COMMONWEALTH SECRETARIAT

IWOKRAMA

Newcastle University

Initial Assessment of the Climate of Guyana and the Region with a Focus on Iwokrama

Hydrological Monitoring & Modelling Strategy

A 4 month pilot study supported by the Commonwealth Secretariat in collaboration with the Iwokrama International Centre for Rainforest Conservation and Development

June 2009

Geoff Parkin
C. Isabella Bovolo
Thomas Wagner

School of Civil Engineering & Geosciences
Newcastle University
Newcastle upon Tyne. NE1 7RU, UK

The full report should be referenced as follows:

Bovolo C. I., Parkin G., Wagner T. (2009) *Initial Assessment of the Climate of Guyana and the Region with a Focus on Iwokrama.* Report produced for the Commonwealth Secretariat. School of Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne, UK

The report has 4 sections. If referencing individual sections only, please reference these as follows (the current section is highlighted in bold):

Bovolo C. I., Parkin G., Wagner T. (2009) *Initial Assessment of the Climate of Guyana and the Region with a Focus on Iwokrama, Main Report.* Report produced for the Commonwealth Secretariat. School of Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne, UK

Bovolo C. I., Parkin G., Wagner T. (2009) *Initial Assessment of the Climate of Guyana and the Region with a Focus on Iwokrama, Part A Appendices – Data Availability.* Report produced for the Commonwealth Secretariat. School of Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne, UK

Bovolo C. I., Parkin G., Wagner T. (2009) *Initial Assessment of the Climate of Guyana and the Region with a Focus on Iwokrama, Part B Appendices – Climate Overview*. Report produced for the Commonwealth Secretariat. School of Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne, UK

Parkin G., Bovolo C. I., Wagner T. (2009) *Initial Assessment of the Climate of Guyana and the Region with a Focus on Iwokrama – Hydrological Monitoring & Modelling Strategy.* Report produced for the Commonwealth Secretariat. School of Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne, UK

INDEX

List of Figures

1 Introduction

This short report is the final part of a pilot project funded by the Commonwealth Secretariat to collate and analyse climate/hydrology data related to the Iwokrama International Centre for Rainforest Conservation and Development, Guyana. The data collection and climate analysis parts of the project are reported in Appendix A – Dava Availability and Appendix B – Climate overview of Bovolo C. I., Parkin G., Wagner T. (2009) *Initial Assessment of the Climate of Guyana and the Region with a Focus on Iwokrama.* School of Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne, UK.

Water is central to the management and utilisation of the natural capital of rainforests, as it directly or indirectly supports many of the ecosystem services supplied by rainforests, including climate and water regulation, water supply, erosion control and sediment retention, soil formation and nutrient cycling, waste treatment, and ecological and amenity functions supported by the forest growth itself. Any assessments of rainforest ecosystem services and their link to the climate assessments of this pilot project therefore must begin with quantification of components of the water cycle itself.

Water cycling is usually considered at the scale of a catchment, a discrete area of land which drains all precipitation falling within the catchment boundary through a single discharge point on a stream or river. There are many approaches that can be used to quantify water flows, with a wide range of catchment models available. This report provides an outline of a general strategy for how climate and hydrological monitoring and catchment models can together be used to help quantify some of the key ecosystem services provided by rainforests at Iwokrama. The data sets available from the pilot project are not, however, of sufficiently high quality to make construction of preliminary catchment models meaningful at this stage.

2 Outline climate/hydrology monitoring plan for Iwokrama

The proposed hydrometeorological instrumentation and monitoring for Iwokrama is designed not only for a single research project with a single aim, but is intended to serve a broad science community who may have different research interests at Iwokrama related to forestry management and climate change over an extended period of time. The general instrumentation and monitoring strategy is therefore based on the following concepts which attempt to anticipate the different needs which may arise in the future to address issues across different scales:

- **Characterising forest management impacts**
  A paired catchment approach is proposed focussed on the 8-mile Bridge to 24-mile Bridge area of the Iwokrama forest (see Figure 1), in which identical instrumentation will be installed in two similar small catchments, one of which will be harvested within the next two years, the other not being harvested for at least 5-10 years. Two catchments will be monitored in parallel for the period before harvesting, with the period after harvesting providing the contrasting conditions in which the impact of selective logging can be investigated. This proven approach has previously been used in many hydrological studies, including clear-felling studies in the Amazon basin. Monitoring of additional catchments will establish the hydrological behaviour of different landscape types, characterised by topography, forest cover, soil types, climate regime etc.

- **Quantifying rainfall and evapotranspiration budgets at different timescales**
  Many of the forest ecosystem services (e.g. regrowth rates and carbon sequestration) are mediated through water cycling. A primary aim of the instrumentation is to provide information which can help to quantify the main components of the water balance for the Iwokrama rainforest reserve (rainfall, evapotranspiration, and runoff), and to characterise these

at storm, seasonal, and inter-annual timescales. These will also help to support other more detailed studies on nutrient cycling and other related research.

- **A transect through the climate transition zone**
This pilot project, as well as other international studies on regional climate patterns, indicate that Iwokrama is located at a key transition zone between the coastal-influenced climate with higher annual rainfall and two wet seasons, and the drier continental climate typically with a single wet season. The presence of the Rupununi savannah area to the south of Iwokrama also provides an interesting hydrometeorological contrast. The proposed instrumentation is therefore intended to characterise these regional scale transitions/contrasts, taking a north-south transect through the transition zone.

The proposed locations of the field equipment are shown in Figure 1, which are designed to address the multi-scale concepts for forestry management and climate assessments outlined above (note that each weather station, and one of the central catchment areas near Big Turu, include a raingauge).

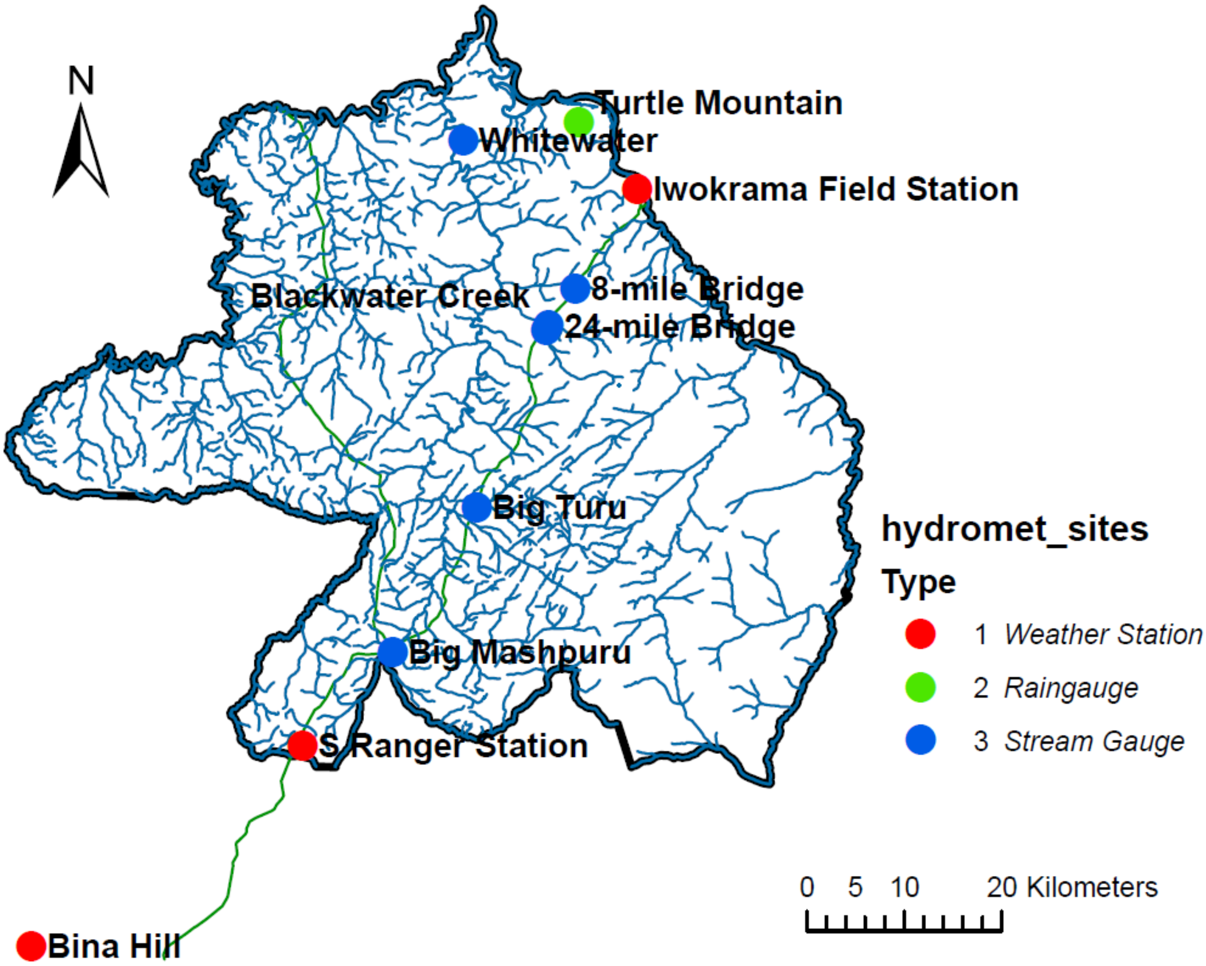

Figure 1 Proposed field instrument locations in and near the Iwokrama forest reserve.

3 Outline hydrological modelling strategy

3.1 Types of catchment models

There are many types of catchment models available, and the choice of an appropriate model for a given application depends on a range of factors, including purpose, data availability, level of conceptual understanding, and time/resources available to complete a study. Models can be classified into *empirical* and *physics-based*. Empirical models are those which aim to find a relationship between sets of variables, without attempting to define any physical basis to the relationship. A physics-based model is one which is constructed on the basis of mathematical relationships which define a set of underlying physical principles. Models can be used in an *interpretive* mode, where they provide a means of analysis of an observed data set to help understand how different variables are related (e.g. forest type and evapotranspiration), or in a *predictive* mode, where they are used to assess the impacts of some external driver (e.g. the impact of climate change on river flows).

The simplest modelling approach is that of *lumped* water balance models. In these, a region is specified (usually a catchment), and an assessment is made typically at annual or sometimes monthly timescales involving calculation of all inflows (e.g. precipitation), outflows (e.g. river discharge, evapotranspiration, abstractions), and changes in internal water storage (including soil and groundwater storage).

Lumped models do not however provide any representation of how water moves within catchments, which is needed to support most studies of the transport of substances such as sediment or nutrients. For many such studies, therefore, *spatially-distributed* models are required. These are based on mathematical (partial differential) equations describing processes as a function of water levels or pressures distributed in space in one, two or three dimensions (x, y, z), and time (t). To use these models, it is necessary to define the geometry of the region over which the equations apply (e.g. the catchment boundaries and soil depths), the boundary conditions (e.g. river or lake levels if these are at the boundary of the model), physical properties and how they vary over space (e.g. hydraulic conductivities, river roughness coefficients), inputs and outputs (including precipitation, potential evapotranspiration, abstractions etc), and initial conditions for a transient model (e.g. groundwater or soil water levels at a specific time after which model predictions are made). These models can then give detailed outputs at any point within the catchment (i.e. distributed outputs), such as river discharges, evapotranspiration rates, canopy storage, and throughfall for different vegetation types, groundwater levels, soil water content etc, as well as overall catchment water balance. They can also form the basis for distributed modelling of soil erosion and sediment movement, and transport of solutes such as nitrates.

There are many other types of models of intermediate complexity, such as semi-distributed or transfer function rainfall-runoff models. In general, the more complex spatially-distributed models require substantially more effort and data than simpler models, but can provide more detailed understanding of the relationships between external drivers of change and hydrological responses. However, for any of these models, questions of model calibration and validation and estimations of predictive uncertainty have to be addressed.

Catchment models are often usefully coupled to other models, to describe and quantify processes related to the water cycle including possible feedback mechanisms. For example, models of forest growth are closely coupled to the water cycle, as growth rates depend on water availability, but are also closely linked to evapotranspiration rates. Different feedback mechanisms can occur across vastly different timescales and spatial scales, may require specific data to be collected, and are often difficult to understand and interpret.

3.2 Hydrological modelling strategy

This section provides a preliminary outline hydrological modelling strategy for how catchment models can support quantification of the impacts of climate change and forest management on water-dependent ecosystem services at Iwokrama. More detailed modelling strategies will be required to address specific issues.

Water balance for the Iwokrama Forest Reserve
A first stage of understanding the water cycle in a region is to estimate an overall water balance. This requires calculation of each water balance component, including: rainfall, actual evapotranspiration, river and stream flows, surface and subsurface flows across the boundaries of the region, and changes in internal water storage (soil water and groundwater). The boundaries of the region over which the water balance is calculated need to be specified, and balances are typically calculated on a monthly or annual basis. It should be noted that there are usually significant errors associated with some components of the water balance, particularly evapotranspiration, and accurate 'closure' of the water balance for an area can be difficult. It may be more useful in some cases to focus on the sensitivity of water balance components to change, for example to climate or forest cover.

For the Iwokrama Forest Reserve, there are currently insufficient data to make a first estimate of the overall water balance until a period of monitoring using the proposed instrumentation has been completed. The key component of rainfall will be monitored along a transect to cover the north to south gradient, and over at least some of the elevation range. The weather station data will allow first estimates of potential evapotranspiration rates to be calculated, although actual evapotranspiration estimates from heterogeneous rainforest cover will have significant uncertainty. The boundaries of the region include two rivers, the Essequibo and the Siparuni – estimates of the magnitude of flows into these rivers along their banks will be required. As there are no suitable measurements of river flows in this region, estimates can be made from analogue calculations from monitored catchments within the region.

Water balance estimates at Iwokrama can help in understanding climate and water regulation, and water supply, through understanding of the components of overall rates of evapotranspiration and runoff. More regional scale analyses would, however, is needed to support research into climate feedback mechanisms.

Lumped water quality modelling
A comparable approach to the water balance can be taken to assess aspects of water quality at the catchment scale, based on some simplifying assumptions. Regular collection of water samples from rivers or streams and analysis of water quality parameters can be used to make broad inferences about flow pathways in catchments (surface, near-surface or groundwater) based on hydrochemical flow separation, with assumptions regarding the mixing of solutes within the catchment. This relatively simple method has been used to interpret large-scale flow mechanisms for sub-basins of the Amazon [1].

Lumped water quality modelling with appropriate data sets can help in understanding overall hydrological pathways carrying nutrients through soils and rivers.

Distributed catchment hydrology modelling
Physically based spatially distributed (PBSD) hydrological modelling systems offer the capability to model the terrestrial part of the hydrological cycle in detail. Physical processes (overland flow, subsurface unsaturated and saturated flow, river/aquifer interactions and vegetation interception and transpiration) are simulated using physically-meaningful parameters which relate directly to the physical characteristics of the catchment (topography, soil, vegetation, geology), taking account of the

spatial and temporal variability of meteorological conditions. Despite computational demands and requirements for large number of input and validation parameters, PBSD models can be used in a predictive manner due to their physically-based nature and are therefore suitable for estimating the environmental impacts of climate change and landuse change. They also offer the possibility of testing hypotheses mathematically rather than by field trials and can help test, interpret and communicate field data and results.

The general approach to using distributed models is to first establish the models capabilities through testing the model outputs against field observations. The traditional approach to this stage of model development is through calibration and validation, although more recently many methods focus on the predictive capability of models through uncertainty analysis. This stage also allows interpretation of the field observations, and is often useful in establishing any inconsistencies between observations which leads to deeper understanding of hydrological mechanisms. A benefit of distributed models is that they predict internal variables within catchments (for example, soil moisture) as well as river flows, allowing more detailed analysis of catchment processes, if appropriate data are available. Once a model has been shown to represent observed data adequately (i.e. once it is shown to be 'fit for purpose'), it can be used to predict the impact of changes on hydrological responses.

For Iwokrama, distributed catchment models can be used in a number of ways, including:

- Characterising the hydrological responses of catchments representing different landscape types (e.g. mountainous/lowland, permeable/impermeable soils, different forest cover). This will help to support overall water budget calculations for the whole forest reserve.
- Interpretation of the impacts of forest management in the paired catchment monitoring experiments.
- Assessing the sensitivity of catchment responses to climate change, particularly related to floods and droughts.
- Providing detailed representations of water flows in catchments for analysis of sediment and nutrient transport studies.

Catchment sediment and nutrient modelling

In general, models of transport of any substances through catchments are significantly more difficult than modelling flow alone, although this is a rapidly developing field. Models related to the forest ecosystem services of soil erosion, sediment loss, and water quality (e.g. nutrients) are available, coupled to catchment hydrology models. The hydrological model components are normally developed first, to ensure that an adequate representation of catchment water flows has been established, followed by development and testing of the transport models against water quality and soil/sediment data collected for this purpose. As discussed above, however, water quality data can also help to constrain interpretations of flow mechanisms.

3.3 The SHETRAN catchment modelling system

It is proposed to use the SHETRAN hydrological modelling system [2], developed at Newcastle University, as the main modelling tool for hydrological studies at Iwokrama. SHETRAN is a physically-based spatially distributed 3-D coupled surface-subsurface finite difference model for coupled water flow, shallow landslide and debris flow, multifraction sediment transport and multiple reactive solute transport in river basins and provides a complete hydrological description of the spatial-temporal dynamics of a catchment at any given time and point.

In particular it simulates:
- the land phase of the hydrological cycle, accounting in a fully integrated way for vegetation interception and transpiration, overland flow, variably saturated subsurface flow and river/aquifer interaction;
- sediment yield as a function of soil erosion by raindrop impact and overland flow and transport by overland and channel flow;
- contaminant transport through surface and subsurface, including nitrogen transformations.

Within SHETRAN, the spatial distribution of catchment properties, rainfall input and hydrological response is achieved in the horizontal direction through the representation of the catchment and its channel system by an orthogonal grid network (Fig. 2) and in the vertical direction by a column of horizontal layers at each grid square.

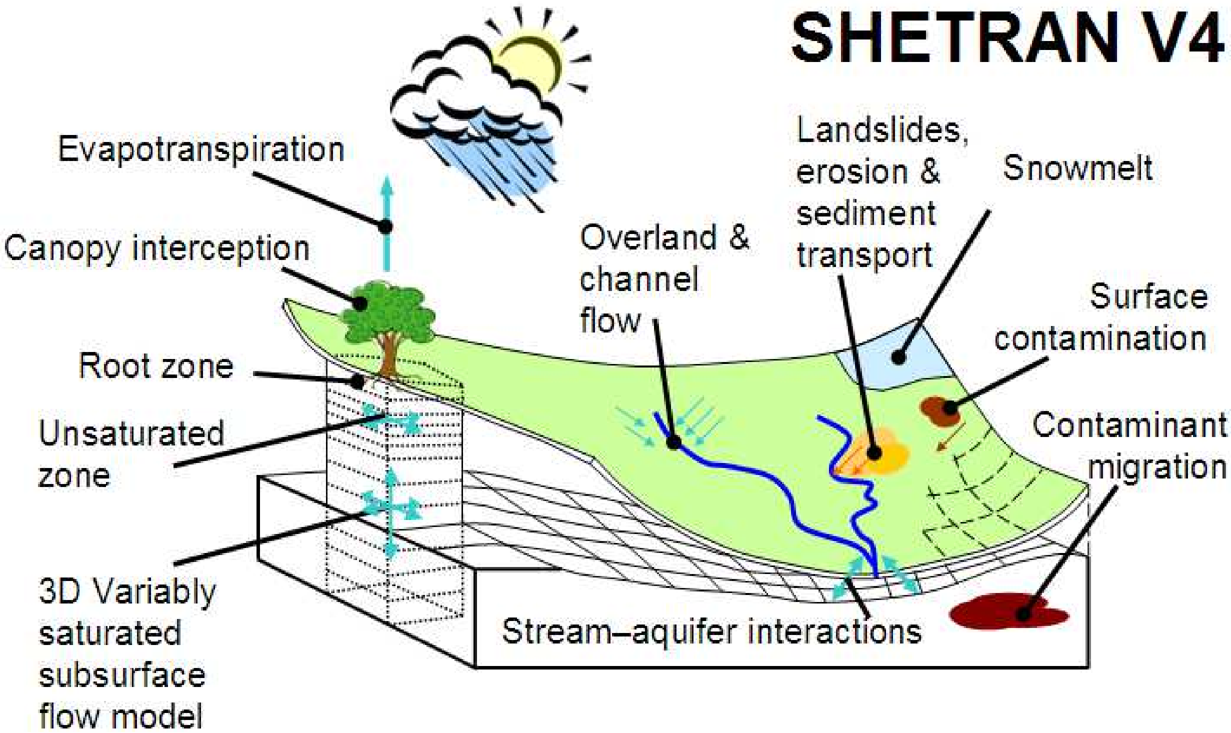

Figure 2 The SHETRAN hydrological modeling system (Version 4).

SHETRAN is an established model which has been extensively tested [3] and used in many applications world wide relevant to studies at Iwokrama. For example, flood-peak response to changes in land use and land management practices is currently being investigated in the Dunsop catchment, north-east England; the impact of forests on catchment response (and landsliding) has been investigated in the Guabalcon, Lise and Panama catchments in Ecuador and La Reina basin in Chile; and the impacts of climate change, land-abandonment, afforestation and agricultural practices have been investigated in the Mediterranean (Val d'Agri, southern Italy and Cobres catchment in Portugal) as part of a decision support system to guide policies of land use to combat desertification.

The data required to run SHETRAN are:

(i) Precipitation and potential evaporation input data to drive the simulation, preferably at hourly intervals;
(ii) Topographic, soil, vegetation, sediment and geotechnical properties to characterize the catchment on a spatially distributed basis;
(iii) Discharge records, and optionally sediment yield and/or water quality, for testing the model output.

SHETRAN provides spatially distributed outputs for each component of the hydrological cycle, including (for the flow model only):

- Net rainfall
- Potential Evapotranspiration
- Transpiration
- Evaporation from soil surface
- Evaporation from intercepted storage
- Drainage from intercepted storage
- Canopy storage
- Vertical flows
- Snow pack depth
- Phreatic depth below surface
- Overland flow
- Surface water depth
- Soil water potential
- Soil water content

4 References

[1] Y. Tardy, V. Bustillo, C. Roquin, J. Mortatti, R. Victoria, (2005). The Amazon. Bio-geochemistry applied to river basin management. Part I. Hydro-climatology, hydrograph separation, mass transfer balances, stable isotopes, and modelling. *Applied Geochemistry*, 20, 1746–1829.

[2] Ewen, J., Parkin, G. and O'Connell, P.E. (2000). SHETRAN: distributed river basin flow and transport modeling system. ASCE J. Hydrologic Eng., 5, 250-258.

[3] Bathurst, J.C., Ewen, J., Parkin, G., O’Connell, P.E. and Cooper, J.D. (2004). Validation of catchment models for predicting land use and climate change impacts. 3: Blind validation for internal and outlet responses. J. Hydrol., 287, 74-94.