**Hydroelectric Potential Assessment**

ENERGY BUSINESS GROUP

EWE Doc No. 300840.01

**March 2006**

Belize Electric Company Ltd.

# Belize Hydroelectric Development

## Technical Report

ELECTROWATT-EKONO
Jaakko Pöyry Group

ELECTROWATT-EKONO

Jaakko Pöyry Group

**Internal document control**

| | |
|---|---|
| **Client** | Belize Electric Company Ltd. |
| **Title** | Hydroelectric Potential Assessment |
| **Project** | Belize Hydroelectric Development |
| **Phase** | |
| **Project No.** | 300840.01 |
| **Classification** | |
| **Drawing/Reg./Serial No.** | |
| **File name** | xxx |
| **File location** | |
| **System** | Microsoft Word 10.0 |
| **External distribution** | Belize Electric Company Ltd. |
| **Internal distribution** | CI, SOU, Project File |
| **Contribution** | |
| **Responsible BU** | Hydropower |

**Revisions:**

**Original**

| | |
|---|---|
| Date of document | February 4, 2006 |
| Author/position/signature | Géraud Soubrier / Hydro-power Engineer |
| Date of control | February 28, 2006 |
| Checked by/position/signature | Ian Clarke / Project Manager |

**A**

| | |
|---|---|
| Date of document | |
| Author/position/signature | |
| Date of control | |
| Checked by/position/signature | |

**B**

| | |
|---|---|
| Date of document | |
| Author/position/signature | |
| Date of control | |
| Checked by/position/signature | |

## Contents

# 1 INTRODUCTION

In response to the Belize Government initiative to promote the development of the country’s hydroelectric potential, and under the auspices of the Finnish Ministry of Foreign Affairs[1], Belize Electric Company Ltd. (BECOL)[2], the company responsible for hydroelectric power generation for the Belize national power supply network, has concluded an agreement with Electrowatt-Ekono[3] for an assessment of the hydroelectric potential of Belize.

The review was initiated on January 31, 2006 with three weeks, reconnaissance mission to Belize (San Ignacio / Mollejon) by a hydroelectric power specialist. This review is intended to be "scheme and implementation oriented", with the principal aims, despite the very real difficulties of access to their sites, of identifying those potential hydropower projects the implementation of which is the most practical, taking into account the economical and environmental context, data availability, the extent of earlier studies etc. It identifies those schemes that are the most promising and merit further study and site investigations, and it summarises the background information used to substantiate this identification. The initial findings of this first mission are summarized in this interim report, under the following headings:

- General review of the power supply system of Belize.
- Previous studies of hydropower development.
- Availability of hydrological data.
- Assessment of environmental constraints.
- Description of the two existing projects: Mollejon and Chalillo.
- Discussion of the proposed Vaca Falls project.
- Discussion of other potential projects.

It should be pointed out that small hydroelectric power plants with a capacity of less than 1 MW are considered to be out of the scope of the present review, as their specific requirements do not normally match the economic criteria of a company of national scale like BECOL. Such schemes, of which there may be quite a number, are best developed by private individuals or companies to serve their own supply needs.

---

1 In the scope of a Finnish Cooperation Program coordinated from Helsinki by the Energy and Environmental Partnership with Central America

2 Sister company of Belize Electricity Ltd. (BEL) in charge of the power distribution as well as of the thermal generation within the Canadian Group Fortis

3 Buisiness Group Energy within the Finnish Group Pöyry

## 2 POWER SUPPLY IN BELIZE: HISTORY AND PRESENT SITUATION

Electricity supply development in Belize can be put in its historical context with the following reference dates:

1950: Creation of the Belize Electricity Board (BEB), a government company for the supply of electricity to Belize City, with other towns being supplied by plants run by their local councils but only for limited periods (from 18:00 to 22:00).

1958 Revision of the ordinance: BEB is granted the monopoly for generating, distributing, and selling energy to Belize City, Belmopan, Corozal, Orange Walk, San Ignacio, Dangriga, Punta Gorda and the islands of Ambergris Caye and Caye Caulker.

1968 Initial programme of hydrological surveys made by S.H. Walker from the U.K. Directorate of Overseas Survey: eight stream gauging stations installed on the Belize River and one on the Sibun.

1971 Programme started to increase generation and distribution in all districts of Belize. End of the initial hydrological survey.

1980 New programme to increase generation and distribution capacity, including a study of future system development (details not yet obtained). New hydrological survey programme with the installation of 17 new stream gauges.

1981 Belize becomes independent and a member of the Commonwealth.

1988 The study of Renewable Energy by CIPS is started.

1992 BEB operates eight diesel stations generating 97 GWh; its revenue is USD 17.5 million from 27'000 consumers.

1993 BEB is partly-privatized, although still with Government participation of 51 %, and the Belize Electricity Company (BEL) is set up with exclusive rights to generate and supply hydropower during a period of 15 years, i.e. up to 2008.

1996 Commissioning of the Mollejon hydropower station.

1999 The Belize government relinquishes its 51% holding in BEB.

2005 Commissioning of the Chalillo dam and hydropower station. BECOL set up by Fortis to build and operate just hydropower stations; BEL made responsible for thermal generation and distribution.

2005 Fortis Inc., Canada, holds 68 % and the Social Security Board 25% of the shares of BEL. BEL/BECOL generates xxx kWh thermal and xxx kWh hydraulic and distributes xxx kWh, with a peak demand of 61 Gwh, for an operating revenue of US$ 101.4 millions and 69'000 customers.

The following data will give an overall picture of the energy supply system as of the end of 2005, and will be completed once certain missing data requested from BELCO are received:

- Annual energy consumption kWh/a:
- Maximum peak power: MW 61
- Break-down of the generation:
  - Local thermal production GWh/a
  - Local hydro production GWh/a
  - Imports from Mexico (peak energy) GWh/a
  - Imports from Mexico (base load) GWh/a
- Cost of energy and power: US cents/kWh
- Distribution tariff: US cents/kWh
- Price of energy imported from Mexico:
  - During the 3 peak hours US cents/kWh
  - Outside the 3 peak hours US cents/kWh
- Cost of diesel / gas turbine generation US cents/kWh
- Purchase price of hydro energy 0.10 US$[4] US cents/kWh

The cost of energy imported from Mexico is relatively low during the off-peak period but much higher during the three peak hours, i.e. 18:00 h - 21:00 h. At present, Mexico is itself short of power during this period and, therefore, will only sell energy at a price which is so high as to compel BEL to cover the peak demand by itself. The result, because this is often not possible, is relatively frequent power cuts.

The daily load curve shows only one, not very pronounced peak period during the evening hours. Due to the high cost of imported energy during this period, hydroelectric production aims at covering this peak as much as possible. Therefore, in case the inflow on any given day is less than that required to generate the peak power needed, daily reservoir storage is called on. Diesel generators and gas turbines have to supply the balance as the installed hydro capacity is still far less than the peak power demand, as shown by the following tables.

[4] Hence, the BECOL benefit of one installed hydroelectric MW generating during the daily 3 hours peak period: 1000 x 3 x 0.10 = 300 US$.

**Annual power peak demand and energy load forecast[5]:**

| Forecast year | Peak Power [MW] | Net Generation [GWh] |
|---|---|---|
| 2005 | 66.5 | 402 |
| 2006 | 69.8 | 422 |
| 2007 | 74.1 | 448 |
| 2008 | 78.7 | 476 |
| 2009 | 83.5 | 505 |
| 2010 | 96.8 | 540 |
| 2011 | 102.5 | 571 |
| 2012 | 108.3 | 603 |
| 2013 | 114.4 | 636 |
| 2014 | 120.7 | 671 |

**Available hydropower capacity (2006):**

| Capacity of existing HEPP | Rated capacity [MW] | Available capacity [MW] |
|---|---|---|
| Mollejon 1 | 9.00 | 8.33 |
| Mollejon 2 | 9.00 | 8.33 |
| Mollejon 3 | 9.00 | 8.33 |
| Chalillo 1 | 3.65 | 3.50 |
| Chalillo II | 3.65 | 3.50 |
| Hydro Maya | 3.50 | 0.50 |
| **Total** | **37.8** | **32.49** |

Given that the national network now covers most of lower areas of the country, and the inter-connection possibilities that this represents for any new power plant, the above tables show that the entire hydroelectric potential can be developed in Belize.

At present, their monopoly for the supply of electric power in Belize could allow BEL/BECOL simply to charge the consumer the actual production cost price of thermal generation, which is tied to the oil price. Therefore, the incentive for BEL/BECOL to develop hydroelectric power plants, despite the strong environmental opposition, can be explained as follows:

- The power tariff cannot be immediately adapted to the actual cost of thermal generation, for social reasons.
- The dependence on supplies from Mexico affects the quality of the service, and the daily price fluctuations pose the same problem as the local thermal generation.

[5] BECOL Report xxx

## 3 PREVIOUS STUDIES OF HYDROPOWER IN BELIZE

Since 1952, when Halcrow made an initial study, the hydroelectric potential of Belize has already been the subject of a number of studies and reconnaissance missions, but most of these were relatively limited in extend and/or not of great detail. The exception is the assessment made in 1988/1989 by Canadian International Power Services Inc. (CIPS)[6] as part of their "Renewable Energy Study", the report of which was submitted in March 1990). This study reviewed the following nine possible power supply options:

- Hydroelectric generation
- Bagasse-fueled generation
- Wood-fueled generation
- Wind energy generation
- Solar energy generation
- Diesel generation
- Coal-fired steam generation
- Power purchase from Mexico
- Cogeneration (combined-cycle gas turbines)

The major findings of the CIPS study were:

- Peak power demand would grow at 5% - 9 % per annum from 1989 to 2008, and this would correspond to an increase in demand of 75 MW over the 20 years ending in 2008.
- Of the above-mentioned renewable energy resource options, only hydroelectric and bagasse-fueled generation (from the Belize Sugar Industry Ltd. at Tower Hills) can represent alternatives to diesel generation and import of power from Mexico.

It should be commented that the bagasse-fueled generation would depend on one or at most two sugar plants only, on the compatibility of their future processing technology, on their future production in line with the great changes in the global market for sugar, as well as on the competition with other prospects such as automotive ethanol. It should, however, be noted that the burning of bagasse to produce electricity does not necessarily conflict with the need to reduce carbon emissions, as these are released when bagasse is burned as waste, used as fertiliser or just left to decompose in the fields.

However, referring to the Kyoto Protocol environmental criteria, the main finding of the CIPS study was that hydroelectric generation is the only satisfactory alternative to

6 Canadian International Power Services inc., 2200 Argentia Road, Mississsauga, Ontario.

present diesel generation in Belize. At the present time (based on 2005 energy figures) Belize's principal sources of power are the following:

Diesel generation ….%

Hydropower …..%

Imports from Mexico ……%

On the basis of their assumption that hydropower characteristics should be fixed based on the hydrological data discussed in chapter 5, CIPS defined the following criteria for the evaluation of hydroelectric potential:

- The installed capacity was defined on the basis of an assumed number of peak operating hours per day (4 to 6 hours) and a percentage of time during the year when this peak could be covered (90% to 100 %, i.e. at least 1314 hours per year).
- The nominal discharge of the turbine units can be derived from the installed capacity.
- Then, for the economical evaluation, the cost per installed kW and per kWh produced were calculated assuming:
  - A load factor of 100%
  - Transmission line energy loss of 2%
  - Economic life of 50 years
  - Discount rate of 10%
  - Annual operation and maintenance costs of 1.5 to 2.5% of the capital cost.

On the basis of these criteria, the following values were determined by CIPS for their identified schemes[7]:

| **Scheme** | **Inst. power** (MW) | **Annual energy** (GWh) | **Plant factor** | **Capital cost** (million USD: 1990) | **Unit cost of capacity** (USD per kW) | **Cost of energy** (US cts per kWh: (1990) |
|---|---|---|---|---|---|---|
| Vaca Falls | 18 | 88 | 55% | 50 | 2778 | 6.6 |
| Mollejon | 12 | 70 | 67% | 42 | 3500 | 6.9 |
| Chalillo | 15 | 84 | 64% | 71 | 4733 | 9.8 |
| Rubber Camp | 15 | 47 | 36% | 60 | 4000 | 14.4 |
| South Stan Creek | 2 | 9 | 51% | 9 | 4500 | 12.7 |
| Swasey Branch | 3 | 15 | 57% | 17 | 5667 | 14.8 |
| Bladen Branch | 2 | 8 | 46% | 25 | 12500 | 38.8 |

7 Other scheme less that 1 MW, such as: Rio On (0.6 MW); Privassion Creek (0.050 MW); North Stan Creek (0.6 MW); Rio Grande (0.8 MW); Blue Creek (0.15 MW) have no dependable capacity due to limited storage and minimum turbine operating capability. They could solely contribute to displacement of Diesel energy. They are normally discarded from the present review as they do not match with its specific criteria.

Of the above schemes, the following four are located on the Macal River (from upstream to downstream) and their present situation is as follows:

- Rubber Camp has was subsequently ruled out for environmental impact reasons[8]

- Chalillo, was designed with a capacity of only 7.0 MW, for an expected production of 36 GWh/a (a plant factor 58%), and was commissioned in October 2005.

- Mollejon, with a capacity of 25.2 MW, producing an average of 80 GWh/a (plant factor 36%), was the first large hydro plant to be commissioned, in 1996.

- Vaca Falls (see Chapter 8) has been further studied and an Environmental Impact Assessment report, prepared by ESL Management Solutions Ltd. (EMSL), Kingston, Jamaica, dated October 2005 has recently been submitted to the Department of the Environment (DOE) for approval.

The large difference originally-estimated and final production figures for Chalillo is due to the much lower head finally selected, compared with that proposed in the CIPS report.

Apparently, as far as the tributaries of the Belize River are concerned, the CIPS study did not consider the potential between (from downstream to upstream) the confluence of the Macal/Mopan Rivers and the Vaca Falls project on the one hand and the border with Guatemala on the other. It should, however, be emphasized that the sites in question could only be evaluated from the 1:50'000 maps and that, for those stations located in remote areas, the CIPS site reconnaissance survey could be carried out only by aircraft. Moreover, as above described later, the CIPS hydroelectric assessment was based on hydrological data of quite limited quality, i.e. scarce[9] (essentially extending over no more that 7 years) and of doubtful reliability, as shown by the low coefficients of correlation. Furthermore, the installed capacity estimates were based on a daily flow: duration curve derived from an average of the dimensionless flow: duration curves of Double Run and Freetown and a mean flow derived from a surface runoff valve selected among those assumed for the different gauging stations.

The assessment of the installed capacities, storage volumes and energy benefits made by CIPS was as a result only very approximate, even if the most sophisticated analysis methods are used. Given the economic challenge facing hydroelectric power generation in Belize, such a limited hydrological base has to be analysed with great care in order not to over-estimate the development benefits. It would have been appropriate for CIPS to have questioned to this effect in their report.

However, during the 15 years that have elapsed since issue of the CIPS Renewable Energy Study report, a number of changes have occurred that favorably influence the feasibility of harnessing sites that may initially have been considered of marginal interest:

8 The large reservoir would have flooded the main nesting area of the scarlet macaw.

9 For instance no stream gauge was available for both major branches of the Monkey River, which represents one of the most promising potential watercourses

- An extensive transmission grid now covers practically the entire country, so that all earlier considerations related to the former regional networks are now superseded and, as a result, interconnection of new power plant at reasonable cost is now possible.

- Environmental considerations are now being given far more attention in studies of new hydroelectric development, so that corresponding allowances will have to be made during planning and design.

- The Chalillo seasonal reservoir, the regulating function of which now increases the production value of all downstream developments, was finally constructed and is in operation, although only in the face of strong environmental opposition.

- The latest developments in mechanical tunneling technology could help to make feasible diversion schemes incorporating small diameter tunnels (see Section 5)[10].

- Most manufacturers now market various ranges of standard generation units, which significantly lower the capital cost of electro-mechanical equipment, particularly for low-head power plants, for which equipment normally contributes a relatively important part of the total cost.

- The price of alternative sources of energy have increased, in particular due to the recent large rise in the price of oil.[11].

10 TBM equivalent diameter of the Mollejon low head Ø 4.5 m horseshoe tunnel: Ø 3.7 m

11 1989 cost of automotive Diesel fuel: BZ$ 1.39 / US gallon w/o taxes (low speed oil: 0.75 %)
1989 cost of crude oil: US$[1989]/barrel 17.0 > US$[2005]/barrel 23.3 (incremental rate: 2.00 %)
1989 cost of Mexico supply:
Power (demand charge): US$[1989]/kW/Mo 6.50 + Energy: US$[1989]/kWh 0.0325
The recently observed increased in constant money compared to that in 1989 is a readjustment only: calculation???

# 4 ASPECTS OF HYDROELECTRIC DEVELOPMENT IN BELIZE

Generally, a limited hydroelectric potential can be developed in Belize, but the question is basically at what price. The topographic and climatic characteristics (moderate altitudes and quite small of the catchment basins) mean that the potential cannot match that of high mountainous regions, nor can sites of high economic viability be expected. The unit costs determined by CIPS for installed capacity (USD/kW), shown in Chapter 3, are high even when allowance is made for the small size of the power stations.

Morphologically and hydrologically Belize can be divided into two regions of roughly similar size: the northern half is low-lying, flat and relatively dry (mean annual depth of precipitation: ~2000 mm); and the southern half (Maya mountains rising to over EL 900, with maximum at Victoria Peak EL 1120[12]) which is mountainous and wet (mean annual depth of precipitation: 4000 mm), and where rivers have steep gradients and follow joints and faults. The eastern Atlantic edge of this southern region is also low and flat. Clearly, these low-lying and flat areas do not have much[13] chance to provide any practicable hydroelectric site and are for the time being ruled out from the present review, so the hydroelectric potential has mostly to be sought in the Maya mountains and their foothills.

Along the valleys human settlement and agriculture have moderately progressed, whereas along the few tracks accessing Maya ruins, agro-tourism and eco-tourism are only starting to develop. Generally, therefore, hydroelectric schemes do not compete with farming (the more as since it is not irrigated); but tourism, on the other hand, appears now to have become an important consideration, for which allowance must be made.

On the one hand the forest cover favours hydroelectric development by reducing sediment transport in the rivers; however, on the other hand, the relatively high evapo-transpiration and the lack of accessibility tend to hamper development. Indeed, in the regions of interest, the question of access applies generally to the whole hydrographic system [14] and mainly explains the scarcity and the uneven distribution of gauging stations in the catchment areas, as well as the rarity of proper reconnaissance campaigns conducted to date in the remoter areas. Consistent with the aforementioned objectives of hydroelectric development in Belize, two specific factors are of great importance:

- The very contrasting precipitation regime, with a 4 to 5 month (February/March to June/July) dry season, with insignificant rainfall, and a wet season of very heavy, hurricane-influenced rainfall during the second half of the year.

- The price range for energy imported from Mexico; this is prohibitive during the peak hours and moderate (but still not cheap) during the off-peak hours.

---

12 All units refer to the metric system. Altitudes (EL) are measured in metres above sea level.

13 Possibly only by impoundment, but the development of this limited potential is very likely to conflict with use of the banks, river and settlements as well as infrastructure, and as such is hardly economical.

14 Off the rare tracks barely suitable for 4-wheels drive vehicles, a relatively unsafe track has to be cleared through the jungle.

The consequence of these factors is the essential need for reservoir storage for both seasonal and daily flow regulation. Given an assumed annual runoff, the volume of the seasonal reservoir depends on whether it has to ensure coverage of the peak hours only during the dry season or whether it has to be operated during the peak hours over the entire year. In the first case the plant factor is higher so that capital costs are lower, but the benefits are less than for the second case. So although the net benefit of the second case is normally higher than that of the first, the internal rate of return may be less.

Basically, irrespective of the storage available, all possible power plants in mountainous areas are of only two types, depending on whether the head is obtained by building a dam to raise the water level across the river or by diverting the water into a smooth conveyance structure with low specific head losses so that substantial energy can be created, over a certain distance, with respect to a lower point where the power house is located and water can be returned to the river. The conveyance structure can be a simple open-air channel, a tunnel operating in the free-surface mode, an open-air pressure conduit or a low-pressure tunnel. The two types are in this report denominated as:

- Impoundment scheme (dam to create reservoir, but with power plant at its toe)
- Diversion scheme (dam or intake divert water into pressure tunnel and power station rather downstream)

Clearly, a diversion scheme involving a pressurized conduit can be combined with an impoundment scheme, with or without storage. Such layouts are normally implemented where valley gradients are steep and a large head can be developed over a short distance. The drawbacks of diversion schemes over impoundment schemes are:

- Linear friction losses along the low and high pressure tunnels
- Loss of the catchment area drained between the intake to the tailrace
- Change of the hydraulic regime of the river, requiring possibly compensation flow
- Provision of daily or seasonally storage not implicitly facilitated
- No reservoir flood routing

On the other hand, the advantages are several:

- Reduced spillway costs and less energy dissipation and scouring problems (although, on the other hand, less routing of floods.)
- Insignificant sediment deposition (reservoir accretion), therefore no "reservoir ageing", but possible need for sand traps incorporated in a run-of-river intake.
- Less risk of water-tightness problems (e.g. karst) and limited sensitivity to geology.
- No loss of water by evaporation.
- Environmentally less invasive then impoundment schemes.

Micro-tunnelling[15] has made great technological progress over the last five years and has influenced the implementation criteria for small diameter diversion schemes (see Annex). With the two main advantages of construction (speed and surface quality ruling out overbreak) and greatly reducing the friction head losses, providing the tunnel can be unlined[16], the technology could eliminate many of the shortcomings commonly attributed to normal drill+blast excavation: Compared with the large TBMs now very commonly used, small machines have certain advantages:

- Lower level of sophistication and simpler operation
- Ease of transportation
- High level of operation reliability
- Low power consumption[17] and depreciation costs

On the other hand, the ways of removing the excavated spoil material remain a critical aspect needing either the provision of adits or special mechanical facilities.

The units of low-head power plants (< 10 m) are normally of the Kaplan type, which allow simple or double regulation that provides great flexibility with respect to the variation of discharge and head. Three arrangements of such turbines in weir-type power plants can be considered (see Annex):

- S-turbines
- Right angle drive turbines
- Pit turbines

Harnessing a river in Belize should typically involve the following sequence of different type of power plants, from upstream to downstream:

- Small, high head stations, of low discharge, in the upper river reaches or along its tributaries.
- Seasonal reservoir storage scheme, particularly where the river gradient is low as it should be across plateau forming the top of the Maya mountains.
- Diversion schemes along the steepest reaches of the river, down the mountain escarpment.
- Impoundment schemes where the valley become less steep.
- Low-head schemes with weirs where the valley gradient is much less steep.

---

15 The µTBM method uses full face drilling equipment derived from the TBM technology is applicable for internal diameters up to 4.2 m

16 Progress rate of 20 mm / minute, i.e. about 30 m/day can be expected in granite
Nikuradse roughness of 10 mm instead of 300 mm for drill&blast, leading to a substantial reduction of the tunnel diameter (see footnote 9)

17 400 kVA for a 3 m excavation diameter

With a cascade of power plants operating fundamentally with hourly releases there could be sudden variations in river flows farther downstream. For this reason, the cascade can be ended by a compensation reservoir, so as to ensure a constant flow in the downstream part of the river. However, such a reservoir appears to be neither practical nor necessary in Belize, given the width and discharge of the rivers in the coastal zones, where water levels may also be affected by tidal effects.

# 5 HYDROLOGICAL STUDIES

## 5.1 Summary of the CIPS hydrological studies

- CIPS carried out a comprehensive hydrological review, including field work, data appraisal and statistical analysis, for assessing the hydropower output of potential hydroelectric developments and determining spillway capacities. They systematically inspected the following stream gauging stations but determined that of the 17 gauges set up in 1980 only nine were still in use in 1988.

| Name | River | Location | Readings |
|---|---|---|---|
| Double Run | Belize River | Not yet available | 1981 - 1988 |
| Big Falls | Belize River | Not yet available | 1981 - 1988 |
| Banana Bank | Belize River | Not yet available | 1981 - 1988 |
| San Ignacio | Macal River | Not yet available | 1981 - 1985 |
| Benque Viejo | Mopan River | Not yet available | 1981 - 1988 |
| Cristo Rey | Macal River | Not yet available | 1981 - 1988 |
| Rio On | Rio On | Not yet available | 1982 - 1984 |
| Rio Frio | Rio Frio | Not yet available | 1981 - 1982 |
| Freetown | Sibun River | Not yet available | 1981 - 1988 |
| Norland | Sibun River | Not yet available | Abandoned |
| Middlesex | N. Stann Creek | Not yet available | Abandoned |
| Melinda | N. Stann Creek | Not yet available | Abandoned |
| Kendal | Sittee River | Not yet available | Abandoned |
| Big Falls | Rio Grande | Not yet available | 1981 - 1987 |
| Blue Creek | Moho River | Not yet available | 1981 - 1983 |
| Aguacate Creek | Moho River | Not yet available | 1981 - 1983 |
| Moho River | Moho River | Not yet available | 1982 - 1987 |

The main finding of the CIPS study was that the hydrological data needed to derive the flow duration curves for the identified power station sites were not available, and in addition that:

- Gauge locations were often not appropriate (San Ignacio gauge is influenced by backwater from the Mopan River).

- Cross-sections were unstable (e.g. Cristo Rey) or influenced by flow obstacles such as bridge piers, culverts, clogging by floating vegetation (e.g. Rio On, Big Falls, Aguacate Creek).

- Staff gauges were tilting, damaged (Blue Creek), lacked bench marks (Blue Creek, Moho River), and thus were giving incorrect readings.

- It was not possible to determine whether rating curves were accurate (certainly that at Big Falls was not, but probably so also many others).
- Some gauging stations were abandoned (Norland, Middlesex, Melinda, Kendal).
- Readings of some gauges needed to be systematically corrected (Big Falls).

CIPS reviewed the available station records with the following findings:

- Only Double Run and Freetown had more or less complete records for the seven-year period 1981 – 1988; all other had large gaps in records.
- Stage:discharge curves were not representative.
- In some cases, stage records may even have been made up.

CIPS reassessed the rating curves by means of multiple regression analysis, as well as manual corrections (Cristo Rey, Rio On, Middlesex, Kendal and Big Falls), except for three gauging stations (Norland, San Ignacio and Rio Frio) for which this was not possible: Some discharge measurements could then be corrected. CIPS processed the available data, specifically:

- Twice daily stage readings between 1981 and 1988 on the aforementioned gauging stations (the main data).
- Rainfall data from 17 pluviometric stations from 1966: summary monthly data only.
- Historic stream discharge data between 1968 and 1971: incomplete mean monthly flows.

They then subjected these data to the following analyses:

- Stage (water level) records were corrected and edited and mean daily readings computed.
- Mean daily flows were computed with the new rating curves.
- Mean monthly flows were computed or compared with mean monthly values for adjacent gauges.
- Computed daily discharge relationships between gauging stations were sought
- For the Belize River gauging stations, mean flows during the 7-year period were directly estimated from the monthly flow relationship with Double Run and run-off values were then computed; the increment of these run-offs over Benque Viejo and Cristo Rey were then computed, compared in order to correct the runoffs and to reassess the mean flows accordingly.
- For the other gauging stations, mean flows and runoff values were assessed by assuming the same runoff as Cristo Rey (Rio On, Rio Frio) or Blue Creek (Aguacate Creek, Moho), by averaging the seven years of available data (for Freetown, Blue Creek) or by assuming runoffs (for Middlesex, Melinda, Kendal, Big Falls and Rio Grande).

- Mean and dimensionless flow duration curves, both monthly and daily, were developed for both the Double Run and the Freetown gauging stations.
- The daily flow duration curves of the different power plant sites were obtained from an average of the aforementioned dimensionless duration curves and mean flow values computed from selected runoff values estimated for the different gauging stations.
- 150-year return period floods were estimated from the maximum daily stage readings and the resulting annual peak daily discharges, by manual plotting of the corresponding ranked floods on probability paper, as well as by the Log Pearson II method.
- Daily and monthly rainfall records were compared and edited to get complete historical records.
- Monthly rainfall records were then correlated between stations as well as with monthly stream gauge records.
- Mean annual isohyets were elaborated for the entire country; missing data were synthesized and filled in.

In the course of this analysis, CIPS identified the following deficiencies and anomalies:

- Inconsistencies between the mean monthly flows for Banana Bank, Big Falls and Double Run due to tidal backwater effects or observer errors
- Poor correlation of flows for gauges in the Moho catchment area as well as for other gauges in the coastal strip.
- Except for Double Run and Freetown, it was not feasible to synthesize the missing data needed to complete the seven years sets, due to excessive gaps and too low coefficients of correlation.
- The runoff increment at the three Belize River gauging stations of Benque Viejo and Cristo Rey are consistent for Double Run and Banana Bank, but much lower at Big Falls.
- Poor correlation of mean flows determined from assumed runoffs for Middlesex, Melinda, Kendal, Big Falls (Rio Grande) confirms the doubts about the validity of the measurements.
- The Blue Creek runoff computed from the mean flow is excessively low.
- The 150-year flood at Double Run is lower that at Big Falls (farther upstream).
- The correlation of monthly rainfall records gave, for most of the pluviometric stations, poor correlation coefficients
- There was also poor correlation between monthly rainfall records and monthly stream gauge flows, and this suggested that rainfall data should not be used to estimate missing stream flow records.

## 5.2 Subsequent and proposed hydrological studies

For the assessment of the hydropower potential of Belize, an important basis will be a reliable hydrological data base, which will be essential for the following tasks:

- Assessing the benefits of the hydropower projects, all the more so since their economic viability may in some cases be dependent on the actual inflows.
- Defining their installed capacities and optimizing the power plant utilization (forecasting)
- Designing the spillway structures for floods of given return periods and determining the corresponding flood hydrographs.

The reliability of the hydrologic base depends on two components:

- The quality of the measurement data bank (quality and quantity of the measurements).
- The accuracy of the data analysis in view of defining the equipment and installations, optimizing the utilization and assessing the project economy evaluation.

The first systematic implementation of stream gauging stations goes back to 1968 with the initiative of S.H. Walker from the British U.K. Directorate of Overseas Survey. After being abandoned in 1971, a new systematic implementation of 17 stations occurred in 1980 under the initiative of the National Meteorological Service, but the 1988 hydrologic data review by CIPS has stressed the poor quality of the measurement data bank (see Section 5.1). Actually, given the limited means at the disposal of the NMS[18], the availability of the data bank must be acknowledged, even if its adequacy for a complete planning is questionable. As the development of the hydroelectric potential in Belize crucially depends on these data, close collaboration between the planning organizations and the NMS will be essential and it is unfortunate that neither the 1988 CIPS review nor the studies related to Mollejon/Chalillo have arranged this, if only for sharing the results of the analyses carried out. At present, data for the following relevant stations[19] are available:

**Pluviometers**

| | | |
|---|---|---|
| • Augustin (Macal River): | 1988 - 1996 | 16°59 / 89°00 |
| • Coocairn (Macal River): | 1965 - 1993 | 16°59 / 88°52 |
| • Chacreek(Macal River): | 2000 - 2006 | 17°06 / 89°04 |
| • Barcreek (Belize River): | 1992 - 2006 | 17°06 / 89°04 |
| • Centfarm (Belize River): | 1966 - 2006 | 17°11 / 89°00 |

18 Conditions are such that the long-term availability of competent and reliable measuring staff has become a problem for NMS so that installing automatic gauges would definitely remedy this situation. As a result, equipment for about seventeen new stations is now stored at the NMS, but the NMS cannot afford their installation.

19 Location of the pluviometric and stream stations are available under www.hydgov.com, however the data themselves have to be requested.

- Spanishl (Belize River): 1968 - 1993 17°13 / 88°59
- Bullrun1 (Sibun River): 1979 - 2006 17°04 / 88°47
- Hershey1 (Sibun River): 1994 - 2006 17°06 / 88°39
- Belmopan (Belize River): 1974 - 2006 17°15 / 88°46
- Hershey2 (Sibun river): 1993 - 2006 17°20 / 88°33
- Pomona01 (Stamm Creek): 1966 - 2006 16°59 / 88°22
- Melinda1 (Stamm Creek): 1973 - 2006 16°59 / 88°19
- Trioblad (Monkey Bladen River): 1989 - 2006 16°27 / 88°38
- Trdp0001(Moho river): 1984 - 1995 16°12 / 89°02
- Puntagor (Moho river): 1966 - 2006 16°08 / 88°51
- Bfalls03 (): 1995 - 2006 16°16 / 88°47

**Stream gauging stations**

- Double Run (Belize River): 1981 - 2003 16°59 / 89°00
- Big Falls (Belize River): 1981 - 2003 Not yet available
- Freetown (Sibun river): 1981 - 2003 17°25 / 88°21
- Benque Viejo (Mopan River): 1968 - 2003 17°04 / 89°08
- San Ignacio (Macal river): 1971 - 2003 17°09 / 89°04
- Cristo Rey (Macal river): 1970 - 2003 17°07 / 89°03
- South Stann (south Stann Creek): 1987 - 1999 16°42 / 88°25
- Kendal Bridge (Sittee River) 1994 – 2003 Not yet available
- Big Falls (Rio Grande): 1981 – 2003 Not yet available
- Blue Creek (Moho River): 1975 – 2003 Not yet available
- Jordan (Moho River): 1993 – 2003 Not yet available
- Blue Creek (Rio Hondo): 1997 – 2003 Not yet available
- Swasey Bridge (Swasey Branch) 1993 - 2003 16°31 / 88°34
- Bladen Bridge (Bladen Branch) 1993 - 2003 16°28 / 88°38
- Hell Gate (Golden Stream) 1994 – 2003 Not yet available
- Medina Bank (Deep River) 1994 – 2003 Not yet available

The gauging stations are the same as those appraised by CIPS in 1988, which suggests that their comments have not yet been taken into account; this may be a consequence of inadequate communication between the two organizations. It should not be overlooked that the poor quality of the data must be attributed to deficient readings and benchmarks rather than to the locations of the gauging stations.

Due to their low number, the pluviometers cannot be representative of the catchments areas, as these have important altitude variations and meteorological influences. Pluviometers should be distributed over the catchment areas according to an appropriate concept taking these factors into account, rather than just their accessibility[20]. These deficiencies may well explain the poor correlation between the measured precipitations and the assessed river runoffs. It could be also explained in certain areas by the karstic characteristics of the bedrock, so that a systematic distribution of pluviometers should be enhanced by a careful hydro-geologic inspection in the catchment areas.

For further studies of hydropower developments, new stations should be set up as soon as possible; these should be automatic stations with data transmission via satellite, to remedy the lack of reliability as well as the difficulty of access in the jungle[21]. Such instrumentation would be also useful for the storage management of Chalillo and the utilization of all present and future schemes on the Macal river.

The eighteen years that have elapsed since 1988 provide a much larger historical database than that available for the CIPS study. Taking into account the pre-1981 measurements (which extend back to 1968) would give a total period of 38 years, which would be acceptable for feasibility studies. Notwithstanding the unchanged location of the gauging stations, an improvement of the post 1988 readings may be expected. Therefore, a comprehensive review of the hydrology appears to be essential and the opportunity could be taken to attempt a consistency check to analyse the present incomplete filling of the Chalillo reservoir.

The NMS has not updated its gauging station rating curves in the past ten years but intends, during the flood period, to send a qualified team to the different gauging stations (according to the meteorological forecasts) to measure higher points of the rating curves[22]. New rating curves should then be computed with all new spot discharge measurements (similar to those done by CIPS in 1988). These rating curves should then be compared to those computed by CIPS and discussions should be held with the NMS.

---

20 Ideal is one pluviometer every 20 km.

21 As their installation implies the use of helicopters, a contribution of the British army, in the scope of their jungle training and in line with some cooperation and humanitarian programme, might be the solution.

22 Checking the calibration of the current meters is highly advisable.

## 6 ENVIRONMENTAL CONSIDERATIONS

In spite of their official approval by the Belize Environmental Committee, Mollejon, but above all Chalillo project faced considerable opposition from environmental NGOs[23]. As a result, construction of the Chalillo project was delayed by about two years. A consequence of this opposition campaign was an increase in public feeling against any new hydroelectric development, even though this may be in the national interest and, nowadays, assessing the environmental impact is an implicit part of any studies of new projects.

On the other hand, the serious ecological impact of other activities such as tourism and the poaching of fauna/flora appear to attract less opposition, with the former being actively encouraged for obvious economic reasons. Uncontrolled clearance of rainforest for human settlements, which also endangers many species, also does not face such concerted opposition.

Now that the Chalillo Dam has been completed its impact on the environment can be assessed in context and it can be seen that important wild fauna are taking advantage of the reservoir [24] whilst its tourist attractiveness will certainly become well-known and of some economical importance. Wild life protection, in and around the reservoir, as well as tourist boat cruises, including introduction to flora/fauna, could be promoted by BECOL with the advice and cooperation of non-profit and non-governmental wild life conservation organizations. Penetrating the forest along the "fiords" that the submergence of small tributary creeks has created is a fascinating way to reach the heart of the Maya mountains. However, the main difficulty in this respect will be the reservoir drawdown, towards the end of the dry season (July), which is the peak tourist period.

A secondary benefit of the Chalillo dam is the seasonal regulation of the river flow which mitigates the excesses of the river regimes, i.e. floods and low flows, thus yielding substantial benefits not only for settlers along the river, and their agricultural activities, but also for some species of wild life (although others adapt to and, to flourish, even require floods).

At present, no alternative and environmentally preferable substitute solutions for generating power in Belize seem feasible. Further thermal generation should be ruled out (with the possible exception of baggasse-fired stations) as climate change is increasingly a matter great of concern, the consequences of which are incalculable.

Due to the pronounced seasonal variations over the year, development of hydroelectric potential unavoidably implies the provision of seasonal storage reservoirs. But, to be effective, storage must on the one hand be located in the upstream part of a river course, on the other, to be economic, it must be located along open valleys of low slope so as to provide the largest impounded volume for a minimum dam height. In terms of ecology, this would mean that reservoirs have to be located in the most remote zones where wild life is the most plentiful.

---

23 See indictment and comments published on internet.

24 Footprints of a big tapir as well as of a small jaguar were identified, and a crocodile was seen near the powerhouse.

Basically, the hydroelectrical potential of Belize is small and a proportion of it could be developed without the need for large storage reservoirs inundating large areas of rain forest. Based on worldwide experience as well as on the lessons that can be learnt from the realization of Chalillo and Mollejon, it appears that development of the Belize hydroelectric potential need not be incompatible with respect for the environment provided that certain basic conditions are scrupulously fulfilled.

- Every endeavour should be made to maximize the quality of the project and its realization. The additional cost is unquestionable but not prohibitive and anyway of little significance compared to the environmental and economical stakes. Two components are essential: geology and hydrology[25]. Matching with the higher international standards and complying with the specific requirements dictated by the tourist appeal of Belize, projects will much more easily benefit from foreign support and subsidies, so that:
  - Whenever economical criteria are similar, the choice between an impoundment scheme and a diversion scheme should be carefully analyzed with respect to environmental criteria, in particular whether the impoundment schemes can operate in run-of-river mode, i.e. without unsightly drawdown below storage level.
  - Whenever possible, underground structures should be selected; this applies particularly to the power stations, and pressure waterways.
  - Switchyards should be gas-insulated (according to the SF6 concept) and located underground - integrated in the power stations - and great care should be taken in selecting the routes of transmission lines.
  - Lastly, appropriate measures should be taken to minimize the reservoir drawdown, even if this implies the need for a larger volume and larger surface area.

- Convergence of the different interests should be reached. For instance, all consequences for the environment and tourism of the access ways created for implementation of a hydropower project should be analyzed with the involved parties, so that a clear policy, compatible with all the various, even conflicting objectives can be defined and implemented. To avoid misunderstandings etc., the local population should be fully and responsibly informed, and to this end an educational campaign of energy consciousness should be initiated.

  In any case, a full Environmental Impact Assessment for each new scheme should be carried out, in conjunction with local organizations involved with the protection of wild life, local professionals in the field of environment and experts at international level. These investigations must comply fully with international standards, such as those issued by the World Bank or WCD.

[25] The cost of any geological or hydrological study being insignificant, compared to the inversion, whereas their importance is crucial: geology for the costs, hydrology for the benefits.

# 7 THE EXISTING CHALILLO/MOLLEJON CASCADE SYSTEM ON THE MECAL RIVER

The two hydro-electric schemes are located on the Mecal river, about 120 km (measured in a straight line) south-west of Belize City. Mollejon, when commissioned in 1996, was the first hydropower station in Belize. Both these power plants, including their electro-mechanical equipment, were designed and built by a Chinese Joint Venture under EPC contracts.

## 7.1 Mollejon

The Mollejon diversion scheme develops a head of about 120 m across a double loop of the river, 20 km south of the town of San Ignacio, by means of a power tunnel about 4.5 km long. The principal dimensions of the scheme are listed given below:

- Scheme type: Diversion run-of-river
- Intake weir crest level: EL 273.5
- Intake weir toe level: Not yet available
- Tailrace water level: EL 143.5
- Low pressure tunnel Ø x L: 4.5 m x 4444 m
- Unit number x type: 3 x vertical Francis
- Turbine rated discharge: 3 x 8.0 = 24.0 m3/s
- Units installed capacity: 3 x 8.4 = 25.2 MW

The intake weir, about 26.5 m high and 150 m long, impounds a daily storage pond with a live capacity of 1.06 million m3.

## 7.2 Chalillo

The recently-completed Chalillo dam and power station, located roughly 15 km upstream of the Mollejon intake weir, is a storage scheme intended primarily to regulate the inflows diverted at Mollejon weir. However, it was found possible to provide it at low cost with a power, situated at the toe of the dam and equipped with two generating units.

- Scheme type: Dam with seasonal reservoir
- Normal Retention Water Level: EL 400.00
- Maximum Flood Water Level: EL 414.50
- Minimum Drawdown Water Level: EL 375.00
- Net storage volume: Not yet available
- Maximum reservoir surface area: Not yet available
- Tailrace water level: EL 360.00
- Unit number x type: 2 x vertical Francis
- Turbine rated discharge: 2 x 10.5 = 21.0 $m^3/s$

- Units installed capacity: 2 x 3.5 = 7 MW

A particular feature of the Chalillo reservoir is its operating drawdown of 25 m, compared to its remaining dead water depth of only 15 m. This is visually intrusive and the operation of the reservoir should be studied in more detail at some later stage to see if the drawdown can be limited somewhat. As the level of the Chalillo reservoir is still 3 m below maximum level at the end of a normally wet season[26], its volume may could be considered excessive. However, provided the installed capacity of the units is sufficient, this excess volume could be used to increase peak generation during the dry season. Alternatively, it could be used to reduce the reservoir drawdown.

With their total head of less than 150 m, the two existing hydropower schemes do not develop even half the gross head of the Macal River, between Chalillo and San Ignacio. Further schemes to harness this remaining have been studies and are discussed in the next capter.

[26] Subject to further analysis

# 8 POSSIBLE NEW HYDROPOWER SCHEMES IN BELIZE

## 8.1 The Vaca Falls project

Located downstream of the existing Mollejon schemes, and about 15 km south of San Ignacio, Vaca Falls would be the third stage of the Macal cascade, or the fourth were Chalillo II to be built, in which case the Macal would be fully harnessed[27] from EL 400 to EL 80, over a distance of 53 km. By taking advantage of the largest catchment area in the Maya mountains, as well of the seasonal regulation provided by Chalillo reservoir, the Vaca Falls Project holds a particular place among potential hydroelectric schemes in Belize.

However, it has still to be decided whether a run-of-river or impoundment scheme should be selected or whether the higher gross head of the diversion scheme would be economically justified. The preliminary salient features of an impoundment scheme are given below with corresponding values for an alternative diversion scheme, as far as these can be determined at present, given in brackets:

- Normal Storage Water Level: EL 143.50; Mollejon tailrace level
- Maximum Flood Water Level: EL 148.50
- Dam toe level: EL 90.0 (EL124.0)
- Net head developed To be determined
- Low pressure tunnel Ø x L: (5.0 m x 2960 m)
- High pressure tunnel Ø x L (3.0 m x 360 m)
- Turbine nominal discharge: 33.0 $m^3/s$
- Units installed capacity: 2 x 9 MW (2 x 7.9 MW)
- Total capital cost of Vaca: To be determined
- Energy generated at Vaca: To be determined
- Operation: To be determined

From the environmental point of view, the Vaca project appears to be able to avoid some of the environmental impacts of the two earlier hydropower schemes but a further full EIA will have to be carried out during more detailed studies and the design phase, when mitigating measures will have to be incorporated in the project. Implemented as an impoundment scheme, and operating in tandem with Mollejon, any water level drawdown should be kept to a minimum, so that the environmental and scenic impacts of the reservoir can be considered as positive; furthermore there appears to be little or no human settlement in the submerged area. The reservoir would submerge the Vaca Falls themselves, but even though these are only rocky sills with a vertical drop of no more than a few meters, it will be very important possibilities for maintaining them as a tourist attraction will have to be studied Implemented as a diversion scheme, on the other hand, without a reservoir, none of the falls would be

[27] In term of gross head geodetically available, irrespective of any economical, geological or environmental consideration.

submerged, so that the impact would be limited to the reduction of river flows in the reach between the intake and tailrace, whereas the following mitigation measures should be contemplated:

- For the very limited periods when there would be no inflow from the intermediate tributaries, provision could be made for a special duct connected to the pressurized tailrace tunnel to allow supplying compensation water at the upstream of the falls. Similar arrangements have been made at other power plants with tourist constraints; alternatively, such releases could be made at the intake structure (headworks).

- The powerhouse and other appurtenant structures should as far as possible be located underground or partly-underground, to reduce their visual intrusion.

- A 4.2 m diameter micro- TBM-excavated, unlined low-pressure tunnel, giving a total head loss of 5.00 m, could be contemplated rather than a 5.0 m drill and blast, unlined tunnel of "V" section, for which the total head loss would be 5.15 m.

- Horizontal Francis turbines could be selected as they are much easier for maintenance and servicing and are compatible with an underground "tunnel" power house of modest cross-section.

- The switchyard can be encapsulated (SF6 concept), this is not only a more environmentally friendly solution but is also common practice nowadays, and could then be also underground.

It should be noted that nor to construct Vaca Falls would bean that advantage would not be taken of the seasonal regulation provided by Chalillo dam, and thus substantial additional power benefits would be sacrificed statement, developing the maximum head available at Vaca Falls appears essential; for instance, the tailrace level should theoretically be at EL 80 (as proposed in the CIPS study), or even lower, rather than at EL 90, as is currently contemplated. Actually, the tailrace level should take into account the change of thalweg gradient, especially if a diversion scheme is selected. If an impoundment scheme is selected, other sites with lower and higher dams and with different reservoirs areas should be investigated.

This priority Vaca Falls project will require careful evaluation at the stage of feasibility study that will in particular address:

- The scheme concept and layout with regard to minimising its effect on the environmental and tourist potential.

- The optimal head to be developed given the morphological features of other possible dam sites, possible combined scheme types, as well as ways of developing of the Macal river downstream of Vaca Falls.

- The optimal use of the intermediate tributaries with regard to future developments.

- The installed capacity needs to be determined on the basis of a careful review of the hydrology.

Indeed, this feasibility study should form part of a comprehensive master plan of the hydropower development of the Macal River, as it is understood that the CIPS study needs to be updated and expanded, taking into account not only the full potential of this river and its tributaries, but also the operation of the completed Chalillo/Mollejon scheme, as well as the most recent hydrological data and environmental findings.

## 8.2 The Chalillo II Project

Between the tailrace level of the existing Chalillo project and the Mollejon intake weir crest level, a distance of only about 10 km, there is a remaining unused gross head of about 95 m. Even if the river gradient over this stretch is less than that utilized by the Mollejon scheme, this head, that could also profit from the seasonal regulation of the Chalillo Reservoir, could be harnessed for the same reasons as the Vaca Falls project, the more so in that it can comply with environmental criteria without need for extensive mitigation measures. Together with Vaca Falls, this scheme would complete the main cascade power plant development of the Macal River, except for any low-head power plants which might be built farther downstream. The following features are considered for the Chalillo II scheme:

- Scheme type: Diversion run-of-river
- Intake weir crest level: EL 360.0
- Tailrace water level: EL 265.3
- Low pressure tunnel Ø x L: 4.2 m x 9000 m (TBM unlined)
- Unit number x type: 2 x horizontal Francis
- Turbine rated discharge: 2 x 10.5 = 21.0 $m^3/s$
- Units installed capacity: 2 x 8 MW
- Net head developed Approx. 90 m

This project can take advantage of the following advantageous features:

- Apparently competent rock for tunnel excavation; the length of the tunnel would certainly justify the use of a small-diameter (micro) TBM (see Section 5)
- Easy access to the construction sites as well as for transmission lines.
- Relatively simple studies as, on the one hand, the need for master planning and optimization seems to be limited and, on the other, a major environmental impact is must not be expected, as a wholly underground project is contemplated.

Optimizing the power plant could well show that the Chalillo II stage should be incorporated in the existing Chalillo I stage, thus utilizing the full head, including that of the Chalillo reservoir, as the incremental cost of the electro-mechanical equipment would be only marginal. The new Chalillo II powerplant would then produce 23 MW and reservoir drawdown would have a much less detrimental influence on the overall production. The two existing 3.5 MW units at Chalillo I could be used as reserves, for instance to use spilled water in the wet seasons.

Because of its favourable features, Chalillo II project could also be considered as the next candidate for development, and it would certainly be interesting and economical to carry out detailed studies of this project at the same time as those of Vaca Falls.[28]

## 8.3 Other Macal River projects, downstream of Vaca Falls

Given, on the one hand, the low river gradient downstream of the Vaca Falls scheme and, on the other, the altitude and the width of the valley, which are insufficient to provide any substantial seasonal reservoir storage volume, only run-of-river schemes can be considered on the lower Macal.

Over a distance of 23 km, downstream of Vaca Falls, at EL 80, the Macal river cuts through the foothills of the Mountain Pine Ridge, down to its confluence with the Mopan River, at EL 48, to form the Belize River. With a slope of only 0.13 % and a rather straight alignment this reach of the river makes any diversion scheme barely economic, so that the only way of utilizing the 32 m head would be to raise the water level as much as possible within its flood valley by means of weirs (gated or not), most probably in steps of approximately 5 m. At each step, standard low-head turbines could be accommodated in small embedded powerhouses. Taking into account the flow of the Vaca Falls scheme, these run-of-river plants could together generate a maximum of 8.4 MW. Their sites may require some resettlement/adaptation of human and tourist activities but they are easily accessible, close to lines of the national power network and environmentally relatively unproblematic.

## 8.4 Sites upstream of Chalillo dam and power station

Due to the relatively flat topography of the Maya mountains, only impoundment developments based on dams could be considered upstream of Chalillo. However, as the Rubber Camp project has already been ruled out due to its environmental impact and the Chalillo power scheme has been developed, albeit only in the face of strong environmental opposition, the potential upstream of Chalillo is considered as non-existent.

## 8.5 Small Macal right bank tributaries draining the Mountain Pine Ridge

A steep stretch of the Rio On, between EL 420 and EL 350, offers favourable conditions for the construction of a small hydroelectric plant which, if provided with daily regulation storage could justify a capacity of about 2 MW. The Privassion Rio offers similar conditions between EL 420 and EL 380, but only for a power plant of less than 1 MW. However, it is considered that such isolated power plants could not comply with BECOL requirements and should be owned and operated by local private organizations, with possibly back-up support from BECOL.

The Rio On Creek and the Privassion Creek are two of a system of parallel tributaries draining towards the Macal River from the Mountain Pine Ridge. These tributaries, all of which are easily accessible from the track linking Guacamallo Bridge with Santa Helena, are:

- First Creek

[28] It could use the same TBM machine as the Vaca Falls project

- Vaqueros Creek
- Planchon Creek
- Mahogany Creek
- Mollejon Creek
- Rio On
- Pinol Creek
- Oak Burn
- Privassion Creek
- Little Vaqueros Creek

These small watercourses could be intercepted by a tunnel of less than 10 km length, designed for free-surface flow and leading to a penstock shaft/high pressure tunnel and a powerhouse taking advantage of the best site available. Alternatively, they could be fed into the low-pressure tunnel of the Chalillo II station by means of secondary intakes. The optimum utilization of this potential should be investigated within the scope of the comprehensive planning of the Macal River, of which the Vaca Falls project is part. If its integration into the Macal system is confirmed, its development will implicitly becomes compatible with the BECOL criteria.

## 8.6 Low-head power plants along the Mopan River

Between the border with Guatemala (KM 250) and its confluence (KM 216) with the Macal River (also called the Belize River Eastern Branch), i.e. over a linear distance of 34 km and a geodetic distance of 15 km, the Mopan River (also called the Belize River Western Branch) drops from EL 102 to EL 48, with a mean discharge of approximately 35 m3/s. These features would favour hydro-electric generation by means of run-of-river low-head power plants in, for example, ten steps of 5m head. Alternatively, taking advantage of the rapids located within the seven upstream kilometres, where the river loses 22 m in altitude, one diversion canal step of 20 m with tailrace at KM 243 could be considered, followed by six steps separated by reaches of 4.5 km.

This cascade system would represent a potential of approximately 15-20 MW (if designed for a discharge greater than the mean annual value). Operating without daily storage, the run-of-river power stations would participate to the coverage of the off-peak demand.

The Mopan valley is already well-served by road and transmission lines. As is also the case for the lower Macal development, these sites may require some resettlement/adaptation of human and tourist activities, but would be easily accessible, close to the national power network and environmentally relatively insignificant. Due to the waterfalls and the steep slope of the river, the backwater should not extend back across the Guatemala border.

## 8.7 The Chiquibul development

At the border with Guatemala, the Ceibo River flows in a gorge at least 350 m deep after draining approximately 625 $km^2$ of the northern slopes of the Maya mountains watershed (the southern slope of which is drained by the Bladen branch of the Monkey River). This site may well offer very good opportunities for building a seasonal reservoir as well as diversion and impoundment schemes, in a similar way as the Chalillo/Mollejon/Vaca development. Even if, compared to Chalillo, the catchment area is smaller (only about 70%), it is likely that its runoff is at a higher rate due to heavier rainfall.

This development would, however, need approximately 12 km of access road from the existing track to Sapote Camp and a 35 km transmission line to the Chalillo powerhouse. Both could gain from the implementation of a border track at present needed to mark and supervise the boundary of the country.

Due probably to the remoteness of this region, to date neither reconnaissance documentation nor hydrological information are available on the Chiquibel projects. A morphological reconnaissance of the sites should now be envisaged, possibly, in such a hazardous and remote area, to be coordinated by the Belizean and British armies. Then, if the potential is confirmed, automatic stream gauging stations and pluviometers should be installed (see Section 7).

## 8.8 The Bladen branch development of the Monkey River

Draining approximately 300 $km^2$ of the southern slope of the Maya mountains watershed, the Bladen branch of the Monkey River can be seen as the symmetrical development of the Chiquibul Project with respect to this watershed. It should benefit from the highest precipitation for Belize and thus will require seasonal storage.

However, the development of the hydroelectric potential in this valley will be mainly governed by the karstic nature of the limestone. Only a careful review of the morphology, based on comprehensive site visits, will enable the optimal development of this difficult valley to be defined and an assessment to be made of whether it can be made economically viable. Therefore, the following comments can only attempt in the first resort to complement the findings of the CIPS project.

In 1988, with a kWh cost of USD 0.39, the CIPS project could only be justified by a very high diesel generation cost. Since then, interconnection to the national BEL network of the small towns and communities has significantly increased the profitability of such a development, as it can now be exclusively dedicated to supplying peak power to local consumers, even though this makes it even more reliant on the technical feasibility of a complementary seasonal storage.

Upstream of the low and flat coastal zone (with a gradient comprised between 0.166% and 0.038%), the steep valley of the Bladen branch (gradient between 0.6% and 0.5%) cuts through apparently highly-karstic limestone. In spite of the relatively low thalweg gradient, therefore, a diversion scheme appears a priori more feasible than an impoundment scheme, due to the fact that for the latter karstic features can require very costly, or even impractical remedial measures. On the other hand, provided that imperviousness of the low-pressure tunnel can be assured by restricted concrete-lined stretches, the limestone may in fact be a good material for rapid and economical low-pressure tunnel excavation using a small TBM.

A minimum project would require a diversion structure between KM 53 (Richardson Creek confluence) and KM 46 for a geodetic head of 38 m, with a tunnel of 5 km. Better, however, would be to identify an appropriate site for a seasonal storage somewhere in the upstream reach, e.g. between KM 67 and KM 53, and to complement it with a low-pressure tunnel serving the power station site of the no-storage alternative. In accordance with the typical development sequence (see Section 5), there is likely to be a certain potential for small high head power plants along the upstream tributaries of the Bladen Branch.

The runoff coefficient of 0.024 $m^3/s/km^2$ (1260 mm/a) considered by CISP seems inconsistent with that of 0.04$m^3/s/km^2$ considered for the Swasey Branch (see below), as it should be greater according to the Belize isohyetal map, which shows over 160 inches per year (i.e. 4100 mm/a). Such a discrepancy between the runoffs of the two adjacent catchment areas could be consistent with the karstic features of the Bladen valley limestone, suggesting a possible transfer of runoff. However, the lower runoff coefficient of the Swasey Branch remains to be clarified.

It should be noted that in 1988 there was no gauging stations on the Monkey river; so that the CIPS evaluation had to be done based on estimated, possibly erroneous values of runoff and mean discharge (see Section 2). The newly available data, for the past ten years, allow a mean discharge of xxx m3/s to be assumed, although it should be emphasized that the same remark applies also to the Swasey branch project.

## 8.9 The Swasey branch development of the Monkey River

Development of the Swasey branch of the Monkey River can take advantage of the following favourable geomorphological conditions:

- V-shaped valley
- Strong and competent Paleozoic Schists

CIPS considered a dam type power plant located at KM 65 (EL 55-47), immediately downstream of the confluence with Sapote Creek, i.e. upstream of the rapids. This is definitely reasonable due to the low gradient of the river (0.33%). Any location further upstream, aimed at extending the dam scheme with a diversion tunnel to increase the head, would be less economical, not only due to the low river gradient but also to the smaller catchment area developed.

However, in line with the remark made on the Bladen branch project, the recent availability of the national transmission network, and the possibility of exporting peak power and importing power outside of this period, changes the vocation of this development, but calls for a seasonal storage. This could be achieved by locating the dam further downstream, whilst keeping the reservoir level the same. The impoundment scheme could be enhanced by an upstream diversion scheme with an unlined power tunnel excavated by TBM. Moreover, a concrete face rockfill dam (CRFD) utilizing, if possible, the tunnel spoil, could be less expensive than the proposed concrete gravity dam.

### The South Stann Creek project

All features and proposed enhancements related to the Swasey branch project apply to the South Stann Creek project, with the difference that a rockfill dam alternative, making use of the alluvium available in the downstream part of the valley, should be considered. Provision of seasonal storage, just like the run-of-river alternative, may face environmental difficulties due to the submergence of an area of 7 km2 of jungle in the jaguar reserve. A fully underground diversion scheme, taking advantage of gradients of between 2 % and 4 % from EL 220 to El 80, with an unlined low-pressure tunnel of 2 - 3 km, could still be economical.

## 8.10 Other sites

Based on a cartographic survey only, the following other interesting catchment areas could be identified:

- Trio Branch (tributary of the Bladen Branch, Monkey river)
- Sittee River
- Blackwater Branch (tributary of the Freshwater Creek)
- Sibun gorge on the upstream stretch of the Sibun River
- Hidden Valley Falls (1600 ft)
- Barton Creek

Sites for power plants in these areas have not yet been identified, but, it must be expected that tourism and environmental organizations will strongly oppose them: For this reason they will need to be studied very carefully and can, therefore, at this time only be designated as second priority.

# 9 CONCLUSION

A small hydroelectric potential exists in Belize which could be developed to contribute a considerable proportion of the present demand of the country and would have the following advantages:

- Freeing the electricity supply of the risk of sudden rises in the oil price and the unavoidable consequences for domestic power bills as well as for the economy of the country as a whole.
- Improving supply reliability and limiting dependence on the import of energy on which Belize depends at present.
- Improving the balance of trade by reducing the import of oil and electricity.
- Contributing to the reduction of carbon dioxide emissions, in compliance with the most urgent environmental criteria[29].

Studies should be made to assess the technical feasibility of the identified hydropower schemes and to determine their economic rates of return, as alternatives to thermal generation.

Due to the seasonal variation of precipitation and river discharge, deveopment of this potential inevitably implies the provision of reservoir storage capacity, and this in turn increases the environmental impact of the scheme(s). Detailed EIA studies are therefore essential to determine if such storage projects are acceptable and to define necessary mitigating measures. In this respect, several lessons can be drawn from the existing Chalillo and Mollejon schemes:

- The seasonal fluctuation of reservoirs, as much as the valley inundation in the first place, is serious environmental impact, so that possible mitigating measures to limit reservoir drawdown need full analysis.
- Every endeavour should be made to minimize the visual environmental impact: most obviously by selecting as far as possible underground structures (waterway tunnels, cavern power houses, encapsulated switchyards) whilst giving consideration to the architectural design of those structures which have to be located surface.
- Environmental impact assessment investigations and studies must be carried out in accordance with best international standards.
- Responsible wild life and nature protection organisations must be involved from the early stages in the planning of hydroelectric development and synergy should be promoted.

---

29 Raising by 2 m the sea level, as it is could occur within 50 years if the carbon dioxide emanations continue at the same rate as now, would result in the loss of 10% of Belize territory, particularly of the tourist coral islands

Developing the hydroelectric potential in Belize implies a need to make full allowance for:

- The difficult accessibility of access to many sites
- The still-limited availability of basic data (hydrological, meteorological etc.)
- The marginal economic return of the projects and its close dependence on the reliability of the hydrological assessment.
- The importance of thorough feasibility studies (technical, economic, environmental and social-economic)
- The time required to obtain permissions from all authorities despite the urgency of the need to develop more capacity.

To respond to the above constraints, a prioritised development programme is suggested, as detailed below:

- One or two projects should be selected, depending on their level of maturity, for optimisation as part of a master plan, and their study should be completed without delay in order to be able to initiate the construction as soon as possible
- As a consequence of the realisation of the Chalillo seasonal reservoir, priority should be given to completing the harnessing of the Macal river and, from the environmental point of view, the Chalillo II and the Vaca Falls projects appear particularly favourable for early study.
- Not to develop schemes further downstream on the Macal river would mean that full advantage would not be taken of one major benefit of the existing Chalillo dam and reservoir, i.e. the seasonal regulation of the flow.
- At the same time, topographic and geological investigations, as well as a full assessment of hydrological data should be carried out for projects in areas located close to the centres of consumption; these could be the lower Macal and the Mopan low-head developments.
- Topographic and geological reconnaissance activities, and map studies, should be initiated for projects in other areas such as the Monkey river valley and, should the potential for hydroelectric development here shows promise, the installation of automatic hydrologic measuring stations should be considered.
- Establishment of the contracts necessary to investigate the potential of remote sites such as those of the Chiquibul projects.
- A programme of support to the National Meteorological Service should be promoted with the aim of improving and facilitating collection of data. Stream and pluviometric stations should be installed in the upper Macal catchment area, in view of the future development of the Vaca Falls, Chalillo II and low-head projects, as well as to optimize reservoir management.

Given the difficulty of and time needed for installing hydrological stations in the more remote areas, this work should be initiated as soon as office review studies and geological site inspections have identified promising projects. The next phase of studies should be concentrate on:

- Geological and hydro-geological inspection of all sites; a mission with a geologist/hydrogeologist should be initiated to assess:
  - The Vaca Falls and the Chalillo II projects
  - The Lower Macal and Mopan projects
  - The Monkey River projects (Bladen and Swasey)
  - The Chiquibul Project, if possible.
- Hydrological review, based on the new data
- Feasibility studies, tender documents and final design of the Chalillo II and Vaca Falls projects: review of hydrology, geology; benefits and capital costs, cost of operation and maintenance, cost of kWh, layout, design; Financing

Pre-feasibility of low-head projects on the lower Macal River, as well as on the Mopan River based, on 1/1000 topographical maps.

**Fig. 1: Chalillo Dam**
Height above foundation: 60 m. Capacity 7 MW.
The RCC steps on both sides of the service spillway, serve as energy dissipation device for the emergency spillway. At the Dam toe, the Powerhouse with its unfortunate blue roof.

**Fig. 2: Chalillo Dam**
By pure coincidence, the steps of the RCC gravity Dam have very fortunately given a Maya like architecture that achieves an integration of this massive construction in the environment.

**Fig. 3: Chalillo Dam**
The Chalillo Dam from upstream. At the end of the wet season, the water level is still 3.2 m below the spillway crest sill. If hydrologically confirmed, this could be used to reduce the reservoir drawdown.

**Fig. 4: Chalillo Reservoir**
Part right upstream of the dam. In the background, the upstream part of the Reservoir turns to the left, see Fig. 5-6.

**Fig. 5: Chalillo Reservoir**
On the left of the picture, the tail of the Reservoir disappears in the rainforest. The downstream extension can be seen on Fig. 6 (panorama, with the protruding bush is overlapping).

**Fig. 6: Chalillo Reservoir**
The Mountain Pine Ridge, in the foreground, showing the devastation on the pine trees caused by the 2002 insect pandemic that occurred before the dam was built.

**Fig. 7: Mollejon Intake Dam**
Small gravity concrete dam with uncontrolled overflow spillway commissioned in 1996. It serves as intake dam; daily storage and regulation pond.

**Fig. 8: Mollejon Intake Dam**
Spillway crest at EL 265.3. Dam toe flip-bucket. The water level reaches the crest sill after a Chalillo operation cycle, then is drawn down during the 3 hours peak demand period.

**Fig. 9: Mollejon Low Pressure Tunnel Intake**
The intake structure includes a large concrete structure accommodating a bridge crane for moving the stoplogs elements and cleaning the trash-rack.

**Fig. 10: Mollejon Daily Storage Reservoir**
Small run-of-river reservoir with a length of about 2 km well integrated in the rain-forest environment. The daily drawdown during the peak-hours is hardly noticeable.

**Fig. 11: Macal River downstream of the Dam**
Still water at the impact area of the flip bucket jet downstream of the spillway. As the Mollejon powerplant implements a diversion scheme, the river flow is discontinued in the upstream part of the valley.

**Fig. 12: Mollejon Powerhouse**
The powerhouse of the Mollejon HEPP roofs 3 vertical Francis units of 8.4 MW each. Conventional switchyard. Between the powerhouse and the river, with a tailrace level at EL 143.5.

**Fig. 13: Vaca Falls Dam Site on the Macal River**
Impoundment alternative. Gravity dam: Normal water level at EL 143.5; Crest at EL 150; Toe at EL 90. right abutment area where the forest has been felled. Rock sill of the so-called Vaca Falls.

**Fig. 14: Vaca Falls Dam Axis - Left Abutment**
Impoundment alternative. Left abutment with the dam axis benchmark B1. The outcropping massive granite shows favorable conditions for dam foundations.

**Fig. 15: Vaca Falls Dam Site - Upstream**
300 m upstream of the dam axis, another Vaca Fall. The picture shows the downstream area of the future reservoir should the impoundment alternative would be selected.

**Fig. 16: Vaca Falls Dam Site - Downstream**
The picture shows the river bed downstream of the dam axis with another Vaca Falls rock sill. Downstream of this sill would be located the powerhouse of the diversion alternative.

**Fig. 17: Vaca Falls Dam Site - Granite**
Detail of the rock in the dam foundation area showing the massive nature of the intrusive macro-crystalline granite with its inclusions of sedimentary material.

**Fig. 18: Vaca Falls Powerhouse Site**
A few hundred metres downstream of the contemplated dam axis, the powerhouse site of the diversion alternative. Less favorable morphology for a 10 m higher dam.

**Fig. 19: Blackrock Curve Upstream Stretch**
At a distance of approximately 5 km downstream of the Vaca Falls dam site, the steep Blackrock reach of the Macal River still shows favorable morphology for hydroelectric development.

**Fig. 20: Blackrock Curve Downstream Stretch**
The Macal River slope has substantially reduced so that diversion schemes can basically no more be economical, whereas the implementation of higher dams is questionable.

**Fig. 21: Blackrock at U/S Fall > U/S**
Rock sill downstream of the Blackrock curve (see above pictures). The Macal River flows in a relatively narrow V-shaped valley cut in the black schist.

**Fig. 22: Blackrock at U/S Fall > D/S**
High dam implementation is quite unlikely in this very foliated schist. On the other hand, it could be quite acceptable for low-head hydroelectric development.

**Fig. 23: Blackrock at U/S Fall > Right Bank**
View of the right bank of what could be the axis of a low-head powerplant. Due to the tributaries, despite the Mollejon powerplant not being operated there is a considerable flow in the river.

**Fig. 24: Blackrock at U/S Fall > Schist**
Detail of the schist massive showing some strong foliation. In spite of the clear signs of erosion, the transportation of sediments is relatively moderate due to the strong biomass cover.

**Fig. 25: Blackrock at U/S Fall - Upper Limestone**
The upper part of the valley displays the Pleistocene Limestone, followed by overburden materials covered by the rainforest. Concretion formed by small tributaries witness this limestone.

**Fig. 26: Blackrock at U/S Fall - Upper Limestone**
Detail of the karstic features of the Limestone upper cover. Unfortunately, this Limestone cover is systematically present in the May Mountains, and may jeopardize prospects for storages.

**Fig. 27: Blackrock at D/S Fall > U/S**
This Fall corresponds to the ultimate sill of the Macal river.

**Fig. 28: Blackrock at D/S Fall > D/S**
Downstream of this rocky sill, the Macal River flows smoothly down to San Ignacio, then to its confluence with the Mopan river, where it forms the Belize River.

**Fig. 29: Blackrock Downstream > U/S**
In spite of a better accessibility, the Macal Valley is practically devoid of human installation, even along the orchards area, so that resettlement for low-head powerplants should not be a problem.

**Fig. 30: Blackrock Downstream > D/S**
The clearly subcritical lower reach of the Macal River can be influenced by the Belize River backwater whenever it is swollen by the Mopan flood discharges.

**Fig. 31: First Creek**
The First Creek is indeed the first of 9 right bank Macal River tributaries, draining the southern slope of the Pine Mountains, that are encountered along the track from Mahacunga Bridge to Santa Elena.

**Fig. 32: Vaqueros Creek**
Then follows the Vaqueros Creek, that, similarly to the First Creek, shows neither important discharge nor large slope. Neither of them is equipped with any stream gauging station.

**Fig. 33: Mahagony Creek**
The Mahagony Creek, just like the following Mollejon Creek, has not much more flow, but substantially more slope. These 4 creeks have never been considered for power generation.

**Fig. 34: Mollejon Creek**
The Mollejon creek joins the Macal River right at the site where the dam and Intake of the Mollejon powerplant are located. This creek has no flow measurement station.

**Fig. 35: Rio On**
With the Privassion Creek, the Rio On Creek is the only other stream considered by CIPS for development. A stream gauging stations was operated from 1971.

**Fig. 36: Pinol Creek**
In spite of its relatively small slope, the runoff of this small stream appears to be of some importance even if it was neither considered by previous studies, nor equipped with stream gauges.

**Fig. 37: Oak Burn**
The same remark as made for the Pinol Creek applies to this stream. If utilized as stand alone powerplant, it is clear that this potential does not match with the contemplated development criteria.

**Fig. 38: Privassion Creek**
With substantially higher runoff, this creek was identified by CIPS (1988) for a powerplant supplying a local network.

**Fig. 39: Little Vaqueros Creek**
The Little Vaqueros is the last creek encountered along the track between the Guacamallo Bridge and Santa Elena.

**Fig. 40: Mopán River at Melchor > U/S**
After flowing already 3 km in Belize, the Mopán River makes a small meander inside Guatemala, right at its border town Melchor, from the bridge of which the picture was taken.

**Fig. 41: Mopán River at Melchor > D/S**
View from the bridge at Melchor. Further downstream, the Mopán River flows in the Belize territory over a geodetical distance of 15 km, down to its confluence with the Macal River.

**Fig. 42: Mopán River at Benque > D/S**
From Benque (2 km downstream of Melchor) at EL 102 to the confluence with the Macal River at EL 50, most of the 52 m head is lost along a series of falls starting at short distance from the border.

**Fig. 43: Mopán River at KM2 > U/S**
The Mopán River shows an important runoff, a strong longitudinal slope, a well embedded thalweg as well as quasi virgin banks lending itself to low-head powerplants.

**Fig. 44: Mopán River at KM2 > D/S**
The low-head powerplants would be fully run-of-river, thus generating also during the period outside the peak hours and substituting part of the imported energy.

**Fig. 45: Mopán River at KM4 > U/S**
Further downstream, the Mopán River flows practically without falls, in the subcritical mode. The falls being located upstream, the powerplant backwater should not affect Guatemala.

**Fig. 46: Mopán River at KM4 > D/S**
In the picture background, the Mopán River flows in a very wide bed, then branches around an island, which are not quite favorable for the implementation of a dam.

**Fig. 47: Mopán River at Clarissa > U/S**
The Mopán River development would seek for optimum weir locations, with steps of approximately 5 m. The weir should be designed as a barrage with gates being fully open in case of floods

**Fig. 48: Mopan/Macal Rivers Confluence > D/S**
In the right of the picture, the Macal River, in the left, the Mopán River and in the background, the Belize River flowing down to Belize City where it flows into the Atlantic.

**Fig. 49: Chalillo Reservoir**
Foot prints of a big tapir.

**Fig. 50: Chalillo Reservoir**
Foot prints of a young jaguar.

**Fig. 51: Vaca Falls Project**
Opening an access with a machete.

**Fig. 52: San Ignacio**
Colonial architecture.

**Fig. 53: National Meteorological Service**
The NMS building at the Belize City airport

**Fig. 54: Belize River mouth in the Atlantic**