Impacts on the Terrestrial Water Cycle from Climate Change of Precipitation Magnitude, Pattern, Timing, and Intensity

Ph.D. Dissertation Proposal

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Introduction

The climate is a complex system that encompasses numerous Earth surface systems, i.e. the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere. The preponderance of scientific evidence indicates that anthropogenic actions such as excess generation of greenhouse gases are causing serious climatic change. Water is a critical resource to humans, commerce, wildlife, and the environment. This resource is already over-used and stressed in much of the United States and the world. A thorough understanding of the relationships between climate change and water resources could help improve the construction and evaluation of accurate climate models.

Changes of many of the atmospheric climate elements, such as temperature, radiation, wind speed and direction, humidity, and precipitation can impact water resources (UN IPCC, 2007). Precipitation is the most critical element for water impacts. It is typically characterized and measured mainly in terms of total annual precipitation. However, precipitation can be further classified by other characteristics such as the intensity of precipitation events, duration of events, frequency of precipitation events, and recovery time between events (Trenberth, Dai, Rasmussen, & Parsons, 2003).

The terrestrial hydrologic cycle is that portion of the global hydrologic cycle that takes place on the land surface and sub-surface. It is a complex system with many transport and storage components, such as evaporation, overland flow, infiltration, soil moisture, plant uptake, transpiration, percolation, stream base flow, and groundwater recharge (USGS, 2009).

Each precipitation characteristic can influence how water partitions among the various hydrologic cycle components. In fact, changes of each precipitation characteristic could produce a quantitatively different impact on each of these components.

Rationale

This proposed research is concerned with the connections and impact of climate change on water resources. This work is motivated by statements such from the Stockholm International Water Institute and the World Wildlife Fund in late 2009 that “Water is the primary way that climate change will impact people, society and ecosystems.” which echoes the UN-Water in early 2009 that “Water is the primary medium through which climate change influences the Earth's ecosystems and therefore people’s livelihoods and well-being” (UN-Water, 2009). Given the existing deficiencies in water availability and quality, further impacts from climate change could be especially challenging.

Precipitation is not modeled in Global Climate Models (GCMs) with nearly the same accuracy or confidence as has been achieved with temperature projections. In fact, a current Nature report identifies precipitation as one of the fundamental gaps in current climate change research and that IPCC models “offer wildly diverging pictures” of precipitation (Schiermeier, 2010). The same problem is also true of regional downscaling methods which have been shown to successfully represent air temperature, but not have similar success in representing precipitation (Fowler, Blenkinsop, & Tebaldi, 2007).

This proposed work's scientific merit stems from its contribution to a thorough understanding of the climate connections to the hydrological cycle. Climate science has not yet identified the most sensitive and important precipitation variables impacting the water cycle, nor how these might be different in different regions. This research could benefit the efforts to develop more accurate climate models by identifying the most important precipitation characteristics to investigate and to incorporate in the models (U.S. GCRP, 2009). Similarly, by identifying those important comparison variables to be studied, this research could advance related work that evaluates and compares climate models.

Understanding water and climate has scientific value beyond climate science. For example, ecologists are concerned about adequate water for the health of ecosystems and endangered species, including availability of soil moisture and riparian streamflow. Stormwater runoff and subsurface saturation and overflows impact water quality through erosion and sedimentation, an environmental science issue. Horticulture is dependent on suitable levels of resident soil moisture and losses from evapotranspiration. Water supplies for domestic and industrial use and for crop irrigation require extraction of water resources from groundwater and surface water bodies. The concerns of these other research fields are dependent on components of the hydrological cycle and how they could be impacted by climate change, all of which are subjects of this research.

It is well known and accepted that energy usage impacts climate change. Water-related energy consumption plays a major role. Currently in California, nineteen percent of all electricity and thirty percent of natural gas usage is water-related for extracting, transporting, purifying, heating, cooling, cleaning, and disposing (CEC & Krebs, 2007). To the extent that climate change impacts water resources, then such water shortages could induce energy-intensive efforts for replacement supplies or adaptation efforts, i.e. a positive feedback.

Information is needed by a society already stressed by water shortages as future climate change threatens to impact their water supply and its quality. It is important to know what impacts to expect to do effective planning. Long-term efforts are essential, so prompt but accurate scientific knowledge is needed. In particular, numerical impact assessments are needed since you can not plan or manage something that you can not measure. This work could help advance the science and move closer to providing the guidance needed.

Hypotheses

The thesis for this research is that a single precipitation metric of total annual quantity is not adequate for predictions needed to plan for and adapt to coming global climate change. The effects from changes to precipitation event intensities, timing and altered precipitation patterns could produce significant impacts on the water cycle and on its availability and quality burdens. Regions with no predicted annual precipitation reductions, or perhaps even expected increases, could still suffer water impacts because of changes in precipitation patterns (UN IPCC, 2007) and (Trenberth et al., 2003).

Understanding the full details of impacts of climate change on the terrestrial hydrologic cycle could be help contribute to more reliable computer models of climate systems by identifying the most important characteristics of precipitation. This work should also reinforce the value in being able to deliver not just a single number for water impacts, but values for the range of variability and the confidence level for those impacts.

Background

GCMs are coarse-grained computer representations of the climate of the entire Earth, e.g. temperature, radiation, moisture, winds, ice, biology, ocean currents, and land surfaces. Regional Climate Models (RCMs) are more fine-grained representations of a portion of the Earth and are driven by global model output or observations at their common boundaries (UN IPCC, 2007).

Climate & Precipitation

Precipitation is currently not well represented in GCMs. Unlike predictions for temperature, precipitation predictions are known to be less reliable and thus suspect, for example “Future changes in total precipitation due to human-induced warming are more difficult to project than changes in temperature.” (U.S. GCRP, 2009). As mentioned, a Nature report identifies precipitation as one of four fundamental gaps and that models “offer wildly diverging pictures” of precipitation (Schiermeier, 2010).

Intercomparison efforts evaluate climate models for their ability to predict past climate by comparing their results with observational data (Felzer & Heard, 1999). The models evaluate their future predictions by comparing with each other's projections and their annual precipitation forecasts have been shown to be poorly correlated (Mesinger et al., 2006).

Precipitation comparisons examine longer term precipitation averages, typically total monthly accumulation. The comparisons of GCMs for their predictions of other precipitation characteristics, such as event intensity, is not adequately studied (UN IPCC, 2007) and (Dai, 2006).

In spite of severe modeling uncertainty, precipitation changes are not just theoretical or predictions for the distant future. Significant changes to precipitation magnitude, intensity and frequency are already being observed (U.S. CCSP, 2008). For example, it is reported that “Widespread increases in heavy precipitation events have occurred, even in places where total rain amounts have decreased.” and “One of the clearest precipitation trends in the United States is the increasing frequency and intensity of heavy downpours.” and “The widespread trend toward more heavy downpours is expected to continue, with precipitation becoming less frequent but more intense.” (U.S. GCRP, 2009)

In addition to the standard precipitation metric of annual amount, the other precipitation property study is the triple intensity-duration-frequency. This is assessed from historical data and is most often used for civil engineering and flood estimation work (Beguería, Vicente-Serrano, López-Moreno, & García-Ruiz, 2009). One study that seriously investigates various precipitation characteristics much as proposed in this research is (Dunkerley, 2008). But this work primarily studies how such characteristics have been measured in observations and there are no connections to hydrology in it at all.

Hydrology Impacts

The relationship between climate change and water systems are poorly understood today . For example, “Changes in surface and groundwater have been observed in many systems, and some have been linked with statistical significance to trends in temperature and precipitation, but because of different trends in regional climate change, climate variability, and the complexity of non-climatic influences on surface and groundwater, uniform global trends have not been identified.” (CEC, 2009).

Much research has been done on climate impacts upon snowpack because this is primarily affected by temperature change, a metric that is more understood and quantified. Temperature increases will cause more precipitation to fall as rain instead of snow and what does accumulate will melt earlier. For example, a current assessment is that the snowpack in the Sierra Nevada might decline 70 to 90 percent by 2100 depending on the emission scenario selected (Stewart, Cayan, & Dettinger, 2004) and (Kapnick & Hall, 2009).

However, many water processes and regions are not dominated by snowpack. For example, only 30% of the water supply in California is from snowpack sources. The quantitative impacts of changes of all kinds of precipitation on the full hydrologic cycle, especially surface base flow and groundwater availability, is needed to complete the picture.

Some studies have extracted from a GCM or a RCM an estimate of the impacts on local water resources (Wetherald, 2009). Other studies have coupled such a climate model to a hydrological model (Tu, 2009), (Qi, Sun, Wang, McNulty, & Myers, 2009), and (Hanson & Dettinger, 2005). Of course such climate model based estimates are of limited value due to the precipitation uncertainties already mentioned.

Method

This research will perform a series of tests to determine the differential impact of precipitation characteristics on various hydrological components. Each test will repeatedly invoke a sophisticated, complete hydrological model with climate inputs in which one precipitation characteristic is varied at a time. The computed water budget outputs of the model will be analyzed to compute the sensitivity of each hydrological component to the change of that one precipitation characteristic being tested. Tests will also be repeated with multiple values of other non-climate background model parameters to yield confidence levels for the computed sensitivity values. Finally, testing will be repeated for other watershed and groundwater basin locations to assess dependency of the results on the basin choice.

Principles

There are several key principles for the experimental design of this research.

It is necessary to supply results with a reasonably precise numerical **quantification** for this research to be useful for effective decision making. Relying on data from observations to understand impacts can be insufficient because natural parameters can be difficult to measure.

For example, simply measuring groundwater levels to try to quantify recharge can mislead because other groundwater inputs and outputs can be unknown or poorly estimated and their contributions can be delayed many years.

It is important to ensure **repeatability** in order to conduct valid experimentation. Clearly nature conducts climate “testing” every year. But reality can be so chaotic and semi-random that it can be quite challenging to make correct inferences from such data. In addition, the experimental setup for natural testing in not under any control. Repeatability is also important to allow other scientific researchers to reproduce, verify, and extend this research.

Experiments must achieve a **separation of confounding factors** in order to produce insight into the fundamental processes at work. In nature everything changes at the same time and conditions are different from one year to the next and never seem to repeat. All this hides the cause and effect relationships which need to be discovered and made known. Of course, factors can have linkages, feedbacks, and offsetting factors and this can make separation challenging.

It is desirable to provide, not just a numerical result, but also **confidence levels** for the results. These would be metrics such as a range of values, experimental error, and numerical sensitivity. of how other factors of the experimental setup might affect results. Confidence metrics seem important for scientific results to be helpful for making critical societal decisions and investments.

This testing requires a hydrological model for a specific watershed and groundwater basin. It will be important to evaluate how the validity of results might vary with choice of a model with other basin features such as different topography, vegetation, drainage, or geology.

Research Design

To produce the precise numerical metrics and the experimental repeatability that are difficult to achieve in the field, this research will employ numerical hydrological models. The testing will be performed with a hydrological model together with the historical climate record with which the model was validated to serve as the initial baseline. This research could be performed with a model for some abstract, idealized basin. However, a model for an actual basin location will be utilized so the results will be more convincing.

Separation of multiple confounding input factors will be accomplished by performing testing by modification of a single input factor. A single precipitation characteristic will be varied across a range of values from +10% to -10%. The outputs for the hydrological cycle for that changed precipitation characteristic input will be analyzed to extract the corresponding changed quantity of each water cycle component. This will yield sensitivity metrics relating the proportionality of water component output change for a unit change of the input.

Next a stochastic Monte Carlo variation of important other background model parameters such as hydrologic conductivity or porosity will be tested. Variation of these parameters across a range of reasonable values in a combined sensitivity testing arrangement will involve statistical processing of the hydrological model outputs from this ensemble. This will yield a metric of the confidence level for each statement about a water component sensitivity to change of a precipitation characteristic.

Finally, all this analysis will be repeated with models for several physical basins to identify if the methodologies can work in a variety of basins and to demonstrate how responses would vary in different settings.

Precipitation Specification

This research will investigate the impacts from changes of various characteristics of precipitation shown in Table 1.

Precipitation Characteristic	Units
1. Total yearly, monthly, or seasonal precipitation	mm
2. Length of precipitation season (for regions with distinct seasonality)	days
3. Number of identifiable events in the season/year	count
4. Average duration of events in the season/year	hrs or days
5. Delay time between events in the season/year	hrs or days
6. Average rate of events in the season/year	mm/hr
7. Maximum event intensity in the season/year	mm/hr

Table 1: Precipitation Characteristics for Investigation

To be able to accurately quantify precipitation characteristics and to generate precipitation records that evidence such values, each characteristic requires a precise specification. For example, does a few seconds of noticeable mist, drizzle, or fog drip constitute a precipitation event or is a certain minimum rate, duration, and/or total accumulation required? How is precipitation that is too light or little to be considered an event to be treated? If the precipitation during an event decreases or even stops briefly, as it often will do, does this constitute a second event? How is a beginning and end of the rain season identified for each year's record? Only with such specifications can the number of events be counted, the duration of season computed, and other statistics produced.

All the precipitation characteristics described here have the advantage of a single scalar metric. So it seems easy in principle to modify a precipitation record to gradually increase or decrease that metric value. However, there are other possible precipitation characteristics that are more complex and perhaps have no such simple metric. For example, one could characterize precipitation by a fit to a complicated distribution of event sizes such as shown in Illustration #1. Depending on the distribution function selected, there might be no single numerical precipitation metric which controls this distribution and against which one could compute impact sensitivities or confidence levels. Of course, this event size characteristic may well be represented sufficiently by combinations of other listed characteristics such as the average rate of events and their maximum intensity.

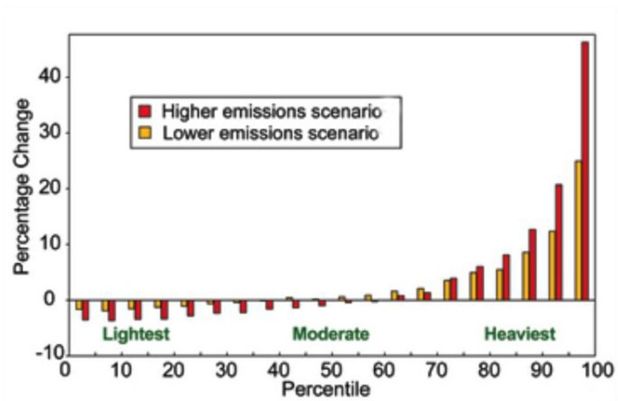

Illustration 1: Projected Changes in Light, Moderate, and Heavy Precipitation by 2090s (U.S. CCSP, 2008)

It is necessary to have precise definitions for these characteristics in order to properly quantify existing climate records and to generate appropriate artificial climate records. If there are currently official or de-facto specifications for such terms, then these must be discovered and utilized. If there are no standards, then mathematical definitions will need to be produced that hopefully can incorporate any recommendations of scientists, practitioners, and literature such as (Dunkerley, 2008) and (Cosgrove & Garstang, 1995).

Precipitation Calculation Software

For these precipitation specifications, a set of software routines will need to be coded that take a climate record, in particular a daily record of precipitation amounts, and then calculate the values for each of the seven specified precipitation characteristics shown in Table 1. This calculation would be used to establish the initial values for a supplied precipitation record or to verify the values in a modified record. The simplest example would be to take a precipitation record and increase its annual amount by X%.where the obvious technique would be to just increase the precipitation value recorded for each day by the same X%.

Climate Model Precipitation Intercomparison

The precipitation code described above for computing precipitation metrics from a climate record could be of direct utility for climatology studies. This proposed research will analyze how these precipitation characteristics are handled and predicted by GCMs or RCMs. It should be worthwhile to compare how similar or different are the projections of these precipitation characteristics by the various climate models.

The UCSC Climate Impacts Laboratory is already analyzing outputs of several models to compare their impacts on California climate. The existing output data from each of the models will be taken and the values for each of the seven precipitation characteristics will be calculated for each year of the output record. These yearly precipitation metric sequences will then be compared to demonstrate how well or poorly these models perform in reproducing current observations and the amount of agreement of their future projections. This task will also include preparation of a paper and its submittal to a climatology relevant journal such as Journal of Climate or Climate Change.

Precipitation Adjustment Software

The second set of software routines will need to be coded which would take a precipitation record and generate a modified record with some characteristic(s) adjusted by some amount larger or smaller than its starting value. The simplest example would be to take a precipitation record and increase its total annual accumulation amount by X%.where the obvious technique would be to just increase the precipitation value recorded for each day by the same X%.

Changing one precipitation characteristic at a time to measure its effect on hydrologic components sounds simple, but can be tricky in practice because of precipitation interdependence. Unfortunately, the precipitation characteristics described in Table 1 are not completely independent. In particular, the total annual precipitation can only be increased by increasing one or more of the others. In fact, one could equate yearly precipitation to be the yearly number of events times the average event duration times the average event precipitation rate and then add any non-event light precipitation. Decreasing the length of a rain season would require decreasing the delay between events or else merging and reducing the number of events.

The interdependence of the desired precipitation characteristics will need to be studied and documented. A testing sequence will then have to be carefully composed where each test element may include changes to more than one precipitation characteristic. The test elements will be specified so that they can be mathematically combined to expose just the impact of a single characteristic. This might be setup as just a simple linear algebra sort of problem where

$$X = ½ * [test [+X,+Y] + test [+X,-Y]).$$

This issue will necessitate a test sequence longer than just the seven listed characteristics. A requirement for a test sequence of fourteen precipitation elements will therefore be mandated.

Hydrologic Cycle Component Specification

The terrestrial hydrological cycle is a very complex system. In its fullest exposition it is composed of many specialized fluid reservoirs and even more fluid flow pathways, see Illustration 2 for the details. The key components of the hydrological cycle proposed to be investigated by this research are the eleven flow quantities shown in Table 2.

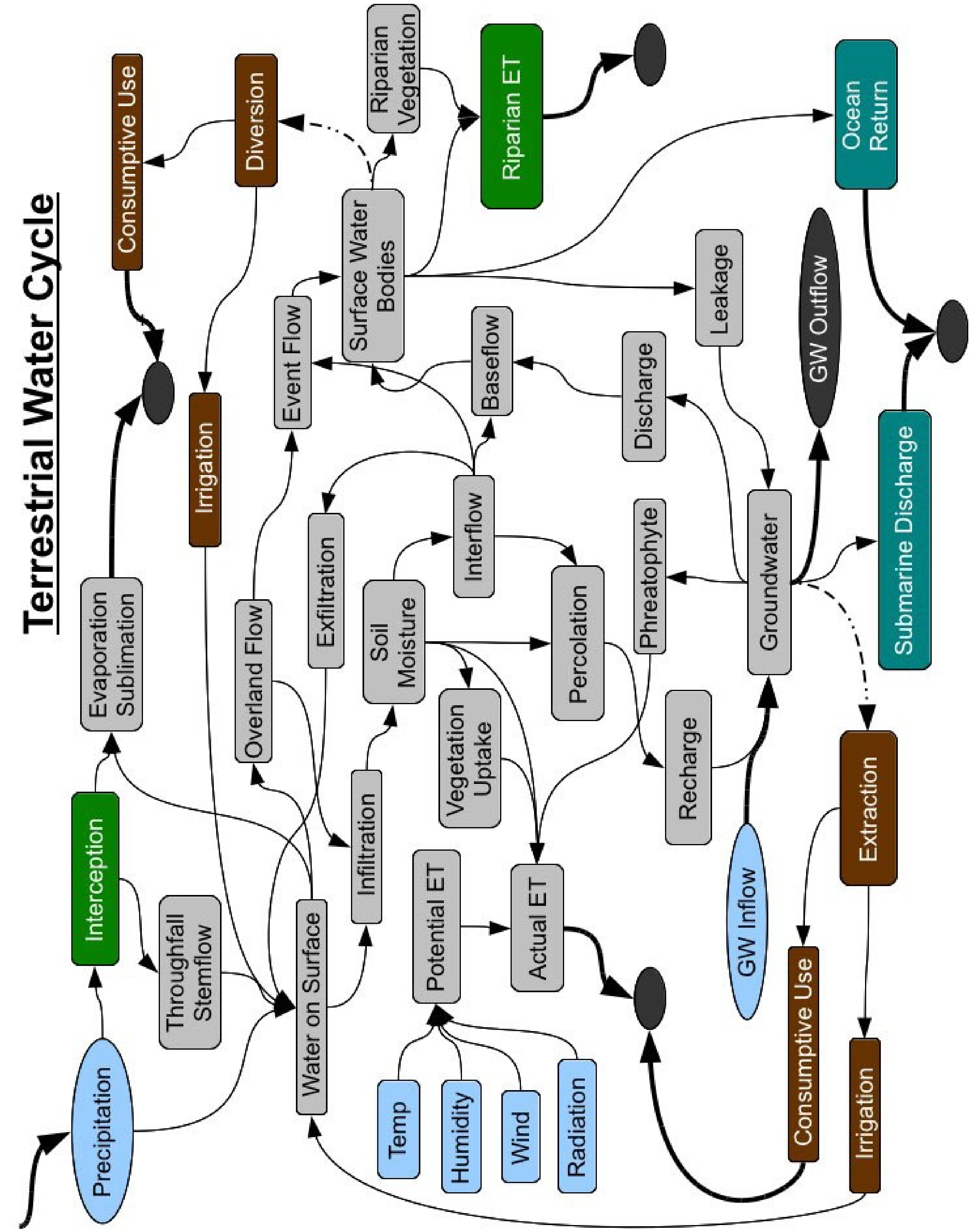

Illustration 2: Terrestrial Hydrologic Cycle Diagram (personal creation)

1. Interception evaporation/sublimation
2. Snowpack sublimation
3. Surface evaporation

4. Dunnian saturation-excess overland flow to streams
5. Horton infiltration-excess overland flow to streams
6. Infiltration into soil
7. Soil evapotranspiration
8. Interflow to streams
9. Groundwater recharge
10. Baseflow to streams
11. Stream leakage

Table 2: Hydrologic Cycle Components for Investigation

A thorough understanding of precipitation impacts would detail exactly how water is partitioned among these hydrologic components. Therefore, this work proposes to compute how a change in the amount of each precipitation characteristic would impact or change the amount partitioned to each of these hydrologic components.

Hydrologic Software Choice

This research will utilize the hydrological model code Ground-water and Surface-water FLOW (GSFLOW) created and maintained by the USGS (Markstrom, 2008). It consists of a merger of two older USGS models, the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW).

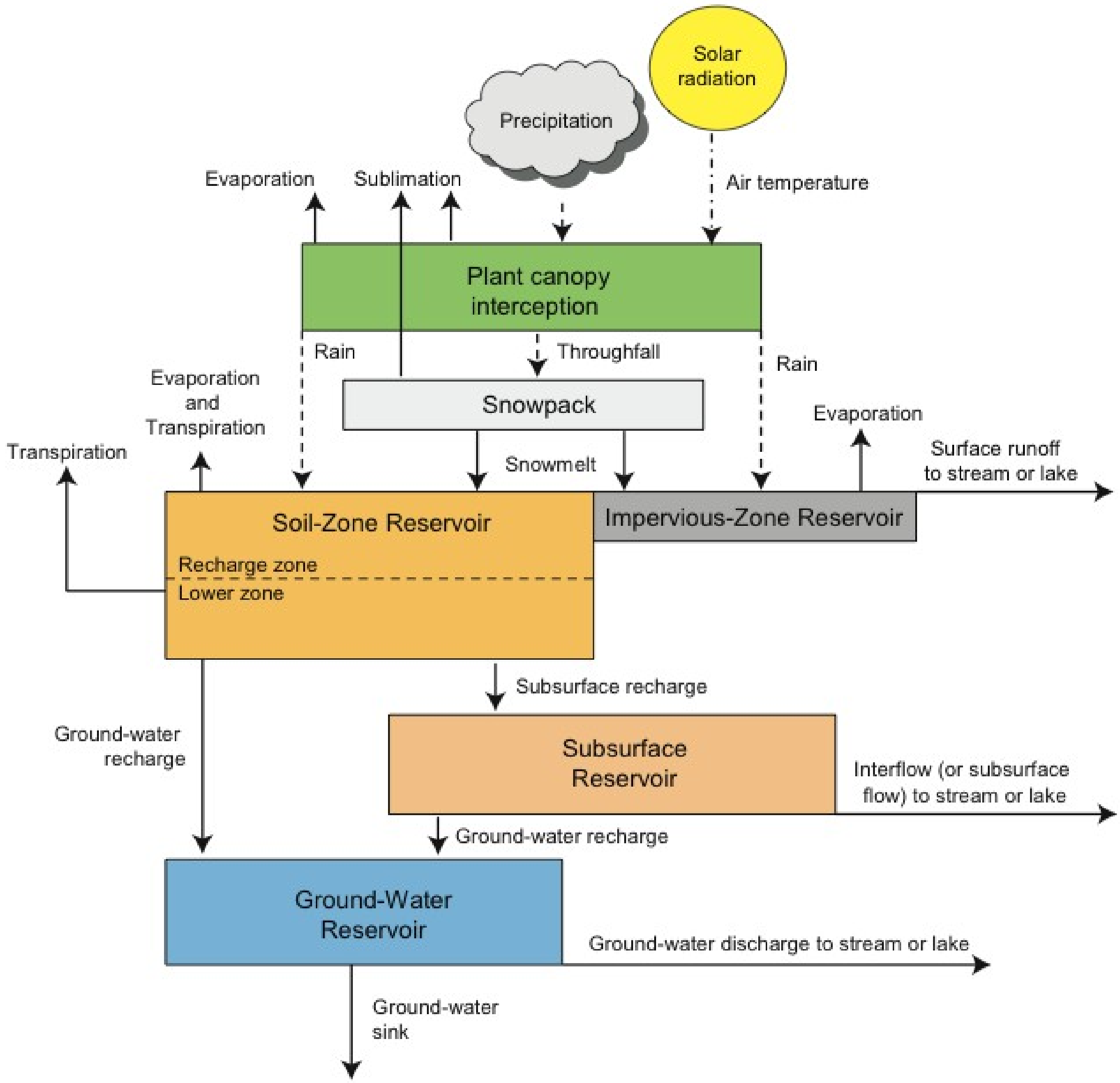

Illustration 3: Schematic diagram of a watershed and its climate inputs (precipitation, air temperature, and solar radiation) simulated by the Precipitation-Runoff Modeling System (PRMS) (Markstrom, 2008)

PRMS is a semi-distributed hydrologic model used to assess surface and non-saturated sub-surface water resources. It can evaluate the impacts of various combinations of precipitation, climate, and land use on streamflow, sediment yields, and general basin hydrology, see Illustration 3. Basin response to normal and extreme rainfall and snowmelt can be simulated to evaluate changes in water-balance relationships, flow regimes, flood peaks and volumes, soil-water relationships, sediment yields, and ground-water recharge (G. H. Leavesley, 1983).

MODFLOW-2005 is a three-dimensional finite-difference groundwater model with add-on packages to handle solute transport, variable-density and unsaturated-zone flow, aquifer-system compaction and land subsidence, parameter estimation, groundwater management, etc. (Harbaugh, 2005)

MODFLOW-2005 was chosen because it is the most widely-used 3D groundwater flow model in the world and is now considered to be the de facto standard code for aquifer simulation. It is the groundwater model recognized by courts, regulatory agencies, scientists, and industry.

The choice of surface water model was more difficult as there are several dozens of widely known and used models with varying levels of capability and applicability. PRMS was chosen primarily because it is one of a relatively few that performs fully distributed, continuous simulation of complete 3-D watershed flow and it incorporates all important components of the hydrological cycle.

The enhancement of PRMS and MODFLOW-2005 and their combination into GSFLOW, now provides a single supported tool that can model the complete terrestrial hydrologic cycle. Another advantage of GSFLOW adoption is that the USGS is actively employing it to produce models for many basins around the country. This means that this proposed research can save the considerable time it would take to construct and calibrate even one hydrologic model.

Storage reservoirs represented in GSFLOW include the plant canopy, snowpack, impervious surfaces, streams/lakes, and the soil, unsaturated, and saturated zones in the subsurface. Water flows in GSFLOW represent movement of water both into and out of the model and also the various flows between the storage reservoirs, i.e. a total of 37 labelled flow quantities. For much more technical details on the structure, operation, and scientific basis of GSFLOW, please see Appendix A

Sensitivity And Differential Impact

At the Groundwater Resources Association conference on "Climate Change: Implications for California Groundwater Management" held August 13, 2008 in Sacramento, CA, it was mentioned that the decade-long drought in parts of Australia was the result of about 20% less rainfall. This shortfall did not produce a decrease of groundwater recharge of a similar magnitude as might be expected. Instead the impact on recharge was a surprisingly much larger 70% reduction (Abernethy, 2008).

If one considers carefully the workings of the hydrologic cycle, it is possible to rationalize how a reduction of rainfall might cause a 3.5 times larger reduction of recharge. But science needs a much more rigorous and quantitative impact analysis than such a rationalization of an anecdote. We do not know if this impact factor of 3.5 times larger reported for Australia is the result one should always expect. If there is instead a range of values to expect, then we do not know if Australia is on the high end of this scale or what the factors are that control the applicable impact factor in each particular case.

Impacts are all different. The amounts of relative change vary. Even the signs could differ. For example a particularly intense rain event could increase more water into storm runoff, producing more erosion & flooding, while decreasing water from percolation and recharge, yielding less water supply. For a light rain or drizzle, most would be absorbed by vegetation or the soil surface which increases evaporation and simultaneously reducing percolation and recharge.

The sensitivity of a hydrologic component on the changed precipitation characteristic is a measure of relative change, i.e. the ratio of how much the component changes to the amount of precipitation change. To compute this ratio, the relative change for a single component will have to be extracted from hydrological outputs for a model run and then divided by the relative change of the precipitation characteristic for the input record that drove the run.

If variation of inputs for each of the 14 test sequence precipitation elements yet to be defined requires a range of seven values to be run to determine the basic sensitivity of the outputs for all eleven specified hydrologic components (Table 2), then 100 model repetitions would be needed for a basic sensitivity test.

Non-linear Response

Responses to impact changes are not always going to be linear. Consider for example that a light rain just wets the plants and the earth surface which provides water for evaporation but no recharge. Additional amounts of rain would infiltrate the soil and the root zone which allows plant uptake and evapotranspiration (ET) to occur, but still little or no recharge. Even more rainfall finally allows percolation and thus significant recharge to take place. However much more intense rain would saturate the sub-surface and cause most of this extra water to be lost to runoff but relatively little more to recharge. So the response of recharge to varying levels of rainfall would

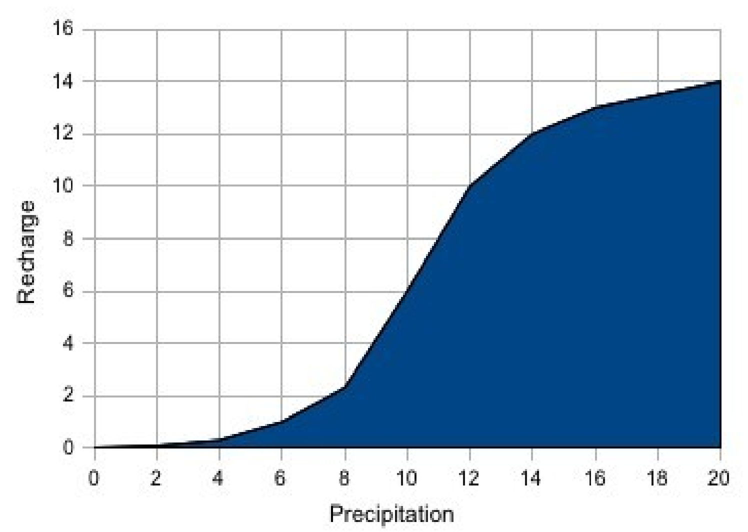

Illustration 4: Cartoon of a Non-Linear Relation Between Precipitation and Recharge (personal creation)

be a non-linear response curve that looks much like Illustration #4. With such a non-linear response curve, a modest 20% change in precipitation might be able to cause a large 70% change in recharge at one place on the curve and almost no change at others.

A goal of this research is to analyze each impact and determine whether the actual response is a linear or non-linear function. To distinguish between these two situations, it will be necessary to extend climate inputs past the narrow range of typical experienced values, where the response may well be linear, beyond to much more extreme values. This could necessitate about 15 values to run for each sequence element. It is probably safe to expect that most impact functions are non-linear.

For non-linear responses an attempt will then be made to categorize the shape of the response curve and the quantitative piece-wise slopes or control parameters for the response function. To extract the function curve shapes and to get decent quantitative estimates of function parameters, it will be necessary to utilize a relatively dense sequence of input values. But the choice of how many values are needed and their optimal value placement could be made after the curve shape has been determined. This non-linearity situation could easily lead to a further doubling of the number of input values which must be processed which would mean that 35 values are needed. As a result, around 500 model repetitions would be performed for a complete sensitivity test in order to discover and process all non-linearities.

The basic Sensitivity and Differential Impact task together with this full Non-linear Response task performed for a single basin location would probably be worthy of a journal article. So this task will also include preparation of a paper and its submittal to some journal concerned with aspects of hydrology such as Hydrological Processes or GroundWater or a hydroclimatology publication such as Journal of Hydrometeorology or Climate Dynamics.

Stochastic Confidence

A stochastic Monte Carlo variation of important other background model parameters such as hydrologic conductivity or porosity will be conducted. Variation of these parameters across a range of reasonable values will allow statistical processing of the hydrological model outputs from this ensemble. This will yield a metric of the confidence level for each statement about the water component sensitivity to changes of precipitation characteristics.

As mentioned, 500 model repetitions would be required for a complete sensitivity test. This proposal plans to repeat such complete sensitivity tests with Monte Carlo variation of background model parameters such as horizontal and vertical hydraulic conductivity, porosity, and specific yield. If 100 such stochastic parameter sets are needed, then that would mean 50,000 model executions would be required.

This task will also include preparation of a paper and its submittal to a hydrology or hydroclimatology relevant journal.

Basin Choice Dependency

The initial basin location for testing will be the U.S. Geological Survey (USGS) model for Sagehen Creek in the Sierra Nevada Mountains near Truckee California (Markstrom, 2008) which has already been obtained and tried.

Approval has been granted to get access to the additional basin model being created by USGS for Black Earth Creek Minnesota which is a study site in the USGS Priority Watersheds Program. This area has been described as an area of 103 square miles with a glaciated morainal landscape containing features such as depressions and kettles (Wisconsin Dept Nat Rsrs, 2002). The geological stratigraphy is mainly soil-covered sandstone, shale, and dolomite bedrock. The NOAA precipitation for the region is reported as about 31 inches per year with most of that falling within a four month window (Graczyk, Walker, Horwatich, & Bannerman, 2003).

Approval has also been granted to the USGS basin model being created for Santa Rosa, California (USGS, 2007). Studies show that this location is underlain by two prominent Cenozoic sedimentary basins separated by a shallow west-north- west-striking bedrock ridge. These are overlain by Quaternary and Late Pliocene alluvial fan and basin deposits over early to late Pliocene fluvial and estuarine sediments and then Miocene fluvial to estuarine sedimentary rocks. Exposed basement rocks include rocks of the Franciscan Complex, Coast Range ophiolite, and Great Valley sequence (McPhee et al., 2007).

The USGS has announced that it is actively employing GSFLOW to produce models for sixteen basins in a wide range of hydroclimatic settings around the country, e.g. Trout Lake Watershed WI, Spring Creek Watershed PA, Incline Basin near Lake Tahoe NV, Walker Lake Watershed NV, Santa Rosa Plain northern CA, and Rialto-Colton Basin southern CA. Use of these USGS models for this research can allow the results to be checked and compared across several locations with different geology, hydrology, and climate settings.

With such an extensive level of model development effort, there will be several basin models that become available during the term of this research work. So it would make sense to adjust basin choices as research progresses depending on what becomes available. Basins that are heavily snow dominated will probably show less of the impact from changes of precipitation characteristics which this research wishes to demonstrate. Therefore, the four basin locations proposed to be tested for this research will just be identified in this document as basin #1, #2, #3, and #4.

Test Automation

It is not really possible for this work to be done with totally manual preparation of inputs, execution of models, and extraction and analysis of outputs. Automation of these steps is required. The investigation into such automation will start with consideration of the USGS software program UCODE that was created to perform parameter estimation and calibration for model programs (Poeter, 1998). This software tool has been designed to adjust the numbers in program input files, to invoke the executions of the program, and then to extract values from their output files. UCODE states that its only requirement is that programs have textual input and output files that contain numbers represented as text characters. It claims to be able to use the output values to automatically compute sensitivities and to quantify the statistical uncertainty of model predictions.

It is not known if UCODE can be used to perform all the specialized computations needed for this investigation, such as adding or subtracting a precipitation event from a precipitation input record. If UCODE is not completely satisfactory, then it should be possible with some reasonable additional effort to utilize UCODE's modular construction to reuse the software modules and to write additional code to assemble a suitable automation system. A widely-used similar software program called PEST could also be investigated as an alternative solution.

Assumptions And Limitations

Climate Change Skipped

It is immediately obvious that this research does not propose to actually model or measure the direct impacts of climate change on water resources. Although GCMs or RCMs can be coupled to hydrological models to predict impacts, this research does not propose to perform such a study. Given the general consensus of climate scientists that precipitation aspects are poorly represented in current climate models, the results from such a complete system would be suspect and thus of limited value.

This work instead focuses on understanding how changes of climate, and especially precipitation changes, could impact water resources. This body of work could then be of value to inform climate modelers and evaluators about those precipitation characteristics critical to water resource impacts. It is also hoped that this work might demonstrate the complexity of the terrestrial water cycle. Perhaps this could motivate that a full hydrology sub-model would provide significant modeling benefits over the simpler hydrology parameterizations employed in current land models.

Hydrologic Model Accuracy

The validity of the results of this proposed research are evidently dependent on the capability of the chosen hydrologic model(s) to accurately represent the responses of the real systems (George H. Leavesley, 1994). There are issues of trust for both the model software implementation chosen and also how it is used to model a specific watershed and groundwater basin.

Uncertainty is a particular concern for brand new model software implementations. This should be much less a concern for software such as PRMS which has been available for a long time and probably been used and checked for its capability to reproduce observations hundreds of times. Concern is even less for MODFLOW with usage in the thousands. The major issue with such established model software is to take care in constructing models so that they do not violate its range of validity. So for MODFLOW, the groundwater flow velocity must be keep within the laminar flow range where the Darcy equations are valid, i.e. no karst flow regions are allowed. The GSFLOW time step is daily so no hourly flood stage info for stormflow would be reasonable to calculate. But we are not interested in either of these special applications. The GSFLOW manual has a whole chapter entitled "Assumptions and Limitations" that will be used to guide this its proper use for this research (Markstrom, 2008).

For the basin models to be used in this research, there is some confidence in their accuracy because they are being created, calibrated and checked by the USGS who also created the GSFLOW model software. So they would know how best to use and not abuse the GSFLOW technology. In addition, for the models that we have obtained, and hopefully will continue to receive, the USGS supplies both the input record and observational data record against which the basin model was constructed and calibrated. Therefore, we can and will execute the model against this input data and then verify the accuracy of model predictions against the observations for each basin model.

Stochastic Computation Limitations

This research involves many model computations with different sets of inputs. The current GSFLOW model takes about two cpu-hours to execute once. So the 100 iterations required for the initial Sensitivity and Differential Impact tests for a single basin location would just require 200 cpu-hours, i.e. two days on my personal quad-core PC. The 500 repetitions needed by Non-Linear Response testing for a basin would require 1000 cpu-hours, i.e. a week and a half on my PC. To perform the full exhaustive Sensitivity and Differential Impact, Non-linear Response, and Stochastic Confidence testing, a total computational load of 100,000 cpu-hours (six weeks of a large 100-processor computer system) would be needed to completely analyze one basin.

It would be tricky to get this much computer time to fully process even one basin location. Getting enough time to completely analyze for the desired three or four basins would be much more difficult and maybe even impossible. Although accomplishing this whole research vision for all basins might have some incremental value, the analysis of just one basin would prove the thesis concept and should demonstrate the magnitude of difference that this technique might be expected to yield. So unless circumstances change, the current research plan is to perform the full processing for just a single basin location.

Deliverables

This research will yield numerical statements about the relative impacts of changes of precipitation characteristics upon hydrological components. Sensitivity is computed as the ratio of relative changes $\frac{\Delta\, Output / Output}{\Delta\, Input / Input}$. For example, a measurement of 70% less recharge from a 20% decrease in annual precipitation would be reported as “the sensitivity of recharge to a change in annual precipitation is 3.5”. Consideration of non-linearities might yield a set of sensitivity statements for distinct ranges of input values, such as: “recharge sensitivity is 3.5 to annual precipitation between 20 and 50mm”. Stochastic testing would produce sensitivity statements of the form: “the sensitivity of recharge to annual precipitation is between 3.2 and 3.7 with a 95% confidence”. Usage of multiple basin locations would allow a set of different such sensitivity results to be reported and compared.

From these sensitivity deliverables, it will be simple to identify those precipitation characteristics that produce the largest impact, i.e. that evidences the highest sensitivity, for the hydrological components of interest. Thus these are the precipitation characteristics for which climate models should strive to produce the most accurate results possible.

Schedule

- **DONE** - Hydrologic Cycle Component Specification
  - Hydrologic Software Choice
- **Spring 2010** - Test Automation
  - Precipitation Specification
- **Summer 2010** - Test Automation cont'd
  - Precipitation Calculation Software
  - Climate Model Precipitation Intercomparison
- **Fall 2010** - submit paper for Climate Model Precipitation Intercomparison
  - Precipitation Adjustment Software
  - Sensitivity and Differential Impact runs for Basin #1
- **Winter 2011** - Non-linear Response testing for Basin #1
  - submit paper for Non-linear Response for Basin #1
- **Spring 2011** - Stochastic Confidence tests for Basin #1
- **Summer 2011** - submit paper on Stochastic Confidence for Basin #1
  - Sensitivity & Non-linear Response testing for Basin #2
- **Fall 2011** - Sensitivity & Non-linear Response testing for Basin #3
- **Winter 2012** - Sensitivity & Non-linear Response testing for Basin #4
  - submit paper on Basin Choice Dependency
- **Spring 2012** - Dissertation & defense

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Appendix A – GSFLOW Technical Details

GSFLOW is actually three model execution systems in one. It naturally supports the production of the integrated surface and groundwater models for which GSFLOW was created. But is also supports the execution of existing PRMS and MODFLOW-2005 models. For the full technical details on these two separate, pre-existing systems please look at their respective user manuals (G. H. Leavesley, 1983) and (Harbaugh, 2005). All of the following technical info comes just as presented in the GSFLOW manual (Markstrom, 2008).

Software Architecture

Both PRMS and MODFLOW systems have some overlap of concepts and capabilities. For example, both have the concept and computations for a groundwater reservoir with PRMS's being very primitive and MODFLOW's very advanced. Both have the concept of the generation of recharge with PRMS's being highly complex and MODFLOW's simplistic. So models created in the integrated system use some of the packages from PRMS and some from MODFLOW and ignore or minimize usage of others. Several packages from both sides have been extensively modified to allow for linkage of flows between the two systems and to enhance some capabilities. In particular, a new Unsaturated Zone Flow (UZF) package has been created for MODFLOW which not only adds a new vadose functionality to MODFLOW but also it supports connections to PRMS packages for linked water flows.

The current GSFLOW software is version 1.1.1 released on Feb 12, 2010. USGS is continuing to fix bugs and include functionality enhancements to the system.

Model Composition

Models in GSFLOW involve flow exchanges among three regions. The first surface region contains the plant canopy, snowpack, impervious surface storage, and the soil zone and it is processed by the PRMS packages. The second region contains surface streams and lakes and is handled by the MODFLOW Streamflow Routing (SFR) and Lake (LAK) packages. The third region is the subsurface processed by MODFLOW which handles the unsaturated and saturated zones underneath regions 1 and 2.

An integrated GSFLOW model can be thought of as a four layered zone structure. The topmost surface zone layer consists of Hydrological Response Units (HRUs) and handles all surface processes. Immediately below are either the new PRMS soil zone water reservoirs for horizontal and vertical flow or else MODFLOW lake or stream features. Underneath are the new MODFLOW unsaturated zone finite difference cells for gravity-driven one-dimensional vertical percolation flow. At the bottom are the traditional MODFLOW finite difference three-dimensional saturated flow cells.

Different equations are used to simulate flow and storage on the surface and in the soil, unsaturated, and saturated zones separately, so that model efficiency is improved with some sacrifice of model physical accuracy.

Surface Zone

HRUs are spatial surface regions defined by PRMS for the process of watershed modeling. The land surface is completely overlain by a network of such HRUs. A single HRU is specified by homogeneous values of surface characteristics such as elevation, slope, plant cover, land use, precipitation, temperature, and radiation. The shape of a HRU can be any irregularly shaped polygon.

Inputs of precipitation, temperature, and solar radiation are distributed to each HRU to compute energy budgets, flow, and storage. Precipitation that falls on each HRU can be routed to downslope HRUs, streams, lakes, and infiltration to underlying soil-zone reservoirs. Each HRU contains separate reservoirs that represent its water stored in the plant canopy, any snowpack, and impervious surfaces.

Soil Zone

The soil zone is defined as containing capillary, preferential-flow, and gravity reservoirs . These three are described as separate because they represent separate storage reservoirs for computation in the model. In reality, they are all mingled in the same physical space.

The capillary reservoir represents water held in the soil by capillary forces between the wilting and field-capacity thresholds Its water can be removed by evaporation and transpiration.

The gravity reservoir represents water in the soil zone between field-capacity and a GSFLOW-termed "preferential-flow" threshold. It allows gravity drainage from the soil zone to the unsaturated zone, ground-water returned to the soil zone from an overly full finite-difference cell below, and downslope flow within the soil zone, which GSFLOW calls "slow interflow".

The preferential-flow reservoir represents soil water above preferential-flow threshold and below the saturation threshold. This allows both slow interflow and "fast interflow" which is downslope flow through relatively large openings in the soil (AKA macro-pores). Both fast and slow interflow are routed to downslope soil elements, streams, and lakes. Any soil water amount in excess of the saturation threshold can become surface (saturation excess Dunnian) runoff.

Unsaturated & Saturated Zones

The unsaturated and saturated zones use the same MODFLOW-2005 three-dimensional finite-difference grid which are computational cells used to calculate ground-water heads and flows. It is laid out horizontally as a rectangular grid of rows and columns. The vertical direction is a sequence of one or more layers aligned parallel to the horizontal plane with uniform or variable thickness among cells in a layer. The new Unsaturated-Zone Flow package can simulate one-dimensional flow through the unsaturated cells in the grid above the water table.

Water flowing from the soil zone to the unsaturated and saturated zone is what GSFLOW terms “gravity drainage”. It is dependent on the vertical hydraulic conductivity of the unsaturated zone and the amount of available water in the soil zone. Water also can flow from the saturated zone back into the soil zone dependent on the hydraulic conductivity and ground-water head above the soil-zone base. Flow to streams and lakes depends on the ground-water head above the stream or lake surface, the hydraulic properties of the stream and lake bed sediments, and the hydraulic conductivities.

Model Computations

An integrated GSFLOW simulation executes both PRMS modules and MODFLOW-2005 packages on a daily time step that includes variable-length stress periods. The iteration loop solves the interdependent equations within GSFLOW with computations for the surface, soil, streams, lakes, unsaturated, and saturated zones. A cascading-flow procedure is used for routing surface runoff and interflow among HRUs and to streams and lakes with flow paths starting at the highest upslope HRUs and continue through downslope HRUs until reaching a stream or lake.

Surface Zone

Potential evapotranspiration (PET) is computed for each HRU by one of three user-specified options. The first option is the empirical Hamon formulation, in which PET is computed as a function of daily mean air temperature and possible hours of sunshine according to (Hamon, 1961). The second option is the modified Jensen-Haise formulation (Jensen and others, 1969), in which potential evapotranspiration is computed as a function of air temperature, solar radiation, and two coefficients that can be estimated using regional air temperature, altitude, vapor pressure, and plant cover. In the third option potential evapotranspiration is computed from available measured pan evaporation data and a monthly coefficient.

Interception of precipitation by the plant canopy is computed during a time step as a function of plant-cover density and the storage available on the predominant plant-cover type in each HRU as done in PRMS. Throughfall precipitation, which is precipitation that is not intercepted by the plant canopy, is also computed. The precipitation that reaches the ground is referred to as net precipitation, and is the sum of throughfall and precipitation on HRUs not covered by plants.

Snowmelt and net precipitation that reach the soil surface during a time step is partitioned to the pervious and impervious parts of each HRU. Surface runoff due to infiltration excess, hereafter referred to as Hortonian runoff, and infiltration are computed on the pervious parts of each HRU; whereas storage, evaporation, and Hortonian runoff are computed on the impervious parts of each HRU.

If rain throughfall and snowmelt satisfy available retention storage on the impervious parts of the HRU, Hortonian runoff is generated. Hortonian runoff for the pervious part of each HRU is computed using a contributing-area concept (Dickinson and Whiteley, 1970; Hewlett and Nutter, 1970). Hortonian runoff from pervious parts of a HRU is related to the area where the throughfall and snowmelt exceed the soil infiltration rate. This is represented by either a linear or nonlinear function of antecedent soil-moisture content.

Infiltration occurs on the pervious areas of each HRU and includes Hortonian runoff from upslope HRUs, snowmelt, and rain throughfall. Hortonian runoff from the HRU is subtracted from the available water for infiltration.

Soil Zone

The only outflows from the capillary reservoir are to evapotranspiration and the gravity reservoir. Outflow from the gravity reservoir can be slow interflow, flow to the preferential-flow reservoir, replenishment of the capillary reservoir, and gravity drainage. Outflow from the preferential-flow reservoir can be fast interflow and saturation excess surface runoff, hereafter referred to as Dunnian runoff and replenishment of the gravity reservoir.

A fraction of the infiltration is apportioned to the preferential-flow reservoir to account for fast interflow through large openings in the soil zone near land surface, whereas the remainder of the infiltration is added to the capillary reservoir. Water in excess of the field-capacity threshold in a capillary reservoir is added to connected gravity reservoir. Ground-water discharge from the connected finite-difference cell also is added to the gravity reservoir.

Gravity reservoirs replenish the capillary reservoir up to field capacity whenever storage in the capillary reservoir is below the field-capacity threshold. A deficit in the capillary reservoir can occur following periods without precipitation and can be replenished from gravity reservoirs that have inflow from ground-water discharge.

Water in the gravity reservoirs is added to preferential-flow reservoirs whenever the preferential-flow threshold is exceeded. Slow interflow from the gravity reservoirs represents the perching of water in the soil zone above the water table that can occur as a result of mineralization near the bottom of the soil zone or when soil develops over fine-grained material.

Slow interflow can occur when the water content in the soil zone exceeds the field-capacity threshold. Slow interflow is partitioned to downslope HRUs and(or) stream segments.

Potential gravity drainage from the soil zone is computed as a function of storage in the gravity reservoirs after slow interflow has been removed. Net gravity drainage from each gravity reservoir is dependent on the ground-water heads and the vertical hydraulic conductivity of the connected finite-difference cell. Net gravity drainage is applied to the saturated zone instead of the unsaturated zone if the ground-water head is above the soil-zone base.

Evaporation from bare soil and transpiration from plants is computed from the soil zone through the capillary reservoir. Evaporation and transpiration are subtracted from the reservoir as long as (1) there is water in storage, and (2) the rate of potential evapotranspiration is greater than zero after evaporation from the plant canopy, evaporation from impervious surfaces, and snow sublimation has occurred. If sufficient water is available to satisfy all remaining potential evapotranspiration after surface losses, then that volume is removed from the capillary reservoir. Water is removed from the capillary reservoir during the iteration loop because ground-water discharge into the gravity zone could affect the volume of water stored in the capillary reservoir. For the purposes of computing evapotranspiration, the soil water in the capillary reservoir is partitioned into two parts. The first, termed “recharge soil water,” is available for evaporation and transpiration. The second, termed “lower zone soil water,” is available for transpiration only,and is active only during the seasonal transpiration period.

Evapotranspiration from the capillary reservoir is subtracted from the remaining potential evapotranspiration for each HRU. The unused potential evapotranspiration is made available for the unsaturated zone and the ground-water system in MODFLOW-2005 when the rooting depth of plants is beneath the soil zone.

Dunnian runoff is simulated from the soil zone in an HRU when storage as a volume per unit area in the preferential-flow or gravity reservoirs exceeds the saturation threshold. Dunnian runoff from an HRU is routed to the capillary reservoir of downslope HRUs and(or) to stream segment. Dunnian runoff typically occurs from HRUs that define riparian areas next to streams or lakes or depressions in the topography.

Fast interflow is simulated whenever water is stored in the preferential-flow reservoir. It is computed every iteration of a time step using the same empirical equation as slow interflow from the gravity reservoirs. Fast interflow from an HRU is routed to the capillary reservoir of downslope HRUs and(or) to stream segments.

Unsaturated & Saturated Zones

Unsaturated-zone flow is simulated in GSFLOW using a kinematic-wave approximation to Richards' equation that assumes diffusive gradients (capillary pressure gradients) are negligible (Colbeck, 1972; Smith, 1983). This allows Richards' equation to be solved using the method of characteristics, which was originally done by Smith (1983) and Charbeneau (1984).

The approach of simulating unsaturated flow in GSFLOW differs from previous approaches that coupled a one-dimensional finite-difference form of Richards' equation to two- or three-dimensional ground-water flow equations (Pikul and others, 1974; Refsgaard and Storm, 1995) because it does not have a fixed-grid structure. The method adds flexibility for simulating an unsaturated zone that can change in thickness through space and time. The package simulates ground-water discharge directly to the soil zone or land surface as well as evapotranspiration from the unsaturated and saturated zones.

An increase in the infiltration rate from the soil zone into the unsaturated zone will cause a wetting front to form, which is represented by a lead wave. A decrease in the infiltration rate will cause a drying front to occur, which is represented by a trailing wave. Thus, waves are used to represent both wetting and drying fronts. Attenuation of a lead wave occurs as a trailing wave of higher velocity overtakes it. When a trailing wave overtakes a lead wave, the water content of the lead wave becomes equal to the water content of the trailing wave. Consequently, this reduces the velocity and water content of the lead wave. Conversely, when a lead wave overtakes a trailing wave or another lead wave of lower velocity, the overtaken wave is removed, and the water content and flux of the uppermost lead wave are maintained, resulting in rewetting. A lead wave's velocity and water content will decay during a subsequent period of less infiltration as trailing waves overcome the lead wave.

Where soils are thin and the root depth extends beneath the soil-zone base, evapotranspiration that is not satisfied by storage in the soil zone is removed from the underlying unsaturated and saturated zones. Evapotranspiration is removed from the saturated zone (ground water) using the same method implemented in the MODFLOW-2005 Evapotranspiration Package.

Recharge to the saturated zone is computed on the basis of the volumetric flow in the unsaturated zone across the water table plus any water that may be in storage in the unsaturated zone when the water table rises. When the water table declines, the thickness of the unsaturated zone is increased and a wetting front must advance through the interval of the decline before there is recharge.

Appendix B – Glossary

Baseflow = Sustained or fair weather runoff composed largely of groundwater effluent, i.e. not stormwater runoff.

Discharge = In its simplest concept discharge means outflow; therefore, it can be applied to describe the flow of water from a pipe or from a drainage basin such as a canal or a river. It is also correct to speak of the discharge of a canal or stream into a lake, a stream, or an ocean. It is the opposite of recharge which means inflow.

Diversion = The taking water from a stream or other body of water into a canal, pipe, or other conduit and sometimes associated with water usage or consumption.

Evaporation = The process by which water is changed from the liquid or the solid state into the vapor state. In hydrology, evaporation is vaporization that takes place at a temperature below the boiling point. The sum of water lost from a given land area during any specific time from open water surfaces, moist soil, and snow or from wetted plant surfaces, i.e. Interception.

Evapotranspiration = Water withdrawn from a land area by evaporation from water surfaces and moist soil and from plant transpiration.

Exfiltration = That part of the discharge from a drainage basin that occurs from groundwater flow to the surface. The loss of groundwater by discharge into a stream channel from spring or seepage water.

Extraction = Water removed from groundwater usually via pumping for usage or consumption.

Field Capacity = The maximum volume fraction of water in soil that can be retained against gravity, typically about 30% for loam.

Gaining Stream = A stream or stream segment in which the rate of base flow gain is larger than the seepage/leakage loss.

Hyporheic Flow (Bank Storage) = The water absorbed into the banks of a stream channel, when the stream stages rise above the water table in the bank formations, and then returns to the channel as effluent seepage when the stages fall below the water table.

Infiltration = The absorption of falling rain or melting snow through the surface into the underlying soil. It connotes flow into a body in contradistinction to the word percolation, which connotes flow through a porous body.

Interception = The capture of rain or snow on vegetation leaves and branches and eventually evaporated back to the air. Interception equals the precipitation on the vegetation minus stem flow and throughfall.

Interflow (Throughflow) = Flow in the unsaturated zone that is horizontal or downslope, i.e. non-vertical movement.

Leakage, see entry for **Seepage/Leakage**

Losing Stream = A stream or stream segment in which the rate of seepage/leakage loss is larger than the base flow gain.

Overland Flow (Surface Runoff) = The flow of rainwater or snowmelt over the land surface toward stream channels. After it enters a stream, it becomes runoff. There are two forms:

--> **Infiltration (Horton) Overland Flow** = Overland flow caused by a rate of precipitation impingement larger than surface pore absorption capacity, AKA saturation from above. This typically occurs in arid and semi-arid regions, usually with high rainfall intensities on soil exhibiting low infiltration capability.

--> **Saturation (Dunnian) Overland Flow** = Overland flow caused by subsurface soil saturation, AKA saturation from below. This is the main mechanism of runoff generation in humid regions, characterized by high groundwater table.

Percolation = The downward movement, under gravity and hydrostatic pressure, of unsaturated water through the interstices of a rock or soil, except the movement through large openings such as caves.

Phreatophytes = A class of vascular plants which grow near streams and wetlands and obtain their water via deep roots directly from groundwater below the surface, e.g. saltcedar, arrowweed, cottonwood, and willow.

Ponding (Depression Storage) = The volume of water that accumulates from precipitation into natural depressions in the land surface, such as puddles.

Potential Evapotranspiration = Water loss that will occur if there is no deficiency of water in the soil for the uptake and use of vegetation.

Precipitation = Flow of water, in liquid or solid state, out of the atmosphere, generally upon a land or water surface. This includes rainfall, snow, hail, and sleet, and is therefore a more general term than rainfall.

Recharge = The movement of percolating water from the unsaturated zone down into and the resulting enhancement of the saturated groundwater.

Runoff = Water which travels over the soil surface promptly after rainfall or snowmelt from a drainage basin to the nearest stream channel.

Seepage/Leakage = The loss of streamflow water down into the stream bed or out through the stream bank into the saturated groundwater as recharge or the unsaturated zone as infiltration.

Soil moisture (Soil water) = Water diffused in the soil, the upper part of the unsaturated zone from which water is discharged by the transpiration of plants or by soil evaporation.

Stemflow = Rainfall or snowmelt transmission to the ground down the trunks or stems of plants.

Sublimation = Transition from the solid to gas phase with no intermediate liquid, i.e. going directly from snow or ice to water vapor.

Throughfall = In a vegetated area, the precipitation that falls directly to the ground or the rainwater or snowmelt that drops from twigs or leaves.

Transpiration = The process by which water vapor escapes from living plants, principally the leaves, and enters the atmosphere. It does not include soil evaporation.

Underflow = The downstream flow of water through the permeable deposits like sand or gravel that underlie a stream instead of through the surface channel and thus is not measured at a gauging station.

Uptake = The water absorbed by living plants from the soil moisture and used directly in the building of plant tissue or for transpiration.

Wilting Point = The volume fraction of water in the soil below which plants will be unable to draw up moisture and so will become and stay wilted, typically one-third to one-half of field capacity.

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most entries obtained from Hydrologic Definitions, W. B. Langbein and Kathleen T.Iseri, 1995, Manual of Hydrology: Part 1. General Surface-Water Techniques, Geological Survey Water-Supply Paper 1541-A, U.S. Geological Survey. <http://water.usgs.gov/wsc/glossary.html>