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Methodology for Estimating Electricity Generation Vulnerability to Climate Change using a Physically-based Modelling System

Matthew Bartos and Mikhail Chester

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METHODOLOGY FOR ESTIMATING ELECTRICITY GENERATION VULNERABILITY TO CLIMATE CHANGE USING A PHYSICALLY-BASED MODELING SYSTEM

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Matthew D. Bartos
Research Engineer
matthew.bartos@asu.edu

Mikhail V. Chester, Ph.D.
Assistant Professor
mchester@asu.edu

Civil, Environmental, and Sustainable Engineering
Arizona State University
www.urbantransitions.org/southwestheat/

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1. Introduction

In recent years, concerns have grown over the risks posed by climate change on the U.S. electricity grid.[6] The availability of water resources is integral to the production of electric power,[16] and droughts are expected to become more frequent, severe, and longer-lasting over the course of the twenty-first century.[33] The American Southwest, in particular, is expected to experience large deficits in streamflow.[29] Studies on the Colorado River anticipate streamflow declines of 20-45% by 2050.[29,30] Other climactic shifts—such as higher water and air temperatures—may also adversely affect power generation.[8,10,12] As extreme weather becomes more common, better methods are needed to assess the impact of climate change on power generation. This study uses a physically-based modeling system to assess the vulnerability of power infrastructure in the Southwestern United States at a policy-relevant scale.

Thermoelectric power—which satisfies a majority of U.S. electricity demand—is vulnerable to drought. Thermoelectric power represents the backbone of the U.S. power sector, accounting for roughly 91% of generation. Thermoelectric power also accounts for roughly 39% of all water withdrawals in the U.S.—roughly equivalent to the amount of water used for agriculture.[16] Water use in power plants is primarily dictated by the needs of the cooling system. During the power generation process, thermoelectric power plants build up waste heat, which must be discharged in order for the generation process to continue. Traditionally, water is used for this purpose, because it is safe, plentiful, and can absorb a large amount of heat. However, when water availability is constrained, power generation may also be adversely affected. Thermoelectric power plants are particularly susceptible to changes in streamflow and water temperature. These vulnerabilities are exacerbated by environmental regulations, which govern both the amount of water withdrawn, and the temperatures of the water discharged.[7] In 2003, extreme drought and heat impaired the generating capacity of more than 30 European nuclear power plants, which were unable to comply with environmental regulations governing discharge temperatures.[32] Similarly, many large base-load thermoelectric facilities in the Southeastern United States were threatened by a prolonged drought in 2007 and 2008.[6] During this period, the Tennessee Valley Authority (TVA) reduced generation at several facilities, and one major facility was shut down entirely.[34] To meet demand, the TVA was forced to purchase electricity from the grid, causing electricity prices to rise.[6]

Although thermoelectric power plants currently produce most of the electric power consumed in the United States, other sources of power are also vulnerable to changes in climate. Renewables are largely dependent on natural resources like rain, wind, and sunlight. As the quantity and distribution of these resources begins to change, renewable generation is also likely to be affected. Hydroelectric dams represent the largest source of renewable energy currently in use throughout the United States.[15] Under drought conditions, when streamflow attenuates and reservoir levels drop, hydroelectric plants are unable to operate at normal capacity. In 2001, severe drought in California and the Pacific Northwest restricted hydroelectric power generation, causing a steep increase in electricity prices.[35] Although blackouts and brownouts were largely avoided, the Northwest Power and Conservation Council estimated a regional economic impact of roughly $2.5 to $6 billion.[36] In addition to hydroelectric power, it has also been theorized that solar energy resources may also be susceptible to predicted increases in surface temperature and atmospheric albedo. One study predicts that solar facilities in the Southwestern U.S. may suffer losses of 2-5%.[31]

The aim of this study is to estimate the extent to which climate change may impact power generation in the Southwestern United States. This analysis will focus on the Western Interconnection, which comprises the states of Washington, Oregon, California, Idaho, Nevada, Utah, Arizona, Colorado, Wyoming, Montana, South Dakota, New Mexico and Texas. First, climactic and hydrologic parameters relevant to power generation are identified for five types of generation technologies. A series of functional relationships are developed such that impacts to power generation can be estimated directly from changes in certain meteorological and hydrological parameters. Next, climate forcings from the CMIP3 multi-model ensemble are used as inputs to a physically-based modeling system (consisting of a hydrological model, an offline routing model, and a one-dimensional stream temperature model). The modeling system is used to estimate changes in climactic and hydrologic parameters relevant to electricity generation for various generation technologies. Climactic and hydrologic parameters are then combined with the functional relationships developed in the first step to estimate impacts to power generation over the twenty-first century.

2. Methodology

Changes to electric power generating capacity are estimated based on variations in relevant hydrological and meteorological parameters. These parameters vary depending on the type of power system under investigation. In this study, six power generation technologies are considered: (1) hydroelectric power, (2) steam-condensing thermoelectric facilities employing open-loop cooling, (3) steam condensing thermoelectric facilities employing recirculating cooling, (4) combustion turbine facilities, (5) solar photovoltaic facilities, and (6) wind turbines. Quantitative relationships between climactic parameters and power generation are discussed for each technology in Section 1.3.1. Relevant climactic conditions are determined for the historical period (1949-2010) using daily gridded (1/8-degree) observed meteorological forcings.[1] Future climactic conditions are then modeled using daily gridded (1/8-degree) forcings from the CMIP3 multi-model ensemble of downscaled general circulation model (GCM) outputs.[2] A physically-based modeling framework is used to estimate streamflows, water temperatures and other climactic variables that may constrain power generation (including incoming shortwave radiation, ambient wet-bulb temperature, and ambient dry-bulb temperature). The modeling framework consists of (1) the Variable Infiltration Capacity (VIC) macro-scale hydrological model,[3] (2) an offline routing model,[4] and (3) a one-dimensional stream temperature model, RBM.[5]

This section is divided into two parts. The first part of this section (2.1.) identifies how climactic conditions may affect particular generation technologies, and presents quantitative relationships to help estimate the effect of climate change on power generation. In the second part of this section (2.2.), the methods for determining future and historical climactic and hydrological conditions are outlined for each generation technology.

2.1. Relating Climate to Power Generation

Each power generation technology is vulnerable to different climactic and hydrological conditions. In this section, adverse climatological conditions are identified for each generation technology. Quantitative relationships are then developed to relate climactic changes to power generation impacts. Hydroelectric power is susceptible primarily to decreases in streamflow.[6] Thermoelectric power plants are susceptible to a number of climatological and hydrological conditions, depending on the fuel source and cooling system used (adverse conditions include low streamflows,[7] high water temperatures,[7,8, 9,10] and high ambient wet/dry bulb temperatures).[7, 8, 9, 11] Solar photovoltaic systems are vulnerable to decreases in shortwave solar radiation and increases in ambient air temperature.[12] Wind turbines are vulnerable to changes in wind speed.[13] Climactic effects on particular technologies are discussed in detail in the following sections.

2.1.1. Hydroelectric Power

Hydroelectric power harnesses the power of falling water to generate electricity. The generating capacity of a hydroelectric facility can be described as a function of two hydraulic variables: the flow rate of the water passing through the turbine and the total hydraulic head acting on the turbine.[14]

$$P = \eta_{turbine} \cdot \rho_w \cdot Q \cdot g \cdot h$$

Where P is the power output (in Watts), $\eta_{turbine}$ is the dimensionless turbine efficiency, ρ_w is the density of water (in kilograms per cubic meter), Q is the flow rate through the turbine (in cubic meters per second), g is the acceleration due to gravity, and h is the net hydraulic head acting on the turbine (in meters) where the net head is approximately equal to the elevation difference between the top of the reservoir pool and the elevation of the turbine.[14] For this study, it is assumed that the net head remains relatively constant over the analysis period: in other words, the amount of water stored in reservoir systems does not accumulate or attenuate significantly over time. This assumption implies that dam operators will coordinate future releases such that reservoirs operate close to the normal operating conditions. Keeping the net head constant, the instantaneous power output from a particular hydroelectric facility can be expressed as the average historical firm power output (P_m) times the instantaneous streamflow (Q_i) divided by the average historical streamflow (Q_m):

$$P = P_m \cdot \frac{Q_i}{Q_m}$$

2.1.2. *Thermoelectric Power*

Thermoelectric power represents the bulk of the power sector, generating 91% of electricity used in the U.S.[15] The majority of thermoelectric power in the U.S. is produced by steam condensing plants.[15] These plants require cooling water in order to reject heat.[8,16,17] Access to cooling water can present an operating constraint for thermoelectric power plants if cooling water is either (1) not available in sufficient quantity or (2) too hot to meet operational or environmental demands. In the southern U.S., recent warm and dry weather patterns have caused shortages in cooling water availability and cooling capacity.[18] Cooling water withdrawals and discharge temperatures are often also constrained by state and federal regulations aimed at preserving riparian ecosystems. Under drought conditions—when water is scarce and ambient water temperature is high—plants often reduce generation capacity or shut down operations entirely in order to avoid non-compliance.[10]

Climatological impacts on thermoelectric power generation depend on the type of cooling system employed. For power plants using open-loop cooling, usable capacity is constrained by low streamflow conditions and high water temperatures.[7] For power plants using recirculating cooling systems, ambient wet bulb temperature presents an additional constraint.[7,8,9]

“Open-loop cooling” (also known as “once-through cooling”) is a relatively simple cooling scheme in which cold water is removed from the environment (typically a stream), passed through a heat exchanger (where it absorbs heat from the condenser), then discharged back into the environment (several degrees warmer than before).[9] Because these facilities rely on a constant stream of cool water, facilities employing open-loop cooling are vulnerable to periods of low streamflow and high inlet water temperature. To determine the water demand and reduction in capacity for these facilities, the following approach from van Vliet et al. (2012) is first used to determine the water requirements for each open-loop facility:[7]

$$q = P \cdot \frac{1-\eta_{total}}{\eta_{elec}} \cdot \frac{(1-\alpha)}{\rho_w \cdot C_p \cdot \max\left(\min\left((Tl_{max} - Tw), \Delta Tl_{max}\right), 0\right)}$$

Where q is the required water withdrawal of the power plant (cubic meters per second), P is the installed capacity (kW), η_{total} is the net plant efficiency, η_{elec} is the electrical efficiency, α is the share of waste heat not discharged by cooling water (i.e. flue gas losses), ρ_w is the density of liquid water, C_p is the heat capacity of water, Tl_{max} is the maximum permissible intake water temperature (°C), Tw is the ambient stream temperature (°C), and ΔTl_{max} is the maximum permissible temperature rise of the water (°C). Tl_{max} and ΔTl_{max} are determined for each thermoelectric power plant using cooling system data from EIA Form 767.[19] Similarly, $\eta_{total}$and η_{elec} are determined using plant and generator data from EIA Form 767.[19] The parameter α varies depending on the fuel type, and is roughly 12% for coal-fired facilities, and 20% for natural gas-fired facilities.[9] Knowing the water demand for each facility, the maximum usable capacity is determined using the following formula:[7]

$$P_{max} = \frac{\min\left((\gamma \cdot Q), q\right) \cdot \rho_w \cdot C_p \cdot \max(\min\left((Tl_{max} - Tw), \Delta Tl_{max}\right), 0)}{\frac{1 - \eta_{total}}{\eta_{elec}} \cdot \lambda \cdot \ (1 - \alpha)}$$

Where γ is the maximum fraction of streamflow available for power generation, Q is the natural streamflow, and λ is a correction factor accounting for changes in efficiencies. The above equation shows that as Tw approaches Tl_{max}, once-through cooling systems must withdraw additional water to maintain the same generating capacity.[7] If sufficient additional water is not available, then the usable capacity of the plant is reduced. Furthermore, if Tw is greater than or equal to Tl_{max}, plant operation must be curtailed entirely.[7]

Recirculating cooling systems reject heat by evaporating water (rather than discharging it directly into a nearby water body).[8,9,11] Water that is not evaporated during the cooling process is re-used, meaning that much less water is withdrawn overall. For thermoelectric facilities employing a recirculating cooling system, the above equations must be modified to account for (1) the effect of water re-use, and (2) the effects of additional climatological and physical constraints. In recirculating cooling systems, the ambient wet bulb temperature presents an important design constraint.[8,9] Recirculating cooling systems reject heat primarily through latent heat transfer (in other words, by evaporating water). The ambient wet bulb temperature represents the lowest temperature to which process water can be cooled using evaporative cooling.[11] When the ambient wet bulb temperature is high, recirculating cooling systems will suffer a performance penalty which can decrease the output of the plant.[8] Accounting for additional constraints of recirculating cooling, the water demand and usable capacity of recirculating cooling plants can be described using the following equations:[7]

$$q = P \cdot \frac{1 - \eta_{total}}{\eta_{elec}} \cdot \frac{(1 - \alpha) \cdot (1 - \ \beta) \cdot \omega \cdot EZ}{\rho_w \cdot C_p \cdot \max(\min\left((Tl_{max} - Tw), \Delta Tl_{max}\right), 0)}$$

$$P_{max} = \frac{\min\left((\gamma \cdot Q), q\right) \cdot \rho_w \cdot C_p \cdot \max(\min\left((Tl_{max} - Tw), \Delta Tl_{max}\right), 0)}{\frac{1 - \eta_{total}}{\eta_{elec}} \cdot \lambda \cdot \ (1 - \alpha) \cdot (1 - \ \beta) \cdot \omega \cdot EZ}$$

Where β represents the fraction of waste heat released into the air (i.e. sensible heat transfer), ω represents a correction factor to adjust for changes in air temperature and humidity, and EZ is the densification factor that accounts for blowdown due to increases in cooling water salinity.

Thermoelectric facilities employing a combustion turbine generator require little to no water for cooling.[8] With respect to climactic effects, power generation at combustion turbine facilities is affected only by the ambient dry bulb temperature of the air.[10] In general, as ambient air temperature increases, the heat rate of the plant increases and the power output decreases.[10] However, the relationship between ambient temperature and plant efficiency depends on individual turbine characteristics. At this time, it is not possible to determine temperature-efficiency curves for each gas-combustion turbine serving the WECC region. Thus, combustion turbines are not included in this analysis.

2.1.3. Solar Photovoltaic Power

For solar power facilities, usable generating capacity depends on two climactic variables: net shortwave radiation and ambient dry-bulb temperature. Net shortwave radiation refers to the amount of visible light supplied to the solar cell. Solar cell performance also decreases with increasing temperature "owing to increased internal carrier recombination rates, caused by increased carrier concentrations".[12] Solar power output is calculated on a daily basis using the following equation: [12]

$$P_{mp} = P_{STC} \frac{J_{tot}}{1000} (1 - \beta[T - 25])$$

Where P_{mp} is the instantaneous power generation, P_{STC} is the power generation under standard conditions (25 °C, 1000 W/m^2 incident solar radiation), β is the power-temperature coefficient (which varies depending on the technology),[12] and T is the temperature in Celsius.

2.1.4. Wind Power

Wind power capacity depends primarily on wind velocity. For wind turbines, power generation can be estimated using the following formula:[13]

$$P = \frac{1}{2} C_p \rho A v^3$$

Where P is the generating capacity, C_p is the maximum power coefficient, ρ is the density of air, A is the area swept by the rotor, and v is the wind velocity. Assuming that C_p, ρ, and A remain constant, power generation for wind turbines can be expressed using the following equation:

$$P = P_m \cdot \frac{v^3}{v_m^3}$$

Where P_m is the average historical generating capacity, and v_m is the average historical wind velocity.

2.2. Estimating Climactic and Hydrological Conditions

A physically-based modeling framework is used to estimate climactic and hydrological conditions that may impact power generation. Six climactic and hydrological conditions are needed to assess impacts on power generation. These climactic variables are listed below, along with the power generation technologies they affect:

1) Streamflow (hydropower and thermoelectric power)
2) Stream temperature (thermoelectric power)
3) Ambient wet-bulb temperature (thermoelectric power with recirculating cooling)
4) Net shortwave radiation (solar photovoltaic power)
5) Ambient dry-bulb temperature (combustion turbine and solar photovoltaic power)
6) Wind speed (wind turbines)

Each of the six climactic and hydrological conditions listed above are modeled at a daily time step for both the historical period (1949-2010) and the future period (2010-2100) using 1/8-degree gridded data. Streamflows are modeled using the Variable Infiltration Capacity (VIC) macro-scale hydrological model,[3] along with an offline routing model.[4] To estimate stream temperatures, the previous two models are joined with a one-dimensional stream-temperature model (RBM).[5] Net shortwave radiation and ambient wet-bulb temperature are obtained by running the VIC model in full-energy mode. Ambient dry-bulb temperature and wind speed are obtained from input data to the VIC model. Historical climate inputs to the VIC model are derived from gridded observed meteorological data.[1] Future climate inputs are obtained from the CMIP3 multi-model ensemble, using downscaled outputs from the ukmo-hadcm3.1 and mpi-echam5.3 GCM models.[2] Emissions scenarios include the SRES a1b, a2 and b1 scenarios.

The VIC model works by dividing the study area into discrete grid cells (typically 1/8-degree) and performing water and energy balances at each cell. Using the water balance mode of the VIC model, daily estimates of runoff and baseflow are obtained for each grid cell. Gridded runoff and baseflow are then fed into a routing model, which produces estimates of streamflow by routing these inputs through a stream network at the same resolution of the VIC hydrological model. The RBM model estimates stream temperature by solving the one-dimensional heat advection equation using a mixed Euler-Lagrangian approach.[7] Stream temperatures at each stream segment are calculated based on three characteristics: "upstream water temperature and inflow into the stream segment, the dominant heat exchange at the air-water surface, and the inflow and temperature of water advected from tributaries and (anthropogenic) point sources of heat".[7]

Two types of input files are required to run the VIC model: (1) meteorological forcing files and (2) land cover parameter files. Meteorological forcing files contain meteorological characteristics at a specified time step (typically daily) for each grid cell. VIC requires a minimum of four meteorological forcing inputs: precipitation, daily maximum temperature, daily minimum temperature, and wind speed. For the historical period, daily observed values for these four inputs are obtained at a 1/8-degree spatial resolution.[1] For the future period, daily meteorological inputs for the VIC model are obtained using downscaled General Circulation Model (GCM) outputs from the CMIP3 multi-model ensemble.[2] Two representative GCMs were chosen: ukmo-hadcm3.1 and mpi-echam5.3. These GCMs were chosen because they have performed favorably compared to many other GCM models in previous assessments.[20] GCM model output was obtained for three SRES scenarios: a1b, a2, and b1. The CMIP3 multi-model ensemble was chosen over the newer CMIP5 ensemble because CMIP5 currently does not contain all the meteorological forcings needed to run the VIC model. In addition to meteorological forcings, the VIC model also requires land cover parameter files. Land cover parameter files contain land cover characteristics needed to perform water and energy balances under the VIC model (such as the saturated hydraulic conductivity of the soil). These land cover characteristics are divided into three categories: soil characteristics, vegetation characteristics, and snowband (elevation band) characteristics. For this study, 1/8-degree gridded land cover files (soil, vegetation, and snowband) are obtained using NASA's National Land Data Assimilation Systems (NLDAS) datasets.[21]

The offline routing model produces estimates of streamflow using gridded runoff and baseflow outputs from the VIC hydrological model. In addition to the VIC runoff and baseflow outputs, the routing model requires a flow direction file at the same resolution as the VIC output files. For this purpose, 1/8-degree upscaled flow direction networks are used.[22]

The RBM model combines the routing model with a heat budget model in order to calculate stream temperatures in the routing network. In addition to gridded runoff and baseflow inputs, the RBM model requires the following forcings to perform heat budget calculations: air temperature, vapor pressure, incoming shortwave radiation, incoming longwave radiation, near-surface atmospheric density, near surface atmospheric pressure, and near-surface wind speed. These forcings are obtained at a daily timestep by executing the VIC hydrological model in full-energy mode. The RBM model includes a modified version of the offline routing model. The modified version of the routing model (rout-DA) includes subroutines that calculate the hydraulic geometry (the width and depth) of the stream for a given streamflow value, using the methods of Leopold and Maddock.[23] Hydraulic geometry parameters (sometimes referred to as Leopold coefficients) are required as inputs for this part of the RBM model. These parameters describe how the width and depth of a stream change with respect to streamflow, and are determined empirically using power regressions on historical streamflow and river geometry data. For this study, Leopold coefficients are obtained using empirical observations from 674 gauging stations throughout the U.S., as collected by Allen et al.[24] The boundary conditions for the RBM temperature model (headwater temperatures) are determined using a water temperature regression model used by Mohseni.[25] Mohseni's regression model takes the form of the following logistic function:

$$T_s = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T)}}$$

Where T_s is the modeled water temperature, μ is the minimum water temperature, α is the maximum water temperature, γ is the steepest slope of the function, β is the air temperature at the inflection point of the curve, and T is the measured air temperature. Maximum and minimum temperatures (α and μ, respectively) are determined for relevant streams, using historical water temperature data from USGS. A Levenberg-Marquardt curve-fitting algorithm is then used to fit the additional parameters to the historical data.

The general process for determining relevant climactic characteristics at power generating stations is outlined below:

a) Power generating stations in the WECC region are identified and mapped by latitude-longitude coordinate using eGRID coordinate data.[26]
b) Watersheds containing hydroelectric and thermoelectric powerplants in the WECC region are delineated using a 15-second resolution digital elevation raster.[27]
c) The watersheds delineated in step (b) are upscaled to a 1/8 degree spatial resolution by intersecting the watershed's contributing area with a 1/8 degree grid.
d) A 1/8-degree flow direction raster is clipped to the delineated basin to produce the 1/8-degree flow direction file required by the routing model.[22]
e) To account for the partial contribution of boundary cells, a flow fraction raster is generated. The flow fraction raster consists of a gridded ascii data file containing the fraction of runoff contributed by each 1/8-degree grid cell. The flow fraction for each 1/8 degree grid cell is equal to the internal area of the 15-second resolution contributing area divided by the total area of the 1/8 degree grid cell.
f) The Variable Infiltration-Capacity (VIC) hydrological model is executed in water-balance mode to generate runoff and baseflow data for each 1/8-degree grid cell.
g) The offline routing model is used along with the output from the VIC hydrological model to produce estimates of streamflow at each generating station.
h) For thermoelectric generating stations, the VIC model is executed again in full-energy mode to produce the following outputs: air temperature, vapor pressure, incoming shortwave radiation,

incoming longwave radiation, near-surface atmospheric density, near surface atmospheric pressure, and near-surface wind speed. These parameters are used as inputs to the RBM model.

i) The RBM model is excecuted using the forcings generated in (f) and (h) to produce estimates of stream temperature at each stream segment.
j) For solar photovoltaic facilities, the VIC model is executed in full energy mode to obtain incoming shortwave radiation at a daily time step for each grid cell containing solar photovoltaic facilities.
k) For wind turbines, near-surface wind speed inputs are extracted for all grid cells containing wind turbines.

Steps (a) through (k) above are automated using a series of helper scripts. These scripts are produced by the author and are available online.[28] A full workflow schematic—including all inputs, outputs, executables and helper scripts—is shown in Figure 1.

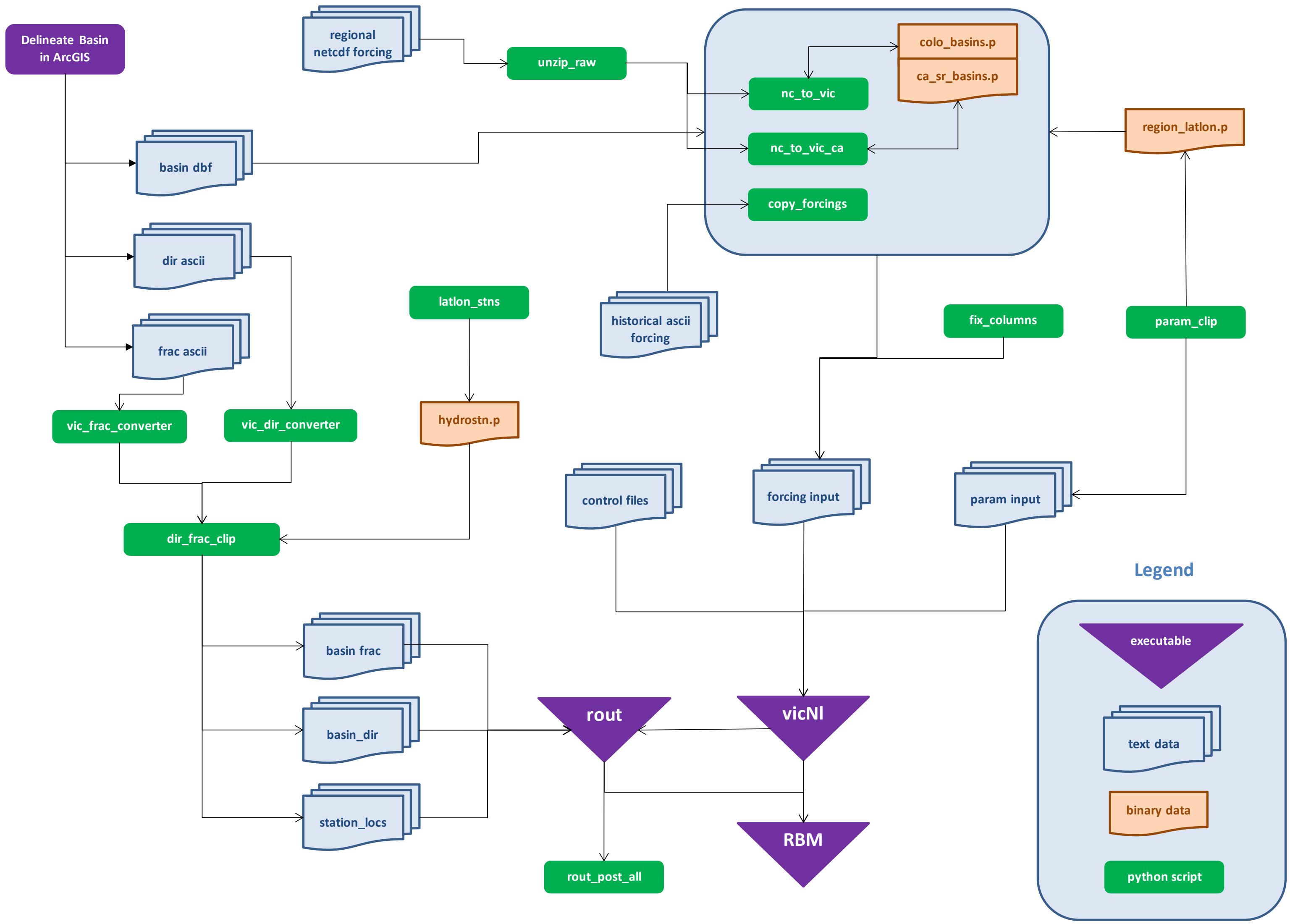

Figure 1. Workflow for pre- and post-processing VIC, rout, and RBM inputs/outputs.

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