to prevent further erosion and sediments reaching Cabral Lagoon.

- **Consider providing an effective floodway at Drenaje Miramar (4000 cms capacity) and check capacity and stability of existing Canoa bridge at Barahona-Azua road.**

  This measure agrees with previous studies and opinions from experts at INDRHI to effectively divert flood flows in excess of bank full flows (150 cms) away from the lower Yaque del Sur River (below Los Robles) through the Drenaje Miramar (also known as Desvio en Canoa). The present capacity and stability of the existing Canoa Bridge at the Barahona-Azua road should be evaluated. Velocity control drop structures and a grade control structure should be evaluated to control floodway velocities and prevent erosion of existing channel bed upstream of the proposed floodway.

- **Consider raising low areas of Neyba-Barahona- road to serve as a levee and provide levee south of Drenaje Miramar with material excavated from Drenaje Miramar floodway channel.**

  Detailed engineering investigations including topographic and existing infrastructure surveys throughout the Yaque del Sur flood plain should be completed to evaluate the feasibility of any proposed structural alternatives. Field observations and photographic evidence of floods clearly shows that the existing roads have been constructed higher than the surrounding grounds and have served as levees during floods. However, the Monte Grande Project includes the construction of several culverts under some roads to improve flooding conditions at several communities caused by perched flood waters. A levee along a portion of the Neyba-Barahona road should effectively prevent overflows from the Yaque del Sur River into the Cabral Lagoon and Lake Enriquillo watersheds and direct flood waters into the proposed floodway at Drenaje Miramar. A levee parallel to the proposed floodway at Drenaje Miramar could be constructed with suitable materials excavated from the channel to reduce the channel size and minimize material disposal.

- **Consider providing a Low Flow Control Structure where proposed levee crosses the Yaque del Sur River at Los Robles to maintain a maximum bank full capacity of 150 cms.**

  A low flow control structure should be evaluated if a levee is provided to direct flood waters into the proposed floodway at Drenaje Miramar. The purpose of the structure is to maintain and control low flow conditions at the lower portions of the river downstream of Los Robles. The maximum bank full flow capacity along this reach is estimated at about 150 cms. This maximum flow should be evaluated to comply with irrigation needs and environmental concerns.

- **Consider improving the capacity and control of the existing the Cristobal Canal Control Structure at Cristobal road.**

  The existing Cristóbal Control Structure should be evaluated for operational effectiveness and stability. Debris racks should be provided at structure inlets and prevent obstruction and/or damage to gates. The Cristóbal Canal cross section upstream and downstream of the structure should be stabilized to prevent further erosion and sediments reaching Lake Enriquillo.

- **Investigate the benefits of restoring Caño Cabral and its Control Structure.**

  Once the flood flows from the Yaque del Sur River are effectively diverted through the channel/levee at Drenaje Miramar, this presently deteriorated control structure and obstructed diversion canal might play an important role in managing freshwater levels at Cabral Lagoon and help manage the amount of freshwater reaching Lake Enriquillo from the lagoon.

Making Difficult Decisions

Regardless of the multiple hypotheses to account for the increase in lake levels and surface area, many major decisions will need to be made in the coming years in the Enriquillo basin. For example:

- How much variability of the lake levels and size is acceptable?
- Should additional engineering structures, with their corresponding financial, environmental and social costs and benefits, be built to help regulate flows?
- Should certain lands along the lake be allowed to flood, even though people may be displaced from their homes and livelihoods?

How will these difficult decisions be made and on what basis?

The Importance of Data

The basis of good decision-making is good data and information. Throughout this report, it has been demonstrated multiple times that better information on elements of the water and sediment budgets such as stream and spring discharge, groundwater levels and chemistry, lake levels and salinity distribution, bathymetry, rainfall and evapotranspiration would have led to improved understanding of the lake dynamics. While the authors and others before them have evaluated some of these dynamics semi-quantitatively, making good decisions depends on having good data.

A detailed analysis of such data needs is beyond the scope of this report, but a brief listing would surely include the following:

1. Daily measurements of the lake level (referenced to a well established datum);
2. Stream gages in control sections to measure discharge of some of the major springs and rivers;
3. Groundwater monitoring wells for both water balance and water quality;
4. Additional weather stations including evaporation pans for water balance;
5. A new bathymetric survey of the lake to establish volume-area relationships and sedimentation rates;
6. Salinity profiles in the lake to identify springs, assess the degree of mixing of the lake during the year, and assist with chemical mass balance efforts; and
7. An information system to complement the increased flow of data.

INDRHI and other parties are already implementing, or have plans to implement, many of these recommendations.

While this team was focused on water resources issues, water management is part of the broader field of natural resource management, which is a subset of the even larger field of planning. The issues surrounding Lake Enriquillo are complicated and involve many sectors—agriculture, ecology, water supply, floods and droughts, transportation, economic activity, and others. There are presumably data needs in these areas as well, but this is beyond the scope of this report.

An Integrated Basin Management and Conservation Plan

While decision-making depends on good data and information, it is essentially a political, not scientific issue. A comprehensive, integrated basin management and conservation plan is necessary for a coherent and unified approach to face the basin’s challenges. The key to good management is to base policy and decision-making on scientific information and a good understanding of the system. Because water is part of a coupled hydro-ecologic and social system, a good understanding of the system must span different sectors and disciplines. Different stakeholders in the basin have their own understanding of the functioning of the system and how it affects them and their livelihoods. Stakeholders may include local and national government actors, representatives of economic sectors in the basin, NGOs, communities, etc. Their perspectives need to be integrated and accounted for, in order to understand the system as a whole and have insights into the effects of interventions.

Individuals' views and understanding of the system are likely to be incomplete and conditioned by their background and experience. However, in a collaborative and participatory process, with representation from all relevant stakeholders, all of these partial conceptual models can be shared and feed into a collective conceptual model. Participatory planning processes help stakeholders understand the physical system, and in particular the spatial distributions of pumping, diversions and land-use management impacts in the basin. Such a participatory process also allows for a better understanding of the drivers and constraints of each stakeholder, of the agencies and institutions being represented, i.e. what limits exist on each stakeholder's range of action. In this way, stakeholders can gain insights into the bases for their divergent viewpoints, and through increased understanding, identify potential strategies to negotiate trade-offs among groups with different interests (Serrat-Capdevila et al., 2009, 2011).

Shared Vision Planning

Perhaps the most widely used participatory planning methodology in the US has been Shared Vision Planning (SVP; http://www.sharedvisionplanning.us/). Motivated by the 1988 drought, the method initially appeared as the Drought Preparedness Study (Werrick and Whipple, 1994) with the goal of finding better ways to manage water during drought. The study presented a methodology to set up a multi-stakeholder process to find planning solutions that can be used to address any water management issue. The method has been used successfully by the US Army Corps of Engineers in many conflict resolution efforts in water management, including planning for the Great Lakes with Canada. It is currently being adapted for use in a series of basins in western Peru and other locations.

SVP is based on three principles: (1) traditional and time tested planning methods and techniques; (2) structured public participation; and (3) use of computer models collaboratively developed in order to support the participatory planning process (Cardwell et al., 2009). This linkage between the social and sciences and engineering is a unique strength of the SVP approach.

The importance of adaptive management: planning for uncertainty, adapting and learning

"Plan for an uncertain future, adapt when it becomes the present, and learn from it when it becomes the past." Regardless of the quantity and quality of available data and information, major gaps generally remain in our understanding of hydro-ecological systems, and especially with respect to their responses to uncertain future conditions. Acknowledging uncertainty, the concept and practice of adaptive management presents a framework for natural resource management under uncertainty that aims at reducing uncertainty through observation during and after management interventions. It is a decision-making process that attempts to manage systems both to maximize short-term benefits and to gain new understanding to improve management over the longer term. To accomplish the second goal – learning about the system – adaptive management relies on a few basic steps:

(a) Characterizing and quantifying the sources of uncertainty in the system.

(b) System observation and monitoring of system response to management actions, during their implementation and afterwards.

(c) If the system is not responding as was expected, develop potential explanations and test them.

(d) Update the understanding of the system by assimilating new data and information.

(e) Management can be specifically geared towards tackling parts of the system where less is known about its functioning or where major uncertainties lie. This can conflict with management goals to maximize beneficial use of the resource in the short term, but is considered a benefit for the long-term as it is likely to reduce uncertainties on the system.

Flexibility is an important aspect of a good adaptive management practice. Institutions should be able to change past policies based on the observed impacts such policies had on the system. The key to this essential feedback linking the latest observations with the next decision-making steps is that it requires close collaboration between those who monitor, study and interpret the behavior of the system and those who do the decision-making (Serrat-Capdevila et al., 2011). Since these groups of people belong to different institutions, new organisms and institutional strategies may be needed to put new knowledge to use at a practical level. For management to be adaptive, the policies must be flexible, not just the institutions.

Crises Present Opportunities: Building on past efforts in the Dominican Republic

Thus, crises present opportunities to mobilize institutional, political and financial resources to address not only the immediate challenges, but also fundamental and long-standing issues that may have contributed to it. They also present a brief window of opportunity to create both knowledge and institutions that may help prevent similar crises in the future.

The situation in Lake Enriquillo presents just such an opportunity. Engaging local and international universities in stakeholder-relevant research in collaboration with government agencies such as INDRHI will often lead to useful findings that can support decision-making while building local knowledge and capacity. International organizations, bilateral development agencies and foundations are often supportive of such collaborative efforts. As real-world systems are often quite complex, integrated water resources management must make use of modeling tools to properly simulate and understand how the system functions. Ideally, as previously mentioned, this forces decision-makers, scientists and model developers to work collaboratively in a cycle of management decisions, implementation, monitoring, interpretation of new data, and inclusion in conceptual and numerical models of the system to help validate past interpretations and/or provide new working hypothesis of how the system behaves.

The crisis mode can also lead to increased flexibility on the part of existing institutions. Development of an integrated basin management and conservation plan for the Lake Enriquillo area may take many forms, and participatory frameworks can adopt a variety of formats and structures convenient to a specific country and regional setting. But it will require at a minimum the political will to collaborate among the many institutions of government and civil society. It may be useful to create one or more new institutions, such as a basin commission, to assist in long-term planning and management, which may be given legal authorities to accomplish their mission. Whatever the form chosen, it will be helpful to take advantage of the current society-wide focus on the issue to create forward momentum and help overcome barriers to an improved management of the basin. These efforts can build on the many existing efforts and initiatives already in place in the Dominican Republic and the Enriquillo Basin, and capitalize on the considerable expertise in government agencies, institutes (such as INDRHI) and other entities such as universities.

Conclusions

Overall, evidence appears strong that the increase in major rainfall events in the Enriquillo and Yaque del Sur catchments, combined with the entry of Yaque del Sur water into the Enriquillo basin through failure of an important control structure and other uncontrolled flow, was a major contributor to the rise in the lake level during the past decade. At a minimum, the volume of flow into the lake from the Yaque del Sur basin is on the same order of magnitude as the increased volume of the lake during that period. It is reasonable to believe that local streams and springs may have contributed as well, but there is at present little data to support this. Increased sedimentation, and higher rates of groundwater flow from Lake Azuei (with or without the influence of the 2010 earthquake in Haiti) seem unlikely to be major contributors, but improved data collection can either refute or confirm this conclusion.

In addition to the acquisition of additional data, including long-term monitoring, we recommend the development of an integrated basin management and conservation plan for the Lake Enriquillo area. Appropriate mechanisms and institutions for the creation and ongoing maintenance of such a plan should be established while the current crisis creates the political will and momentum to address past, present and future issues in the basin. Participative and integrative planning approaches, such as shared vision planning, combined with adaptive management can be a powerful framework in this context.

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