BOYLE | AECOM

In Association with amec LEONARD RICE ENGINEERS, INC. STRATUS CONSULTING Canyon Water Resources, LLC

Boyle
215 Union Blvd, Suite 500 | Lakewood CO
T 303.987.3443 | F 303.987.3908

Technical Memorandum | Final

To:	**Blaine Dwyer (Boyle/AECOM)**
Distribution:	
From:	**Subhrendu Gangopadhyay, Ben Harding (AMEC Earth & Environmental)**
Subject:	**CRWAS Phase I | Task 7.5 | Climate Change Approach | Hydrology Model Selection**
Date:	**January 19, 2009**

Introduction

One of the objectives of Task 7 is to:

Provide agency coordination, literature review, diagnostic analysis, data preparation, and model testing to generate projections for temperature, precipitation, weighted and scaled alternate hydrology, and water use relative to potential changes in forest and climate scenarios.

This memo is associated with subtask 7.5 (Climate Change Approach) and 1) provides an overview of the role of hydrology modeling in the evaluation of impacts of projected changes in climate; 2) describes several candidate modeling approaches applicable to CRWAS; 3) documents our recommendation that the Variable Infiltration Capacity (VIC) Model be used for hydrology modeling; and 4) provides additional documentation (in the attached Appendix) about the nature and capabilities of the VIC Model.

How Hydrology Modeling Relates to Other Tasks in the CRWAS

The development of alternate streamflow for CRWAS will work from generally accepted natural flow data and proceed to develop alternate streamflow data in three steps, development of extended streamflows, development of projected streamflows and development of extended projected streamflows. The streamflow data sets will be developed at two scales, for the entire Colorado River Basin (based on the CRSS natural flows), and for the tributary basins within Colorado (based on the CDSS base flows).

The existing natural flow data sets (CRSS or CDSS) will represent the observed streamflows. As proposed in a separate Task Memorandum, these observed flows will be re-sequenced to reflect the statistics of drought and wet spells represented in the paleo record. This re-sequencing will be done in Sub-task 6.5 using techniques identified and developed in Sub-tasks 6.1 through 6.4. The resulting extended streamflow data set will contain flows with the same magnitudes as in the observed streamflows, but in sequences that reflect the patterns of drought and wet spells that are captured in the paleo record.

The observed streamflows will be adjusted to create the projected streamflow data set, which will represent an estimate of the streamflows that would have occurred if the projected climate change had been fully developed at the start of the observed streamflow record. Development of the projected streamflows will proceed in several steps. First, the observed and projected climate data will be obtained in Sub-task 7.6. Next, a calibrated hydrologic model (the subject of this memorandum) will be developed in Sub-task 7.7 and run using the observed climate data to generate a set of baseline streamflows. In Sub-task 7.9 and 7.10 the observed climate will be perturbed to represent the projected future climate conditions (for a set of projections selected in Sub-task 7.8) and the hydrology model will be run using that perturbed climate to generate a set of perturbed streamflows. The difference between the baseline streamflows and the perturbed streamflows (calculated on a monthly basis) will represent the changes in streamflow caused by projected changes in climate. These changes will be added to the observed streamflows to generate the projected streamflows.

Finally, also in Sub-task 7.10, the extended projected streamflows will be created by re-sequencing the projected streamflows using the same sequences that were used in Sub-task 6.5 to re-sequence the observed streamflows.

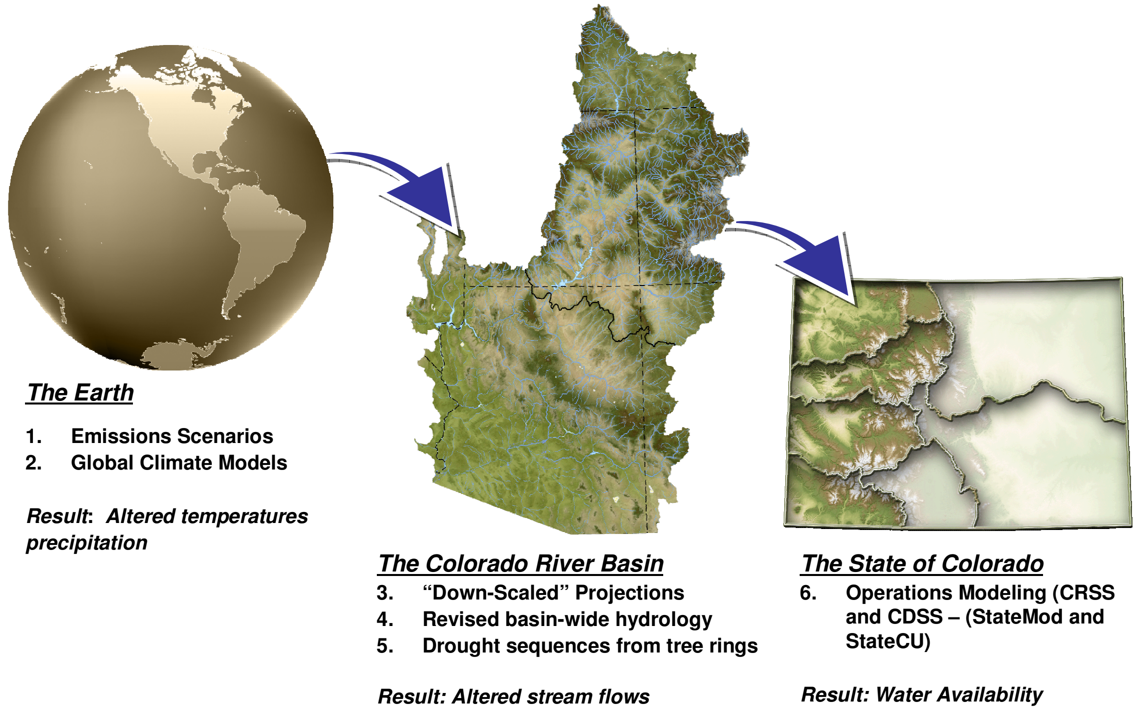
Role of Hydrology Modeling in Estimating Climate Change Impacts

General Circulation Model (GCM) projections of future climate over a multi-decadal time frame indicate that the Colorado River basin will become warmer. Temperatures in Colorado are projected to increase by 2.5º F by 2025 and 4ºF by 2050. (Ray et al., 2008) Projections of future precipitation are more complex, with multi-model average projections showing little change in annual precipitation, but generally showing a seasonal shift in the temporal pattern of precipitation. Changes in temperature and precipitation will influence hydrologic processes on the land surface, which in turn will cause changes in streamflows. Increases in temperature alone will cause a reduction in annual streamflow along with a shift in the seasonal distribution of streamflow (due to changes in snow accumulation and ablation) and these changes in streamflow will affect water availability for consumptive and non-consumptive uses.

The purpose of hydrology modeling is to use GCM projections of future precipitation and temperature to simulate future streamflow.

Figure 1 depicts the analysis process required to estimate impacts from projected changes in climate. The subject of this memorandum is hydrology modeling (Step 4 in Figure 1). Task 7.10 of the CRWAS will apply the hydrology model to generate altered streamflow scenarios (compared to historic naturalized flows) that are consistent with projections of changes in precipitation and temperature in the Basin, at points of interest throughout the Colorado River Basin. Existing downscaled GCM projections will be used (see Step 3 in Figure 1), and the altered streamflows will be re-sequenced based on tree-ring analyses (see Step 5 in Figure 1). Water allocation models, specifically the CRSS and CDSS models, will be used in Step 6. The utilization of altered streamflows in those models will be discussed in a future technical memorandum.

Figure 1.
Climate Change Modeling Approach



Colorado River Water Availability Study | Phase I

A wide variety of hydrology models have been used to estimate future streamflows based on projected temperature and precipitation, ranging from pure statistical models to models that represent hydrologic processes in varying degrees of detail. Different approaches to hydrology modeling have their respective advantages and disadvantages—in general the more explicit and detailed a representation the more costly is its implementation and the more data it requires. Projected temperature increases can be expected to result in substantial shifts in the seasonal distribution of runoff (Maurer, 2007). Because those projected seasonal patterns of streamflow are not reflected in the observed record, pure statistical models, which rely on observed relationships, will not be well suited to estimating the impact of climate change in this region. Accordingly, we have surveyed models that simulate hydrologic processes[1]. In the following section we survey a number of candidate approaches to hydrology modeling for climate change impact assessment.

[1] No hydrology model is a pure simulation of hydrologic processes, because in practice some processes or components of processes are lumped together and represented by empirical relationships that are often developed statistically.

Summary of Candidate Hydrology Models

Five candidate hydrology model codes are summarized below. These models were selected based on our judgment of their technical and practical applicability to CRWAS. In so doing, we considered the following: has the model been applied to assessing impacts of climate change; has the model been applied to all or part of the Colorado River Basin; have these applications been published in peer-reviewed literature; is the model appropriate for continuous simulation of discharge (as opposed to short-term event-based simulation); is the model being used in the Front Range Vulnerability Study (FRVS); and the availability and accessibility of experienced model users and other technical resources.

Information is provided about the following eight attributes for each model code:

(1) *Spatial representation*. Distributed parameter hydrologic models generally can be categorized into two broad types—gridded models and watershed-delineated models. In a gridded model the parameters and data representing land surfaces, hydrologic forcings (precipitation, temperature, solar radiation, etc.) and physical processes are represented on a grid rather than according to watershed boundaries. In many cases the spatial scale at which the model grid is defined is smaller than for watershed-delineation models. A well-designed watershed delineation model will define sub-watersheds that have similar physical characteristics (e.g. elevation, vegetation, subsurface characteristics) but in diverse terrain this can be difficult. The process of adding a new location where flow is to be simulated in a watershed-delineated model requires that the existing delineation be revised (for at least two watersheds), which requires a new estimation of parameters and forcing data for the revised watershed delineations. If done on a significant fraction of the area of a model, recalibration might be advisable. This process is generally more mechanical and less costly in a gridded model.

(2) *Temporal representation*. Models will represent physical processes at a certain time step. For this study streamflow data are necessary on a monthly time step, so that temporal resolution finer than one month is not a requirement. However, most comprehensive hydrology models operate at a daily or finer time step specifically to resolve vadose zone processes.

(3) *Hydrologic processes representation*. Models vary widely in the degree to which they explicitly represent physical processes. There is a trade-off between the types of representations of model physical processes and the complexity of the model and the cost of development. For example, a model may represent snow accumulation and ablation based on a simple temperature threshold, or it may represent snow physics based on an energy balance approach. The latter, when well implemented, provides a more realistic representation of snow physics, but is more complicated to develop and more computationally intensive. Models generally represent soil moisture in one or more layers, represented as conceptual reservoirs

(4) *Calibration*. More complex models have more parameters that can be adjusted to achieve calibration, but with a corresponding increase in the effort required. Automated calibration methods are often used to provide an initial calibration that is usually refined manually.

(5) *Model documentation*. To what degree is formal documentation of the model structure and application available (e.g. technical manuals, users' guides)? Has the model been the subject of peer-reviewed publications?

(6) *Model application*. In what types of applications has the model been used? Are these similar to the applications in the CRWAS?

(7) *Complexity*. What is the level of complexity of the model? Complexity usually confers an advantage in terms of flexibility and the reliability and realism of model results, but with additional complexity there are additional costs of model setup, calibration and runtime.

(8) *Compatibility with available data*. How readily can existing input data be used in the model? How compatible are model outputs with data requirements for the CRWAS?

We discuss in the following paragraphs the attributes of five hydrology models:

- Variable Infiltration Capacity Model (VIC)
- Modular Modeling System/Precipitation Runoff Modeling System (MMS-PRMS)
- National Weather Service River Forecasting System - Sacramento Soil Moisture Accounting Model (NWSRFS/SAC-SMA)
- Thornthwaite-Type Water Balance Model (TWB)
- Water Evaluation and Planning Tool (WEAP)

(1) Variable Infiltration Capacity Model (VIC)

The VIC model is a distributed gridded physical hydrology model with several applications to climate change studies and successful application to numerous basins around the world (Wood et al., 1992; Liang et al., 1994; Liang et al., 1996; Lohmann et al., 1998a; Lohmann et al., 1998b). A calibrated VIC model of the entire Colorado River Basin has been developed. (Christensen et al., 2004, Christensen and Lettenmaier, 2007)

Model Attributes

(1) *Spatial representation*. VIC is a distributed parameter gridded physical hydrology model. Model grid resolution is data driven and within practical bounds is limited only by data availability and model performance.

(2) *Temporal representation*. VIC can run at hourly up to daily time steps.

(3) *Hydrologic processes representation*. Physical representation of soil moisture using three soil layers. Energy balance modeling of snow dynamics and aerodynamic resistance based (Penman Monteith type) evapotranspiration calculations.

(4) *Calibration*. Automated calibration methods available.

(5) *Model documentation*. The model has been applied primarily by academic scientists and has a limited formalized body of documentation. There is not a comprehensive manual describing the use and application of the VIC model, although adequate supporting information is available at the University of Washington web site. (VIC Macroscale Hydrologic Model, 2002).

(6) *Model application*. VIC has been successfully implemented and validated under a variety of climatic conditions and on basins worldwide. A calibrated model for the entire Colorado River Basin exists, and the model application to climate change in the Colorado River Basin is reported in peer-reviewed literature. (Christensen et al., 2004, Christensen and Lettenmaier, 2007)

(7) *Complexity*. VIC is a complex model and has a learning curve for doing a first time application.

(8) *Compatibility with available data*. There are existing land surface data available at multiple resolutions – 2-degree data are available worldwide and 1/8th degree are available for the continental U.S. and other parts of North America. The 1/8th degree grid resolution used in the existing VIC model of the Colorado River Basin is also compatible with available gridded climate data representing observed climate (historical precipitation, temperature, etc.) and downscaled and bias-corrected GCM projections of future climate conditions (precipitation and temperature).

(2) Modular Modeling System/Precipitation Runoff Modeling System (MMS-PRMS)

MMS-PRMS consists of a model (PRMS) in a modeling framework (MMS – Modular Modeling System). The PRMS model is a distributed physical hydrology model of moderate complexity developed by USGS (Leavesley et al., 1983; Leavesley et al., 2002; Leavesley et al., 2006) for simulating basin runoff processes. PRMS is a single model within the MMS framework.

Model Attributes

(1) *Spatial representation*. Distributed parameter physical hydrology model based on watershed delineations.

(2) *Temporal representation*. PRMS can be run in storm mode (hourly) and at daily time scales.

(3) *Hydrologic processes representation*. Physical hydrologic processes in the MMS framework can include the default PRMS hydrologic process representations or separate hydrologic process models can be coupled to simulate hydrologic processes. PRMS uses an energy balance representation of snow dynamics, and the Jensen-Haise model for ET. Subsurface and soil moisture simulation uses three storage elements – lower soil zone, subsurface reservoir and groundwater reservoir

(4) *Calibration*. Automated calibration algorithms are available.

(5) *Model documentation*. MMS/PRMS is developed by the USGS and has extensive model documentation on the USGS website (http://water.usgs.gov/cgi-bin/man_wrdapp?prms).

(6) *Model application*. Limited application outside research.

(7) *Complexity*. User can control the complexity of the model processes based on data availability. MMS provides a flexible modeling framework.

(8) *Compatibility with available data*. PRMS cannot use available climate change projection datasets directly. Mapping existing gridded climate and projection data to irregular watersheds requires additional data processing and may introduce new biases, though the magnitude of this effect is not known.

(3) National Weather Service River Forecasting System - Sacramento Soil Moisture Accounting Model (NWSRFS/SAC-SMA)

The National Weather Service River Forecasting System (NWSRFS) model is the operational model of the National Weather Service (NWS) based on the Sacramento Soil Moisture Accounting (SMA) hydrology model (Burnash et al., 1973; Burnash, 1995) with a separate module to simulate snow dynamics (Snow17, e.g. Koren et al., 1999).

Model Attributes

(1) *Spatial representation*. Distributed parameter physical hydrology model based on watershed delineations. A gridded version of the model is available but the model typically been applied as a watershed-delineated model to simulate watershed precipitation-runoff relationship.

(2) *Temporal representation*. The model uses 6-hourly mean areal precipitation (MAP) and mean areal temperature (MAT) to generate streamflow.

(3) *Hydrologic processes representation*. The NWSRFS model is based on the hydrologic process representations of the Sacramento soil moisture accounting model (SAC-SMA, Burnash et al., 1973). There is a separate snow model (Snow 17), which uses a temperature threshold approach to simulate snow accumulation and ablation. Potential evapotranspiration is a static input variable that is estimated using a separate model. The SAC-SMA uses two zones, upper and lower, to model soil moisture storage and runoff. There are several storage elements and processes modeled within these two zones to estimate interflow, supplemental base flow and base flow.

(4) *Calibration*. Automated calibration methods are available. Because this is an operational model (used in flood forecasting, and inflow forecasting for reservoir operations, e.g., inflow to Lake Powell) of the National Weather Service River Forecast Centers, it is calibrated to meet short-term operational needs. As an operational model, forcing parameters (e.g. temperature, precipitation and snow) are routinely adjusted to generate streamflow forecasts. Calibrated model parameters are available nationally.

(5) *Model documentation*. The model is maintained by the National Weather Service (NWS), and has extensive documentation available from NWS/NOAA-Hydrologic Development Laboratory.

(6) *Model application*. The model has been applied all across the US by the NWS River Forecast Centers. It is being used in the FRVS to simulate climate change impacts in the Upper South Platte and Upper Arkansas basins.

(7) *Complexity*. Moderately complex.

(8) *Compatibility with available data*. Mapping existing gridded climate and projection data to irregular watersheds requires additional data processing and may introduce new biases, though the magnitude of this effect is not known. As an operational model, forcing parameters (e.g. temperature, precipitation and snow) are routinely adjusted to generate streamflow forecasts. This calibrated data set covers a period from the mid-1970's to present (the actual period of record varies among sub-basin models).

(4) Thornthwaite-Type Water Balance Model (TWB)

The TWB model is a simple hydrologic model that simulates runoff (and, generally, not streamflow as there is no routing involved). This model can exist in many configurations (hence the generic designation "Thornthwaite-type"), but is typically used in a "two-bucket" setup (e.g., McCabe and Markstrom, 2007). A "two-bucket" model represents two soil layers, each being a conceptual reservoir (hence the term "bucket") where soil moisture is stored temporarily as part of the simulation of precipitation and runoff.

Model Attributes

(1) *Spatial representation*. Can be applied on a grid-cell by grid-cell basis, and also as delineated watersheds.

(2) *Temporal representation*. Suitable for application only at monthly (seasonal) time scales.

(3) *Hydrologic processes representation*. Temperature index based approach to precipitation partitioning – rain or snow. Soil moisture is typically represented by two soil layers. Snow accumulation and ablation is based on temperature thresholds. Evapotranspiration is based on Thornthwaite or Hamon temperature-based approaches. Total runoff is based on saturation excess and snowmelt. No streamflow routing is provided so the model must be applied at a time step that is sufficiently long to eliminate the need for hydrologic and hydraulic routing models.

(4) *Calibration*. The TWB is a simple water balance model with only a few model parameters to adjust. Calibration must be done at a watershed scale and at a time step that is sufficiently long to eliminate the need for hydrologic and hydraulic routing models.

(5) *Model documentation*. These models are described in physical hydrology textbooks. There is a model available from USGS (McCabe and Markstrom, 2007)

(6) *Model application*. TWB-type models have been applied to climate change studies. An application of the USGS TWB model to forty-four watersheds across the US including the Yampa and the Animas in Colorado have been published by Hay and McCabe (2002). McCabe and Wolock (2007) applied the USGS TWB to the Colorado River Basin.

(7) *Complexity*. These models use a simple water balance approach, and the models are straightforward to construct.

(8) *Compatibility with available data*. These types of models being gridded are compatible with gridded climate change projections.

(5) Water Evaluation and Planning Tool (WEAP)

The WEAP model is an integrated modeling system that includes a hydrologic model with tools for simulating water management systems and for conducting policy analysis.

Model Attributes

(1) *Spatial representation*. WEAP is based on watershed delineation.

(2) *Temporal representation*. It is being applied in the FRVS at weekly time step. The upper and lower limits for timestep are not known.

(3) *Hydrologic processes representation*. Simple water balance model, similar to TWB. WEAP is an integrated tool that includes water management capabilities, but these capabilities would not be used in CRWAS. The soil moisture method includes a one dimensional, two-compartment (or "bucket") soil moisture accounting scheme for calculating evapotranspiration, surface runoff, sub-surface runoff (i.e., interflow), and deep percolation for a watershed unit.

(4) *Calibration*. Effort similar to MMS/PRMS. No known automated calibration procedures.

(5) *Model documentation*. Proprietary code but reasonable documentation.

(6) *Model application:* Applications worldwide, but not many have been reported in peer-reviewed literature. The WEAP model is being applied in the FRVS to assess the impacts of climate change on the mainstem Colorado River above Cameo.

(7) *Complexity*. Hydrologic processes are not complex. Potentially more difficult to adapt to large-scale applications with large data requirements due to the integrated nature of the tool.

(8) *Compatibility with available data*. WEAP cannot use available climate change projection datasets directly. Mapping existing gridded climate and projection data

to irregular watersheds requires additional data processing and may introduce new biases, though the magnitude of this effect is not known.

Summary

All of the surveyed candidate hydrology models have their strengths and weaknesses. Most of the models have been applied to several river basins, have been used and continue to be used in climate change studies and have adequate representation of hydrologic processes. However, the selection of a recommended model is influenced as heavily by practical considerations as it is by technical considerations. One requirement of the CRWAS that imposes a substantial practical impact is that alternative hydrology must be developed for the entire Colorado River Basin in order to evaluate the impact of climate change on potential water availability in the Upper Colorado River Basin. Of the surveyed models, two, the VIC model and the NWSRFS model have been applied to the entire Colorado River Basin, and the Thornthwaite (TWB) model has been applied to the entire Upper Colorado River Basin. The cost of developing and calibrating a new hydrologic model for those portions of the Colorado River Basin outside of Colorado would be prohibitive for the CRWAS project.

The NWSRFS model is a widely used and reliable hydrology model, but the VIC model has several advantages over the NWSRFS model for CRWAS, that may or may not apply to other studies such as the FRVS.

- The period of record for the existing VIC model is longer (1950 through 1999)[2] than is the case for the NWSRFS model (for which data begin in the mid-1970's).
- There are a large number of NWSRFS models required to cover the entire Colorado River Basin.
- The VIC model can directly use gridded observed and projected climate data.
- Because the NWSRFS is a delineated watershed model, these delineations will certainly have to be changed to correspond to the base flow locations in CDSS. This is a significant effort in itself, but would also probably require re-calibration of the model.
- The two applications of the VIC model to the Colorado River Basin have been for the purpose of evaluating the impacts of climate change and the results of these studies have been published in refereed journals.

The Thornthwaite Model has been applied to the Upper Colorado River Basin for climate change studies, and these studies have been reported in the referenced literature. However, the TWB model does not have as rigorous a simulation of hydrologic processes, particularly snow behavior, as do any of the other hydrology models. However, many of the technical advantages of the other hydrology models are not as significant when a monthly time step is used. And, the TWB model has the practical advantage that it can be easily formulated to cover the entire Colorado River Basin in a grid that is directly compatible with the available observed and projected data.

Another consideration in the approach used by CRWAS is the degree to which it is compatible or extends the work being done by the FRVS. The FRVS will be conducting work similar to the CRWAS on the Arkansas, South Platte and mainstem Colorado River,

[2] This is a minimum period of record; other climate data sets exist that cover the period from 1915 to 2006, and a longer period of record may be used after a review of the available data sets.

in order to assess the impact of climate change on water suppliers who draw water from those basins. The work by FRVS overlaps the work of CRWAS on the mainstem Colorado River, which is one of four major tributary sub-basins in Colorado that will be modeled by CRWAS. The CRWAS technical team has had two substantial discussions with the FRVS technical team and project leadership. Those discussions have led to the decision that the FRVS and the CRWAS should use the same assumptions in two areas: the selection of climate projections, and the time frames for which future projections will be made. Maintaining consistency in these two fundamental assumptions allows for direct comparison of the two studies. The two groups agreed that there are advantages to using different technical approaches to modeling in the Colorado River Basin--because there are recognized uncertainties arising from the choice of technical approach, using two different technical approaches, while using the same assumptions regarding climate forcings, will provide some insight into the degree to which technical differences contribute to uncertainty in estimates of future streamflow.

Proposed Hydrology Model

Based on the relative advantages and disadvantages of the referenced candidate models, and based on our experience with hydrology models, we feel that the most practical model for the CRWAS applications is the VIC (Variable Infiltration Capacity) model. Purely from the standpoint of cost versus performance, we view the TWB (Thornthwaite type Water Balance model) as a suitable alternative to the VIC model. There are several reasons as to why the VIC model is the recommended choice:

- Comprehensive physical hydrology representation, including sub-grid variability, particularly for snow dynamics and evapotranspiration (Nijssen et al., 2001; Wood et al., 1992)
- An existing calibrated and peer reviewed model for the entire Colorado River Basin (Christensen, et al. 2004; Christensen and Lettenmaier, 2007);
- Direct compatibility with gridded climatological model forcings (historical precipitation, temperature, etc. data) at 1/8th degree resolution that are available for the CRWAS study area;
- Direct compatibility with bias corrected climate change projections of precipitation and temperature from multiple GCMs that are available at the 1/8th degree spatial resolution for the CRWAS study area.

These factors indicate that the VIC model will provide a cost effective and technically defensible approach for the hydrology modeling to be conducted in the CRWAS. The other hydrology models, in particular PRMS, NWSRFS and WEAP have adequate physical hydrology process representations, but the practical advantages of the VIC model, as well as its other technical advantages, lead us to believe that it will provide the most cost-effective approach to developing alternate hydrology for CRWAS.

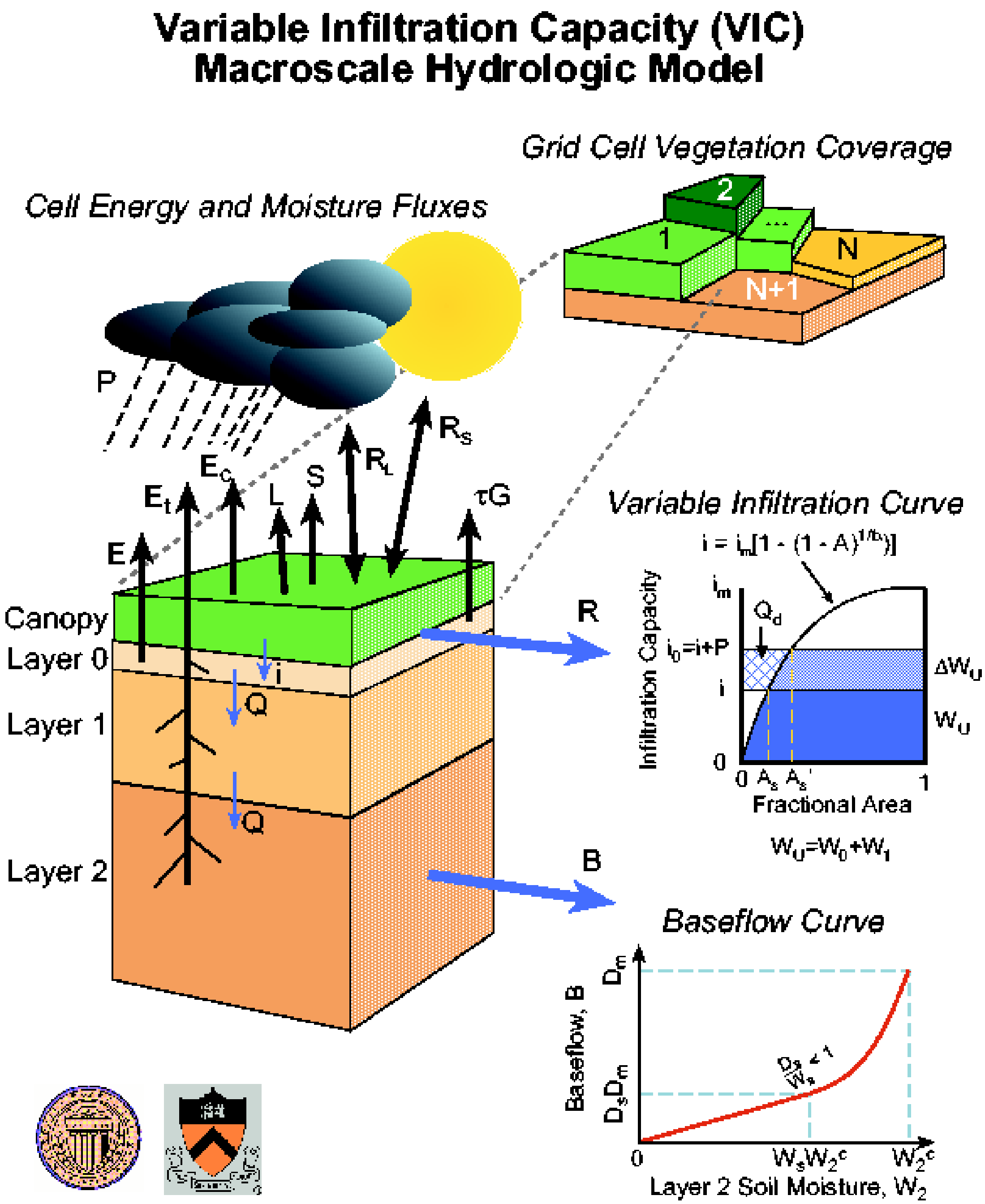
Appendix: Further Information about the VIC Model

Description of the VIC Model

A grid cell schematic of the VIC model is shown in Figure 2. A detailed description of the VIC model can be found in Liang et al. (1994, 1996). To summarize, the model has parameterizations to represent the vertical exchange of moisture and energy between the vegetation canopy and the atmosphere, similar in many respects to other Soil-Vegetation-Atmosphere Transfer Schemes (SVATS). The model's main distinction from other SVATS is its representation of the effects of spatial variability in soil, topography, and vegetation, and their effects on runoff generation, which is assumed to occur dominantly via the saturation excess mechanism. The model also represents a "slow", or baseflow, runoff response via a nonlinear deep soil drainage parameterization. The VIC model is coupled to a streamflow routing scheme that transports the runoff generated within each grid cell through a specified channel network. The routing model does not account for channel losses, extractions, diversions and reservoir operations (the latter are represented in the water management model). The routing model is described in detail in Lohmann et al. (1996). Additional details on the model structure are described in the following sections.

The current implementation of the model (Srinivasan and Laskshmi, 2006) consists of a canopy and three soil layers: a top layer around 10 cm thick, and two bottom layers 10-50 cm thick and 50-150 cm thick. The top layer characterizes dynamic behavior of soil column response to precipitation events and the bottom layer represents soil moisture response to precipitation events only after the top two layers are wetted.

Figure 2.
Grid cell schematic of the VIC model.



The last layer responds at the seasonal time scales (i.e., that of baseflow). The surface condition in the model is described by n = 1, 2, …, N types of vegetation as well as type *(N+1)*, which corresponds to bare soil type (refer to Figure 2). Surface runoff ($Q_d[.]$) and subsurface runoff ($Q_b[.]$) from soil with vegetation cover and bare soil are computed separately, and accumulated to generate the total runoff (*Q*) from a cell.

$$Q = \sum_{n=1}^{N+1} C_v[n].(Q_d[n] + Q_b[n]) \tag{1}$$

where, $C_v[n]$ is the fraction of vegetation cover for the n^{th} (n=1, 2, …, *N*) surface cover class of interest, $C_v[N+1]$ is the fraction of the bare soil covered area, and $\sum_{n=1}^{N+1} C_v[n] = 1$.
The amount of infiltration is controlled by a variable infiltration curve, which is based on the available moisture content of the top two layers. The generated streamflow from each grid is first hydrologically routed to the outlet of that grid cell then into the river system for hydraulic routing. The within-cell routing uses a Unit Hydrograph approach and the channel routing uses the linearized Saint-Venant equation. The river routing model operates under the assumption that all runoff exits a cell in a single flow direction. The river routing model will generate streamflow at gaging sites of interest, which will then be compared with observed streamflow time series, and model parameters will be adjusted to obtain an adequate fit between observed and simulated flows.

The VIC model can be run in several modes, the two primary modes are – (1) water balance and (2) energy balance. The water balance model does not solve the surface energy balance. Instead it operates under the assumption that the soil surface temperature is equal to the air temperature for the current time step. The exception to this rule is that the snow algorithm still solves the surface energy balance to determine the fluxes needed to drive accumulation and ablation processes. By eliminating the ground heat flux solution and the iterative processes required to close the surface energy balance, the water balance model requires significantly less computational time than other model modes.

Overview of the VIC Features *

Source: http://ecpc.ucsd.edu/projects/homepage/vicmodel.html
Note: Highlighted references could not be found.

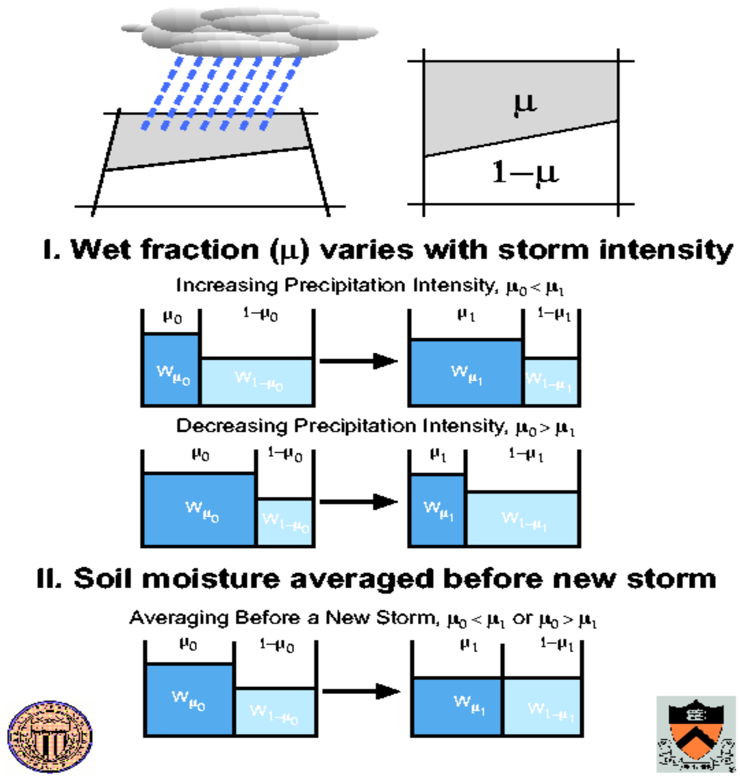
The VIC features:

- subgrid variability in soil moisture storage capacity as a spatial probability distribution
- subgrid variability in precipitation
- subgrid variability in land surface vegetation classes
- subgrid variability in topography through the use of elevation bands
- baseflow as a nonlinear recession

Spatial variable precipitation

The VIC precipitation model is illustrated in Figure A-1.The areal fraction of a model cell that experiences precipitation increases with increasing intensity of the precipitation event (Liang et al. 1996). The parameter relating precipitation intensity to areal extent of the precipitation event is a function of grid cell size, storm type, geography and other factors.

Figure A-1.
VIC Distributed Precipitation Model.



Runoff generation

1. Surface runoff: Using infiltration formulation used in the Xinanjiang model effectively assumes that runoff is generated by those areas for which precipitation, when added to soil moisture storage at the end of the previous time step, exceeds the storage capacity of the soil. There is no canopy storage (throughfall = precipitation).

2. Subsurface runoff: Arno nonlinear base flow. Baseflow is designed as a function of soil moisture in the lowest soil layer. The relationship is non-linear at high soil moisture contents, producing rapid baseflow response in wet conditions.

The VIC model is coupled to a linear streamflow routing scheme, and routing model, developed by Dag Lohmann at NCEP/NOAA, which describes the time of concentration for runoff reaching the outlet of each grid cell as well as transport of water in the open channel system. All runoff exits the grid cell in only one of eight possible directions.

Vegetation

Variations in vegetation within grid cells are described by specifying a given number of land cover classes and the fraction of the grid cell covered by each. For each land cover class, leaf area index, canopy resistance, and relative fraction of roots are specified. There is no restriction on the number of vegetation types, but in the interest of model parsimony, layers usually will be less than 10 (Nijssen et al. 2000).

According to Nijssen et al. (2000), vegetation types were taken from the AVHRR-based, 1km, global land classification from Hansen et al. (1999). Vegetation parameters such as height and minimum stomatal resistance were assigned to each vegetation class based on a variety of sources.

Soil and Soil Layers

Soil textural information and soil bulk density were obtained using the SoilProgram which combines the 5 minute FAO-UNESCO digital soil map of the world with the WISE pedon database (Nijssen et al. 2000, Carter & Scholes 1999). The other soil characteristics, such as porosity, saturated hydraulic conductivity, were based on Cosby et al. (1984), according to Nijssen et al. (2000).

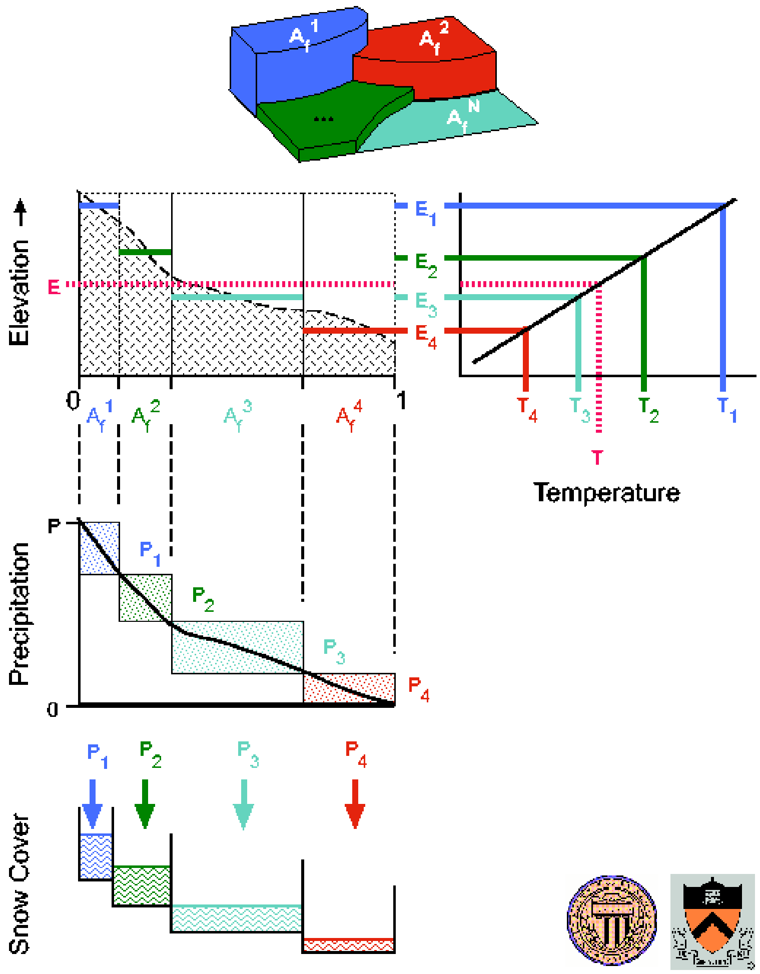
- Canopy
- Layer 1: 10cm, top layer, for the latent and sensible heat flux computation purpose, representing dynamics near surface, particular for the summer months.
- Layer 2: 50cm, designed to represent the dynamic behavior of the soil column that responds to rainfall events.
- Layer 3: 160cm, used to characterize the slowly-varying between-storm soil moisture behavior. Only responds to rainfall when the upper layer is wetted and thus can separate the subsurface flow from storm quick response.

The upper and lower depth is not unique and can be determined if some information is available about behavior of soil within the area of the interest. The spatial variability in soil properties at scales smaller than the grid scale is represented statistically, without assigning infiltration parameters to specific subgrid locations (Liang et al. 1994, Liang et al. 1996).

Elevation bands

The handling of subgrid variability of elevation is shown in Figure A-2. Since temperature and precipitation varies with elevation, the snow accumulation varies within the grid cell in the mountainous region.

Figure A-2.
Subgrid Variability of Elevation.



Nijssen et al. (2000) assume precipitation being constant with elevation within a grid cell, while air temperature is lapsed from the mean grid cell elevation to the mean elevation of each elevation band using a lapse rate of 0.0065degree/meter.

Elevation data were calculated based on the 5 minute global TerrainBase Digital Elevation Model (Row et al. 1995).

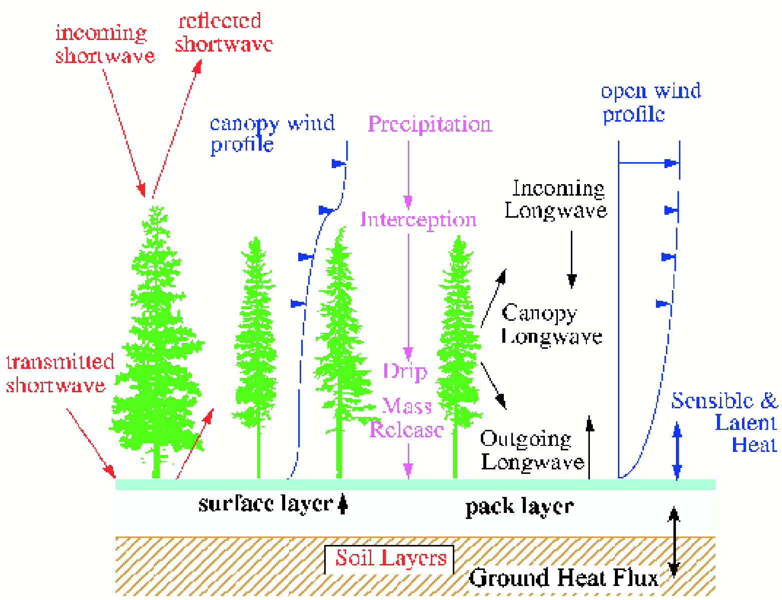
Evapotranspiration

Three types of evaporation are considered in the model: evaporation from canopy layer of each vegetation class, transpiration from each of the vegetation classes, and evaporation from bare soil. Evapotranspiration from each vegetation type is calculated using a Penman-Monteith formulation (Liang et al. 1994). Total evapotranspiration over a grid cell is computed as the sum of the above components, weighted by the respective surface cover area fractions.

Snow cover

The effect of vegetation cover on snow accumulation and melt is represented internally within the VIC model via a coupled snow model (Storck and Lettenmaier 1999). The snow model is illustrated in Figure A-3

Figure A-3.
VIC Snow Algorithm.



The snow model allows snow to be intercepted by the canopy, to fall through it, or to completely cover low vegetation or bare areas. Snow intercepted by the vegetation can be removed via sublimation, melt water drip, and mass release. Drip from the canopy is added to ground snow pack as rain, while mass release is added as additional snowfall. Snow and rain interception by the canopy is calculated as a function of LAI (Leaf Area Index). LAI is also used to attenuate shortwave radiation and wind passing through the canopy. The ground surface snow cover is modeled using a two-layer energy balance approach (Nijssen et al. 2000).

Operational modes

Water balance mode and full energy mode. Water balance mode uses approximations for the relevant energy terms, such as the effective surface temperature as air temperature. The time step is daily. Full energy balance mode calculates all water and energy fluxes near the land surface, and the run time-step is 1 or 3 hours. The surface energy balance is closed by iterating on an alternative surface temperature (Nijssen et al. 2000).

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