Hydrological and Oceanographic Considerations for Integrated Coastal Zone Management in Southern Belize

WILLIAM D. HEYMAN*
The Nature Conservancy
62 Front Street
Punta Gorda, Belize

BJÖRN KJERFVE
Marine Science Program and Department of Geological Sciences
University of South Carolina
Columbia, South Carolina 29208, USA

ABSTRACT / The objectives of this study are to: (1) characterize the meteorology and hydrology of the Maya Mountain–Marine Area Transect in southern Belize, (2) employ a simple water balance model to examine the discharge rates of seven watersheds to Port Honduras, (3) test the validity of the hydrological model, (4) explore the implications of potential landscape and hydrological alterations, and (5) examine the value of protected areas. The southern coastal portion of the study area is classified as wet tropical forest and the remainder as moist tropical forest. Rainfall is 3000–4000 mm annually. Resulting annual freshwater discharge directly into Port Honduras is calculated at $2.5 \times 10^9$ m$^3$, a volume equal to the basin. During the rainy season, June–September, 84% of the annual discharge occurs, which causes the bay to become brackish. Port Honduras serves as an important nursery ground for many species of commercially important fish and shellfish. The removal of forest cover in the uplands, as a result of agriculture, aquaculture, and village development, is likely to significantly accelerate erosion. Increased erosion would reduce soil fertility in the uplands and negatively affect mangrove, seagrass, and coral reef productivity in the receiving coastal embayment. Alternatively, the conservation of an existing protected areas corridor, linking the Maya Mountains to the Caribbean Sea, is likely to enhance regional sustainable economic development. This study aims to support environmental management at the scale of the “ecoscope”—a sensible ecological unit of linked watersheds and coastal and marine environments.

Port Honduras is a proposed marine reserve in the Toledo district of southern Belize and is the core of the Maya Mountain–Marine Area Transect (MMMAT), a corridor of existing and proposed reserves and private lands, reaching from the ridge of the Maya Mountains to the Belize Barrier Reef (Figure 1). The corridor between the Bladen Nature Reserve and Port Honduras has been described as that portion of Belize where a corridor of protected areas from the Maya Mountains to the sea could be established, with the greatest potential for biodiversity conservation (BCES 1990). In order to evaluate the impacts of development alternatives in Toledo, a comprehensive study has been undertaken. The study has been divided into consideration of ecosystem function, resource use and users, and socioeconomic factors. Initial results include an ecological site characterization (Heyman 1996a), an analysis of commercial and sport fishing (Heyman and Hyatt 1996; Heyman 1996a), and analyses of ecotourism (Maheia 1995; Heyman 1996a). This paper is an attempt to describe local climatic and hydrological conditions and provide recommendations for the development of both lands and waters, especially highlighting the interactions between the two.

Watersheds are large-scale integrators of ecosystems and can serve as a measure of ecosystem integrity (King 1993). Thus, hydrology and climate are important components of ecosystem function. There also are direct linkages between hydrology, climate, ecosystem services, and socioeconomic factors. Climate and hydrology either control, or are directly linked to, availability of safe municipal and rural potable water, agriculture, aquaculture, industry, tourism, aquifer recharge, coastal and estuarine primary productivity, and marine fisheries. Because of the alarming global decline in surface water quality and ecosystem services (Abramovitz 1996) and the environmental and economic costs of soil erosion (Pimentel and others 1995), decision makers are becoming increasingly aware of the need to incorporate hydrological concerns into planning (Falkenmark and Chapman 1989). An explanation of the climate and hydrology of southern Belize will contribute to an

*Author to whom correspondence should be addressed.

KEY WORDS: Ecosystem management; Coastal zone management; Belize; Hydrology

understanding of the ecosystem and will assist in developing and managing the Toledo District more efficiently.

Odum (1976) argued that the management of tropical coastal areas should be based on the maintenance of ecosystem functions. Ecosystem functions to be maintained include protection of areas with naturally high productivity; key links in food webs; critical wildlife habitat for breeding, feeding, and nursery; and diversity, among others. Physical factors to be considered include runoff, soil erosion, subsurface water resources, vulnerability to storms and hurricanes, inshore current patterns, and sediment deposition (Odum 1976). Accordingly, this study was undertaken as one component of an overall integrated study aimed at the formulation of management recommendations for an extensive, intact corridor of tropical land and sea areas in southern Belize. The overall hypothesis is that an integrated management program, highlighting ecosystem integrity and the preservation of a land–sea conservation corridor will allow enhanced sustainable economic development.

Figure 1. The proposed Port Honduras marine reserve is at the core of the Maya Mountain-Marine Area Transect (MMMAT) in southern Belize. The corridor is shown in relation to the Gulf of Honduras.
The climate of Central America is controlled by the interaction between the easterly trade winds and the central mountain ridge (Nieuwolt 1977). The mountains divide the isthmus into a dry subtropical Pacific coast and a humid, tropical Caribbean coast (Portig 1976). The trade winds push surface waters away from the steeply sloping Pacific coast to allow nutrient-rich deep waters to upwell into the photic zone (Mann and Lazier 1996) in support of massive phytoplankton blooms and some of the most productive fisheries in the world (Norse 1993). In contrast, the Caribbean coast of Central America has a wide, gently inclined continental margin with onshore winds and does not benefit from upwelled nutrients (Mann and Lazier 1996, Norse 1993). Instead, the primary source of nutrients is watershed runoff, and most importantly, the release of organic material from the degradation of intertidal and subtidal vegetation (mangroves and seagrasses) and from coral reefs (McRoy 1983, Ogden and Gladfelter 1983, 1986). Coastal primary and secondary (fisheries) productivity in tropical estuarine environments, such as Port Honduras, is tightly coupled with upland hydrology (Turner 1977, 1985, Turner and Boesch 1987, Deegan and others 1986, Twilley 1988, Yáñez-Arancibia and others 1993).

Southern Belize had a population density of only 6.2 persons/km² in 1994 (CSO 1995); however, Belize is now beginning to upgrade the Southern Highway, the only road into the region, which is likely to induce increases in population and development. Agriculture (both large-scale and traditional slash-and-burn), aquaculture, forestry, and village expansion may together result in large-scale changes in the vegetative cover of the landscape. Through hydrology, these changes to the landscape are directly linked to a variety of ecological, social, and economic impacts downstream. This is especially the case in parts of southern Belize, where rainfall exceeds 4 m/yr (Walker 1973, Hartshorn and others 1984). For example, loss of vegetative cover can greatly reduce the rate of subsurface aquifer recharge, increase the potential for flooding and drought, and cause distinct increases in soil erosion and coastal siltation (Falkenmark and Chapman 1989).

Because of impending development in southern Belize, the paving of the Southern Highway—the only road access to the district—and the hydrological linkages between upland and coastal waters, an understanding of the region’s hydrology can assist planners to guide development towards sustainability. The objectives of this study are to: (1) characterize the meteorology and hydrology of the Maya Mountain–Marine Area Transect; (2) employ a hydrological model to examine the discharge rates of key watersheds to Port Honduras; (3) test the validity of the hydrological model; (4) explore the ecological, social, and economic implications of potential landscape and hydrological alterations; and (5) examine the value of protected areas.

Study Area

The main focus of study for this paper is the Port Honduras embayment. Because of the linkages between Port Honduras and terrestrial and marine areas, however, the study area was expanded to include the watersheds that impact Port Honduras and the marine waters of southern Belize and the Gulf of Honduras (Figure 1). The great majority of the study area falls within Toledo, Belize’s southernmost district.

Port Honduras is a humid tropical estuarine–marine embayment, openly connected to the Caribbean Sea between latitudes 16°8′N and 16°12′N and longitudes 88°35′W and 88°45′W (Figure 1). The terrestrial portion of the study area can be divided into four major landforms extending from the mountain ridge to the sea as follows: (1) the Maya Mountains, (2) karstic limestone relief, (3) hilly to undulating lowlands, and (4) coastal flatlands. The Maya Mountains were formed from volcanic and Paleozoic marine sedimentary rocks during successive periods of uplifting and seawater inundation (Lara 1994) and peak at only 1120 m. The ridge is steep, however, and highly erodible. The mountains are flanked by a rugged belt of limestone hills (Wright and others 1959). The soils from this parent material are of high natural fertility, thin, and composed of black and erodible smectoid clay. The removal of forest cover on these soils impedes aquifer recharge of subterranean limestone rocks and thus leads to increased surface runoff (A. C. S. Wright personal communication). The karstic limestone belt fuses into a hilly rolling lowland, which is mainly carved from Tertiary calcareous sedimentary rocks including mudstones, sandstones, and shales (Wright and others 1959, Hartshorn and others 1984). These soils are only moderately erodible under native subtropical wet broadleaf forest cover but become markedly eroded when used for traditional slash-and-burn (locally called “milpa”) agriculture of corn and beans (Hartshorn and others 1984, A. C. S. Wright personal communication). Erosion products (silt, clay, and fine sand) are carried in suspension to the sea. The coastal flatlands contain savannah grasslands and seasonally flooded freshwater swamps. Port Honduras is rimmed with an extensive red mangrove (Rhizophora mangle) fringe which can serve to filter upland erosional products. In summary, the geol-
ogy and soils of the MMAT are highly varied and subject to erosion by intense rainfall in Toledo. These erosional products largely enter the Port Honduras directly from five small watersheds, and indirectly from two other watersheds farther north.

The marine portions of the study area include the Port Honduras coastal embayment, the marine waters of the barrier reef lagoon, and the offshore waters of the Gulf of Honduras. Port Honduras contains 138 mangrove cayes, arranged in three, nearly shore-parallel lines and resting on shallow carbonate banks. Deep channels parallel the cayes, providing some sediment trapping and restricting circulation within the embayment. Port Honduras provides an important nursery habitat for a great diversity of marine and coastal fishes, as well as feeding grounds for the threatened West Indian manatee (Trichecus manatus). The embayment shows a gradient in benthic fauna that is dictated by a physical gradient in salinity from inshore to offshore. The inshore environment is dominated by freshwater- and sediment-tolerant algae and some corals, which give way to more marine-dominated habitats in the Snake Cayes. The reefs of the Snakes exhibit hermatypic coral formations that are more representative of offshore barrier reef environments. Finally, the coastal portions of southern Belize are intimately linked to the larger Gulf of Honduras, which also includes the coastal receiving waters of Guatemala and Honduras, the Belize Barrier Reef, and the Cayman Trench (Figure 2).

Measurements and Calculations

Precipitation and temperature data from 10 weather stations were obtained from the Belize Meteorological Service for August 1994–July 1995 (Figure 3). Monthly distributions of temperature and rainfall were plotted on maps (scale 1:1,378,000) and compared to monthly plots of mean precipitation and temperature data for 1930–1959 (Walker 1973). However, the historical plots use data from only five stations (Figure 3), and as a result do not include gauged rainfall in the Maya Mountains and southwestern Toledo.

Watershed discharge is most commonly determined from stage measurements, when a rating curve exists (Falkenmark and Chapman 1989; Kjerfve 1990). A rating curve relates water level height to river discharge upstream of tidal influence. Once a rating curve is established, measurements of water level alone can be used to estimate runoff. The Belize Hydrometeorological Service has placed gauging stations on the Swazey and Bladen branches of the Monkey River, on Deep River, and Rio Grande, and is currently collecting stage height data. Unfortunately, with the exception of Rio Grande, rating curves for these rivers have still not been developed, and thus discharge into Port Honduras is not known.

As an alternative, a hydrological model was employed to estimate freshwater runoff into Port Honduras. An overlay of the seven watersheds (Indian Hill Lagoon, Monkey River, Ycacos Lagoon, Deep River, Golden Stream, Middle River, and Rio Grande) that impact Port Honduras was created using digital watershed data provided by the Land Information Center, Ministry of Natural Resources, Government of Belize (Figure 4). A transparent watershed map was overlaid on each monthly isohyet map. Area-weighted estimates of monthly mean temperature (degrees Celsius) and rainfall (millimeters) were determined for each watershed (Heyman 1996b), and freshwater discharge was calculated for each basin using a simple water-balance model (Schreiber 1904, Holland 1978, Kjerfve 1990, Medeiros and Kjerfve 1993). The hydrological model (Kjerfve 1990) is used to calculate a runoff ratio ($\Delta f / r$), the fraction of monthly rainfall falling on a watershed that becomes runoff.

The water balance for a drainage basin can, in general be expressed as:

$$r = \Delta f + g + s + E_a$$

(Thornthwaite and Mather 1957, Sellers 1965), where $r$ is rainfall, $f$ is surface runoff, $g$ is infiltration to the groundwater, $s$ is soil moisture storage, and $E_a$ is actual evapotranspiration, all expressed in millimeters/month. When $E_a > r$, or if evapotranspiration exceeds rainfall, there is no water available for surface runoff or groundwater recharge. At such times, during the Belize dry season for example, in February through May, vegetation relies on groundwater and thus further depletes soil moisture. When rainfall does begin to exceed evapotranspiration, there will be a period of groundwater recharge and increasing soil moisture, followed by maximum surface runoff.

Schreiber (1904) proposed a simple runoff model based on an approximation to the water balance:

$$\ln \frac{r}{\Delta f} = \frac{-E_a}{r}$$

for situations in approximate steady state. The unitless runoff ratio, $\Delta f / r$, expresses the portion of rainfall that
becomes runoff. $E_p$ is potential evapotranspiration, expressed in millimeters/month, and varies as a function of mean temperature (and thus latitude and elevation) by:

$$E_p = 9.86 \times 10^8e^{-4.62 \times 10^7/T}$$

as expressed by Holland (1978), and where the air temperature, $T$, is expressed in degrees Kelvin. Although not reflected directly in this model, $E_p$ probably also varies as a function of vegetation type, canopy coverage, surface slope, soil type, and other secondary factors. The runoff ratio varies from 0 to 1, depending on the amount of water lost to soil infiltration, evaporation, plant transpiration, and storage. The runoff ratio approaches 1 in areas or times of high humidity and rainfall when the bulk of the rainfall becomes surface runoff. Alternatively, in areas or times of very low rainfall and humidity, the runoff ratio is close to 0, and whatever rain falls is either absorbed into the soil or serves to recharge depleted subsurface aquifers.

Potential evapotranspiration, runoff ratio, and discharge were computed using rainfall and temperature data from the Belize Hydrological Service's monthly reports. The discharge (cubic meters per second) for

---

**Figure 2.** Bathymetry of the Gulf of Honduras. Base map adapted from Walker (1973). Bathymetric data adapted from British Admiralty Chart no. 1220, Gulf of Honduras and Yucatan Channel (1984).
each watershed was calculated by multiplying the rainfall (transformed to units of meters per second), the runoff ratio, and the watershed area (square meters) (Figure 4 and Table 1). The validity of the runoff model was tested using published stage data from May 1981 to May 1982 (GOB 1983) from Big Falls South on the Rio Grande and the most up-to-date rating curve for the Rio Grande, provided by the Belize Hydrometeorological Service as follows:

\[
Q = 26.5165 \times (H - 0.4863)^{1.1650}
\]

where \(Q\) is discharge (cubic meters per second), and \(H\) is river stage height (meters) at Big Falls. The model is valid when \(0.49 < H < 10\). The gauged portion of the river is 535 km\(^2\) of a total 772 km\(^2\) catchment (GOB 1983, Land Information Center, Ministry of Natural Resources).
Thus, the total watershed discharge was calculated by multiplying the discharge at Big Falls by the factor 1.44 to account for the ungauged lower portion of the basin. The modeled discharge was compared to the measured discharge for June 1981 to May 1982, with a paired two-tailed $t$ test (SPSS 1993). The model's validity was again tested by comparing the modeled output of Rio Grande to its measured discharge for the period of August 1994 to July 1995, using a paired two-tailed $t$ test (SPSS 1993) (Figure 5). Unfortunately, a flood washed out the gauge on the 9 July 1995, so data for the remainder of July were not available and instead were estimated. Nonetheless, to check the sensitivity of the model's validity test to the estimated value for July 1995, various discharge values for this month were used in multiple tests of the model.

In addition, surface plumes from the Port Honduras...
rivers were visually observed and photographed during approximately 50 aerial overflights over a 2.5-year period, during both wet and dry seasons. Measurements of salinity and water temperature were taken successively during the same period. Finally, anecdotal information on coastal oceanography was collected from local residents, sailors, and fishermen; checked by personal observation; and added to the database.

Results and Discussion

"... Plans for primary development must be sensible of the strength and direction of the forces of nature so that they travel with and not against the natural current." (Wright and others 1959). In this classic text, The Land of British Honduras, the authors compiled two years of ground survey data into 1:250,000 scale maps of soil, natural vegetation, and potential land use as a basis for land-use recommendations for what is now called Belize. The depth and quality of this work is unparalleled for the area, and still serves as a reasonable guide for soils and major arboreal vegetation. Land-use recommendations, however, should be revisited (Hartshorn and others 1984). The authors of this paper seek humbly to update the description of the local climatic and hydrological conditions and update and broaden the scope of land use recommendations to include both lands and waters, especially highlighting the interactions between the two.

Climate

The climate of Central America is sharply divided by the central mountain ridge, with the Pacific side significantly drier than the Atlantic (Nieuwolt 1977). The

Table 1. Rainfall and runoff ratios for watersheds upstream of Port Honduras

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp (°C)</td>
<td>Rain (mm)</td>
<td>Evap (mm)</td>
<td>Δf/r</td>
<td>Rain (mm)</td>
<td>Δf/r</td>
<td>Rain (mm)</td>
<td>Δf/r</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>----------------------------------</td>
<td>----------------------------------</td>
<td>----------------------------------</td>
<td>--------------------------------</td>
<td>---------------------------------</td>
<td>---------------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>August</td>
<td>24.5</td>
<td>508</td>
<td>178</td>
<td>500</td>
<td>0.64</td>
<td>450</td>
<td>0.64</td>
</tr>
<tr>
<td>September</td>
<td>24.5</td>
<td>460</td>
<td>178</td>
<td>500</td>
<td>0.68</td>
<td>500</td>
<td>0.70</td>
</tr>
<tr>
<td>October</td>
<td>23.0</td>
<td>305</td>
<td>164</td>
<td>187</td>
<td>0.30</td>
<td>125</td>
<td>0.19</td>
</tr>
<tr>
<td>November</td>
<td>22.5</td>
<td>205</td>
<td>160</td>
<td>350</td>
<td>0.57</td>
<td>150</td>
<td>0.31</td>
</tr>
<tr>
<td>December</td>
<td>20.0</td>
<td>152</td>
<td>140</td>
<td>160</td>
<td>0.32</td>
<td>170</td>
<td>0.36</td>
</tr>
<tr>
<td>January</td>
<td>20.0</td>
<td>178</td>
<td>140</td>
<td>150</td>
<td>0.27</td>
<td>99</td>
<td>0.17</td>
</tr>
<tr>
<td>February</td>
<td>20.0</td>
<td>76</td>
<td>140</td>
<td>34</td>
<td>0.00</td>
<td>30</td>
<td>0.00</td>
</tr>
<tr>
<td>March</td>
<td>22.0</td>
<td>156</td>
<td>20</td>
<td>0.00</td>
<td>15</td>
<td>0.00</td>
<td>50</td>
</tr>
<tr>
<td>April</td>
<td>24.0</td>
<td>76</td>
<td>173</td>
<td>120</td>
<td>0.18</td>
<td>110</td>
<td>0.17</td>
</tr>
<tr>
<td>May</td>
<td>24.0</td>
<td>190</td>
<td>173</td>
<td>10</td>
<td>0.00</td>
<td>15</td>
<td>0.00</td>
</tr>
<tr>
<td>June</td>
<td>25.0</td>
<td>457</td>
<td>182</td>
<td>300</td>
<td>0.45</td>
<td>480</td>
<td>0.62</td>
</tr>
<tr>
<td>July</td>
<td>24.5</td>
<td>650</td>
<td>178</td>
<td>620</td>
<td>0.69</td>
<td>650</td>
<td>0.72</td>
</tr>
<tr>
<td>Total</td>
<td>3333</td>
<td>1961</td>
<td>3001</td>
<td>2824</td>
<td>3388</td>
<td>3135</td>
<td>2901</td>
</tr>
<tr>
<td>Mean</td>
<td>22.8</td>
<td>278</td>
<td>163</td>
<td>250</td>
<td>0.34</td>
<td>235</td>
<td>0.32</td>
</tr>
</tbody>
</table>

*Mean monthly temperature, rainfall, and evaporation for Rio Grande Watershed (1930–1959) and rainfall and runoff ratios, computed with a climate and hydrological model. Temperature and rainfall station data were extracted from Walker (1973) (for historical data) and monthly reports of the Belize Meteorological Department for 1994–1995. These station data were used to plot monthly maps of rainfall and temperature for the study area. Values for each watershed were obtained by area-weighting temperature and rainfall for each month, and for each watershed. Runoff ratios (Δf/r) and evapotranspiration were calculated from the water balance model.\n
Figure 5. Modeled versus measured freshwater discharge for the Rio Grande watershed between August 1994 and July 1995. The measured discharge (except for July which was estimated) was gathered from stage data and a rating curve for Rio Grande provided by the Belize Hydrological Service. The hydrological model discharge was compared to the measured discharge using a two-tailed paired t-test and is not significantly different (t = 1.14; P = 0.280) than from the measured discharge. The model slightly underestimates flow during the dry season and overestimates flow during the wet season, as a result of groundwater intrusion into Rio Grande’s limestone soils.
climate is largely dictated by the interaction of easterly trade winds with the ridge (Portig 1976). Blowing unimpeded across the Caribbean Sea, the trade winds are associated with a strong inversion layer, resulting in very low rainfall on the Caribbean islands. The trade winds pick up moisture from the warm sea surface. As the trade winds approach the coast of Central America, they converge with continental air masses where the inversion layer is weakened by turbulence and mixing with humid lower winds. Because of these interactions, rainfall is very high on the eastern coast of Central America during the summer and autumn (Nieuwolt 1977).

Belize, on the eastern coast of Central America, receives significant rainfall because of the orographic lifting described above. Since Belize is north of the Inter Tropical Convergence Zone (ITCZ), but still within the hurricane belt, rainfall in Belize is generated because of thermal convection and cyclones, in addition to orographic lifting (Portig 1976). The Maya Mountains reach 1120 m in southern Belize, tapering to the north. Resulting rainfall in southern Belize is therefore between 3000 and 4000 mm annually (Wright and others 1959, Walker 1973), which is higher than that of 90% of the remainder of Central America. The distribution of the rainfall, however, was unclear before this study. Data presented here, based on the 10 rainfall stations, indicate that rainfall in southern Belize is far more intense along the coast of Port Honduras than in the Maya Mountains, with a distinct gradient from higher rainfall in the south to lower rainfall in the north (Figure 3). The observation here of high rainfall over Port Honduras is consistent with Walker (1973) and with previously unpublished rainfall data collected at Village Farm (near the mouth of Middle River in Port Honduras), but differs from the prediction of Wright and other (1959). Village Farm had an average of 2800 mm/yr between 1980 and 1995, with several years over 3000 mm.

There is significant seasonal variation in precipitation in southern Belize. The wettest months of the year are consistently June–September, with monthly rainfall exceeding 400 mm, and often more than 700 mm/month (Table 1). The driest months of the year are February, March, and April, when the monthly rainfall drops to 40–70 mm/month (Table 1). Easterly trade winds blow throughout the year, stronger in the dry season than in the wet. Higher winds during the dry season result from clear skies (Nieuwolt 1977). October, November, and December are known for northerly cold fronts, locally called northers, which contribute significantly to annual rainfall totals (Portig 1976). Relative humidity normally ranges between about 40% and 99%, but averages 80% throughout the year (King and others 1986). Hurricanes, which are most common in August through October in the Caribbean (Arenas 1983), rarely impact southern Belize (Hartshorn and others 1984).

Seasonal climate is governed far more by variations in rainfall than temperature, evaporation, insolation, wind, or humidity (Heyman 1996) (Figure 6). Seasonal variation in temperature is low in coastal Belize, due to the strong maritime influence (Nieuwolt 1977). Mean monthly data from the Rio Grande watershed for the period 1930–1959 show an annual mean air temperature of 22.8°C with only slight seasonal variations (Table 1). Temperature isolines in southern Belize depend on elevation, with warmer air along the coast and cooler air inland. The coldest month of the year during this study was December (24.8°C) and the warmest months were June, July, and August (28.7, 28.2, and 28.4°C, respectively). In addition to the temperature pattern resulting from elevation, a tongue of relatively cool air, approximately 20 km wide, occasionally pushes inland from between Punta Ycacos and Dangriga at various times of the year.

Diurnal temperature variations increase sharply as a function of elevation and distance from the sea (Portig 1976). Trade winds tend to build in the afternoons in Toledo, only to die at night, when it is not uncommon for gentle west winds to blow cool air from the Maya Mountains to the coast. This diurnal pattern of breezes develops as a result of the differential heat capacity of land and sea. Land heats (and cools) rapidly as the irradiance varies, while the sea temperature remains relatively constant from day to night because of the large heat capacity. This results in diurnal changes in convection leading to stronger sea breezes by day and gentler land breezes by night (Nieuwolt 1977). Because of the diurnal pattern, the heaviest rainfall almost invariably occurs at night in Toledo.

Ecological Life Zones

Ecological life zones have been developed by Holdridge and others (1971) and have been useful in the classification of tropical environments. An ecological life zone map for Belize was developed (Hartshorn and others 1984, p. 91) indicating that Port Honduras and its immediate inland boundaries are moist subtropical. Climate data from this study indicate, however, that Port Honduras and its feeder watersheds straddle two ecological life zones as classified by Holdridge and others (1971). The southern coastal area, including the forests immediately inland of southern Port Honduras, should be classified as wet tropical forest with a mean annual biotemperature exceeding 24°C and annual rainfall...
between 4000 and 8000 mm. The majority of the study area, however, could be classified as moist tropical forest, with mean annual biotemperatures as above, but annual mean rainfall between 2000 and 4000 mm.

Climate data and ecological classifications for southern Belize could be vastly improved with a few new strategically placed weather stations, including Snake Cayes, Barranco, southwestern Toledo, and Richardson Peak. More baseline data on hydrology and water quality are also needed and would be extremely valuable for evaluation of future land-use changes. These data might be incorporated in landscape-scale studies following the examples of the US Environmental Protection Agency (1994).

Hydrology and Coastal Oceanography

The marine and coastal systems in the Gulf of Honduras are controlled by three factors. First, the bifurcation of the northerly Cayman Current leads to a cyclonic countercurrent gyre and a resulting 1- to 2-knot southerly current just west of the Belize Barrier Reef (Craig 1966) (Figure 7). Spawning aggregations of a variety of reef fish species occurs at Gladden Spit, which is proposed to result from an upwelling associated with the south-flowing current (Heyman 1996a). Such an upwelling zone would be a key factor to high production along the southern Barrier Reef and in the Gulf of Honduras. This is because upwellings are notably the ocean’s zones of highest primary productivity (300 gC/ m²/ yr) (Rhyther 1969, Duxbury and Duxbury 1989). Second, the high precipitation in the watersheds leads to significant runoff of sediment and fresh water between June and September, which drives gravitational currents and lowers water transparency. The resulting surface current flows east between Punta Manabique and the Sappodilla Cayes (Figure 7). Third, deep, clear, nutrient-rich oceanic waters occasionally enter the Gulf of Honduras from the Caribbean Sea, with deep currents flowing contrary to prevailing surface currents (Eloy Cuevas personal communication, personal observation) (Figure 7). In contrast, the mixed, primarily semidiurnal tide is of limited importance in southern Belize with a range of only 20 cm (Kjerfve 1981).

River plumes have low salinity and density and a high suspended sediment load. Prevailing southward directed winds and currents advect river plumes towards the south. This trend is most evident at Monkey River. During the rainy season, when easterly trade winds are light, the red–orange surface plume of the Monkey River extends 1 km to the north, 3–5 km to the east, and more than 15 km to the south and southeast, near the Snake Cayes. At times of high discharge, dark-brown, tannin-stained water exits the southern edge of the mouth of Monkey River, originating from a small
mangrove-lined creek near the river mouth. The river carries a high load of granitic sands, which form a submarine fan and contribute to the maintenance of the siliceous sand beach, which extends south to Punta Ycacos. Surface water at the mouth of Black Creek, 300 m north of the river, was measured to have 0‰ salinity and 29°C temperature in both July and August 1995. When these measurements were taken, the normally black waters of the creek, which has a normal salinity of around 30‰, had been replaced by the orange Monkey River floodwaters, perhaps as a result of overbank flooding of the main river channel into the creek. The plume from Deep River extends seaward 2–5 km during the wet season and usually veers south into the large bight formed at the southern end of the river mouth. Surface water at the Deep River mouth was measured at 3‰ salinity and 28.5°C temperature in July 1995, and 0‰ and 29.5°C in August 1995. During the dry season, however, surface plumes from Deep River and Ycacos generally extend less than 0.5 km, with salinities ranging between 29‰ and 36‰, and much of the time are not easily distinguishable from the waters of Port Honduras, whose turbidity is maintained by resuspension of fine-grained benthic muds.

The Ycacos Lagoon is bounded to the east by a thin strip of sand between Punta Negra and Monkey River. During the rainy season, a hydrologic head develops in the lagoon, pushing 10–15 intermittent canals through

Figure 7. Currents of the Gulf of Honduras; base map adapted from Craig (1966).
the granitic sand berm and releasing dark brown, tannin-stained fresh water to the coastal ocean. These waters invariably are advected south along the coast with the prevailing currents. The river plume from Golden Stream extends eastward but is difficult to distinguish from the Middle River plume and the turbid inshore coastal waters of southern Port Honduras. The plume from Rio Grande is characteristically reddish brown and more distinct from slate-colored turbid inshore waters than the other rivers. The plume can extend 4–6 km due east during the rainy season. The Rio Grande plume is advected east and northeast into inshore waters of southern Port Honduras during early morning hours and shifts distinctly southeast in the late afternoon as a result of diurnal variation in the prevailing winds.

Due to variability in rainfall, the runoff ratio varies considerably with season. Dry season (February–April) runoff ratios vary from 0.0 to 0.16, and wet season runoff ratios commonly exceed 0.6 (Table 1). Mean yearly runoff ratio values for all basins under study are 0.32–0.37. In comparison, annual runoff ratios for major tropical rivers range from 0.06 for the Nile, 0.35 for the La Plata, and 0.51 for the Amazon (Balek 1983).

Based on the runoff model, the total runoff directly into Port Honduras (from Ycacos Lagoon, Deep River, Golden Stream, Middle River, and Rio Grande) was calculated to be $2.5 \times 10^3$ m$^3$/yr, of which $2.1 \times 10^6$ m$^3$ (84%) flows during the rainy season, June–September (Table 2). Monkey River alone drains 1292 km$^2$ and flows at a mean annual rate of 66 m$^3$/sec, totaling more than $2.0 \times 10^3$ m$^3$/runoff per year, nearly equal to all of the other watersheds combined (Table 2).

The bottom topography in Port Honduras contains a series of three shore-parallel shallow banks and deep troughs (FMCSC 1996, personal observation), and by morphology, might inhibit mixing. The total volume of Port Honduras was estimated during this study at $2.0 \times 10^9$ m$^3$, therefore, complete water turnover may occur during the span of a single rainy season. Port Honduras is therefore seasonally brackish, and highly sensitive to upland activities that alter sedimentation rates and surface water flow.

Model Validation

To validate the model, modeled discharge data for Rio Grande for the 1994–1995 season was compared to measured discharge (using measured river stage heights and a rating curve developed by the Belize Hydrology Department) for the same period. Figure 5 indicates the tight fit between modeled and measured data. Discharge calculated from the model ($37 \pm 45$ m$^3$/sec) was not significantly different ($t = 1.14; P = 0.280$; paired two-tailed t test) (SPSS 1993) than measured discharge calculated using the rating curve and stage data ($44 \pm 34$ m$^3$/sec) (variability is calculated as root-mean-square) (SPSS 1993). The gauging station was washed out on 9 July 1995, so the month’s measured discharge data are not available for comparison and have instead been estimated at 110 m$^3$/sec. The model is robust ($P > 0.05$) with estimated values for July 1995 runoff between 0 and 140 m$^3$/sec and is considered to work well. The model was revalidated by comparing the modeled to measured discharge for Rio Grande between June 1982 and May 1983. Although monthly variations are clear, the model and measured discharge are not significantly different ($t = 1.14; p = 0.279$; paired two-tailed t test) (SPSS 1993). The model appears to work well during most of the year but tends to underestimate runoff during the dry season and overestimate it during the early part of the rainy season (Figure 5). It is possible that the higher than expected dry season flow is a result of waters released from the limestone aquifer. Rio Grande has by far the largest proportion of limestone soils (58% or 419 km$^2$) of any watershed under study and so should be most sensitive to these seasonal variations.

The runoff model works well and can provide an excellent first-order approximation of annual discharge from relatively small, tropical watersheds. Using time intervals of one month, the model is still accurate (Figure 5). On the other hand, it is not a dynamic model, and thus it can not be used to explain peak discharges associated with short duration storm events. These pulse discharge events can carry a large percentage of the annual suspended sediment load (Falkenmark and Chapman 1989). Nonetheless, given the
Soil Erosion and Sediment Transport

Soil erosion is a critical global environmental and economic problem. Nearly one third of the world’s arable land has been lost to erosion in the last 40 years (Pimentel and others 1995). The soil erosion rate for the United States is about 17 tons/ha/yr, while the average rates for Asia, Africa, and South America exceed 40 tons/ha/yr (Pimentel and others 1995). The economic costs of soil erosion for croplands in the United States alone, calculated as a function of lost nutrients, and thus lost productivity, is more than US$27 billion/yr (Pimentel and others 1995). Erosion also has off site costs associated with roadway and sewer sitation, drainage disruptions, undermining of foundations and pavements, gullying of roads, eutrophication of waterways, sitation in harbors and channels, disruption of hydropower generation, loss of wildlife habitat, disruption of riverine and estuarine ecology, flooding, public health, and increased water treatment costs (Gray and Leiser 1989).

Soil erosion is a function of climate, water balance, rainfall intensity, vegetative cover, soil moisture, soil cover, landform, and slope (Falkenmark and Chapman 1989). Erosion rates are highest in steeply sloping areas with little or no vegetative cover, in areas of high rainfall intensity, and in highly erodible soils. It is commonly accepted that deforested tropical regions are highly vulnerable to accelerated erosion (Balek 1983). For example, the rivers of Java carry more silt in a day than typical temperate rivers with the same drainage area would yield in two centuries (Falkenmark and Chapman 1989). Meanwhile, the rate of new soil formation in the humid tropics is extremely low, taking hundreds of years to develop 1 mm of fertile top soil (Falkenmark and Chapman 1989).

Rainfall intensity (a measure of the volume of rainfall per time) is one of the main controlling forces on the probability and intensity of local floods and soil erosion (Niewolt 1977). Tropical areas generally have short duration, high-intensity rainstorms. Intensity can be compared using values of mean rainfall per rainday, with high values ranging up to 21 and 22 mm for Hong Kong, China, and Bombay, India, respectively, and low values, down to 10 mm for San Juan, Puerto Rico (WMO 1971). Using the definition of a rain day as a day with more than 1 mm of rain, rainfall intensity at the Punta Gorda Agricultural Station was 24 mm during the 1994–1995 study period, and a mean of 20 mm for the period between 1950 and 1970 (data from Walker 1973). Rainfall intensity in southern Belize is as high as tropical monsoon areas, known to be subject to the most intense flooding and erosion in the world. Erosion rates on bare soil of 4%–19% slope can reach 10 tons/ha/yr in temperate areas but up to 170 tons/ha/yr in the humid tropics (Kirby and Morgan 1980).

The ecological health of Toledo’s coastal and marine ecosystems is directly tied to the fate of the uplands. Upgrading of the Southern Highway, for example, could lead to increased agricultural and village expansion and deforestation. Many of the soils within the MAMAT have been deemed marginal for agriculture (King and others 1986, Wright and others 1959). Any land-use conversions will alter the rates and volumes of freshwater and sediment discharges and will be associated with increases in soil loss and erosion. Presently, logging operations within forest reserves for tropical hardwoods, small-scale agriculture for corn and beans, aquaculture development for shrimp and finfish, and village expansion are the fastest development sectors. These will all result in decreased limestone aquifer recharge, increased runoff and sitation to the coast, increased duration and intensity of droughts, and more intense flooding. In short, any land-use decisions in southern Belize will have significant ecological and economic effects and should be carefully weighed as part of an integrated plan for the district. Erosion mitigation must be an integral part of economic development plans for the area.

Effects on Coastal and Marine Ecosystems

The coast of Port Honduras and the rivers, which drain into the embayment, are lined with red mangroves, Rhizophora mangle. The mangroves represent the largest area of intertidal, estuarine mangrove habitat in southern Belize (Zisman 1992), covering an area of 75 km² and representing 10% of the mangrove area in the country (Gray and others 1990). Mangroves are known to provide shoreline protection, filtering of sediments from the uplands, and critical larval and juvenile habitat (Odum 1970, Boesch and Turner 1984). In addition, the embayment with its associated cays and coral reefs contribute to the value of Port Honduras as a nursery ground. Most importantly, these mangroves are the largest contributor to coastal and marine productivity via leaf litter and thus directly or indirectly support most coastal and marine fisheries species, including those inhabiting the Belize Barrier Reef (Odum 1970, Odum and others 1973, Martosubroto and Naamin 1977, Ogden and Gladfelter 1983, 1986, McRoy 1983, Twilley 1988, Yáñez-Arancibia and others 1993).

The health of the Port Honduras ecosystem is critical
tural development on poor soils and with high rainfall intensity leads to soil erosion and coastal degradation and could have long-term, far-reaching negative social, ecological, and economic consequences downstream in the bay. With appropriate community participation and careful management and preservation, the Maya Mountain-Marine Area Transect could contribute importantly to sustainable economic development in Toledo and Belize. Continued research and monitoring of the geology, soils, hydrology, coastal oceanography, water quality, and climate of southern Belize should be supported to assist in land-use planning. Additionally, oceanographic and hydrological studies at the scale of the Gulf of Honduras could assist planners by indicating the effects of development in an appropriate regional context.

Conclusion and Regional Relevance

This study utilized newly developed maps of rainfall and temperature to evaluate the climate and a simple water-balance model to evaluate hydrology. Results include the reclassification of the study area into a portion of “tropical wet forest” and the remainder as “tropical moist forest.” The hydrological model employed is limited, as it does not allow for changes in land cover and is not accurate for periods less than one month. As used, however, the model is considered to work well. The main conclusion of this study is that the uplands are directly linked to the coastal and marine environment in the Toledo district of Belize via intense rainfall and watershed runoff. Thus, economic development plans should be mindful of these linkages such that development maximizes the ecological, social, and economic benefits to the landscape–seascape as a whole. This concept is being embraced by the Toledo Institute for Development and Environment (TIDE), a local nongovernment group that is promoting conservation of the Maya Mountain Transect. To do so, TIDE is training local community members with new skills that are consistent with the preservation of ecosystem functions. For example, TIDE is promoting catch-and-release fly fishing in Port Honduras as an alternative to gill net fishing. Fly fishing is both far more lucrative and less destructive to the environment. In parallel, TIDE is writing management plans for the reserves (Port Honduras and Paynes Creek) with continuous community involvement and is proposing to take on the their management authority. The long-term aim is the conservation of the entire MMMAT. Similarly, the Environmental Social and Technical Assistance Project (ESTAP) is designed to mitigate the social and environmental
impacts of the paving of the Southern Highway and is incorporating hydrological considerations in their plans.

While Toledo watersheds enter the Gulf of Honduras, the gulf also serves as a receiving basin from additional rivers in Belize, as well as much larger rivers in Guatemala (e.g., Rio Motagua) and Honduras (Rio Ulua). The Ulua alone has a watershed area of over 22,000 km², more than 10 times the largest river in this study, and likely impacts the Belize Barrier Reef. A more appropriate scale of analysis of this type therefore, would be at the scale of the inner Gulf of Honduras and its watersheds. Extrapolating, we wish to put forth a new paradigm in environmental management whereby the land-sea interface is considered the center, rather than a dividing line in management planning exercises. Optimally, development planning should be undertaken at the scale of the “ecoscope”—a term put forth here to describe a sensible ecological unit of watersheds and linked coastal and marine environments. The Tri-National Alliance of NGOs for the Conservation of the Gulf of Honduras has embraced this principle. The organization is made up of nine organizations from Belize, Guatemala, and Honduras, which are working together towards the implementation of a trinational coastal management program for the Gulf of Honduras.

Acknowledgments

This work benefited from the logistical and technical support of the Belize Center for Environmental Studies and the Toledo Institute for Development and Environment. The Belize Hydrology Department, the Belize Meteorological Service, and John Spang and Tanya Russ provided raw climate and hydrology data. Several people have participated in the technical aspects of the study including Ramón Frutos, Rudolf Williams, Terence Hyatt, Delia Tillet, and Carl McCollough. A. C. S. Wright provided many helpful conversations and important perspectives. Dr. John Dean, Dr. Hank McKellar, and Lou Nicolait edited the manuscript. Anne Miller provided extensive editing, graphics, and moral support. Steven Stonehill is responsible for several graphics. Funding for this work was provided by The Nature Conservancy, University of South Carolina, and the Central American Regional Office of the US Agency for International Development via the PACA and PROARCA/Costas Projects.

Literature Cited


Craig, A. K. 1966. Geography of fishing in British Honduras and adjacent coastal areas. Louisiana State University Coastal Studies Institute, Baton Rouge, Louisiana.


Thornerwaite, C. W., and J. R. Mather. 1957. Instructions and tables for computing potential evapotranspiration and the water balance. Publication for Climatology X (3). Laboratory of Climatology, Centerton, New Jersey.


