MODELING OF SNOWPACK ACCUMULATION AND LOSSES IN MOUNTAINOUS TERRAIN FOR BOTH SNOWPACK STORAGE MAPPING AND WATERSHED STORAGE ESTIMATES

Hugo Froyland[1], Josh Stackhouse[2], Erik Schiefer[1], and Rand Decker[2]

ABSTRACT

A heuristic watershed-scale snowpack model that has been under development and verification at the University of Utah and now at Northern Arizona University since 1998 is now implemented on an articulate Geographic Information System (GIS) platform. Simple heuristic rules are established for the preferential accumulation and loss of snowpack in mountainous terrain. These rules include elevation and solar wattage, each at the pixel scale. The capacity for modern GIS to provide solar wattage explicitly from the root Digital Elevation Model (DEM), means that indexing this ablative potential with slope aspect and angle is no longer required. Each model run must be initialized with two snowpack Snow Water Equivalent (SWE) observations at different elevation within the watershed. One observation can be snowline. This means the model can be initialized for a water year start date, or an annual snowpack SWE maximum when it occurs, or forensic queries of historic events/years, and virtual events such as a "unit" storm or winter. Additionally, the efficiency with which a given watershed commutes water from snowpack storage to surface runoff is indexed with two different ratios; length of surface water channel in the watershed to area of the watershed, and length of watershed channel to watershed circumference. The test watersheds of Stackhouse (Rohde et al.,2012) are repeated with this model, and include four highland tributary watersheds in different physiographical provinces of the Rocky Mountains; Doyle Peak, San Francisco Peaks, Arizona; Kings Peak, Uintas, Utah; and Mt. Elbert and Jones Peak, Eastern San Juan Mountains, Colorado. These tributary sub-basins ranged in size from 88 to 210 million square meters. Snowpack accumulation and/or loss is modeled to the DEM pixel scale, in all of these cases, 30m by 30m. Snowpack SWE in storage, per pixel, is then integrated for an estimate of watershed aggregate snowpack SWE storage. As an aid in identifying watersheds that are particularly effective at snowpack SWE storage, this model allows for the comparison of SWE volumes in a given watershed to the area of the watershed; a measure of the watershed's snow water volume to area efficiency. Another valuable data product of the model is a detailed mapping of snowpack SWE storage within the watershed at the pixel scale. This information can be used in a variety of ways. As examples of the decision support capabilities of the model, three water resource decision space challenges are investigated in an effort to demonstrate the utility of the model and include the following:

- Watershed target identification and ground based cloud-seeding generator siting for snowpack augmentation, including estimates of snowpack storage volume increases to be realized.
- Forest reclamation (thinning) target areas, at fine scales within a given watershed, that have the highest potential to increase net ground snow accumulation.
- Point locations within a watershed where the accumulation of snowpack storage properties at the pixel scale are indicative of the watershed averages. i.e. for the purpose of establishing ground-based observation stations to extrapolate the basin's aggregate snowpack SWE from one or only a few observation sites.

(KEYWORDS: snow water equivalent, SWE, snowpack, watershed, accumulation, ablation, modeling)

INTRODUCTION

It is human nature to utilize our observations of natural phenomena in acts that better our condition as individuals and societies. Some caveman had to have made the first leap from "nature" to natural resources. As early as 6000 BC, agricultural irrigation arose almost simultaneously on multiple continents, and is an obvious, specialized example this perspective (Butzer, 1976; Doolittle, 1990; Neugebauer). In a similar fashion, the observation of seasonal snowfall and its relationship to valuable water supply later in the planting season can also be found in antiquity (Isaiah).

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[1]Hugo Froyland, Geography, Planning and Recreation, Northern Arizona University, Flagstaff, AZ hf74@nau.edu
[2]Josh Stackhouse, Civil Engineering, NAU, js857@nau.edu
[1]Erik Schiefer, Ph.D., Geography, Planning and Recreation, NAU, Erik.Schiefer@nau.edu
[2]Rand Decker, Ph.D., Civil Engineering, NAU, Rand.Decker@nau.edu

In the modern era the domestic challenge of accurately estimating water supply stored in annual snowpacks arose with the advent of agricultural and development in the arid and semi-arid western US. Snow courses gave way to the familiar SNOTEL automated snowpack SWE reporting system (Barton et al., 1977; Crook et al., 1984). The modern SNOTEL network provides a watershed average or aggregate estimate of SWE in storage at any juncture during the accumulation of a winter snowpack. It is an established, successful, well calibrated tool for estimating snowpack SWE, as well as snow runoff volumes which impact stream and river flow forecasting, and reservoir management for both agricultural and municipal and industrial (M&I) water users. SNOTEL is a valuable tool for this job, and the envy of those nations that depend on their annual snowpacks to supply agricultural and M&I water.

More recently, there is impetus to not only know how much water is stored in the snowpack, but to also know, in some detail, where in that watershed the snowpack is deep and where it has been thinned by ablation over the course of the accumulation season. These efforts take two principal forms; terrestrial and remotely sensed observations of snowpack distributions within a watershed, and modeled estimates of the same (Welch et al., 2013; Painter, 2012). These observations and model estimates of the distribution of snowpack SWE in a watershed can be integrated to reproduce the same aggregate measure of SWE in that watershed that can be had from SNOTEL, if it's available. Additionally, the detailed distribution of snowpack SWE in a watershed can be used to investigate a variety of questions that cannot be explored using the aggregate snowpack SWE data products alone.

SNOWPACK MODEL EVOLUTION

Simple, heuristic rules (rules-of-thumb) can be used to estimate the accumulation of snowpack SWE, as well as its ablation, at very specific per pixel locations within a watershed.

The simplest rule is storm snowfall increases linearly with elevation, starting at the snowline. So, with a DEM and two observations of SWE or one SWE observation and the snowline elevation, the slope of the line describing snow accumulation as a function of elevation can be established. The model literally "paints" snowpack SWE onto the landscape in elevation bands for the point-in-time in the snowpack's accumulation lifecycle when the initializing SWE and/or snowline observations were made. Obvious dates in a snowpack lifecycle might include the start of the water year, or the annual snowpack SWE maximum, which doesn't come on a known date in any given year. Forensic and pre-historic snowfall and snowpack events can be modeled. The season being modeled can also be virtual or "unit" in nature, similar to hydrology's unit hydrographs, which are unique to each watershed, as well. 30m by 30m pixels with 10m elevations are commonly available modern DEM's. Hence, over the watershed, snowpack SWE is estimated, at 30m resolution, in each pixel at that pixel's elevation. Collectively they map or describe the continuous distribution of snowfall SWE into that watershed. That can be integrated over all pixels in the watershed to give total SWE that went into the watershed as snowfall.

Then, some has to be taken away. Not all bounty can remain. The only ablation rule of this model is that ablation goes as solar power to each pixel. In earlier versions of this model, solar gain was indexed by slope aspect and slope angle. Modern GIS provides solar gain, per pixel, from slope aspect and angle of that pixel, and solar angle, leading directly to wattage per pixel.

In the model developed here, the first rule based frameworks were programmed in Visual Basic and later in Microsoft's Excel, by Carey et al. (1998) and Mizukami et al, (2003), respectively. These models where awkward to load with a DEM and to run. A lot of programing went into getting simple parameters like which direction is up or down by subtracting elevations with adjacent pixels. This and many other valuable primitive parameters are now calculated automatically in modern GIS programing arenas. Carey provided "silo'ed" ablation strategies that preferentially would leave most of the snowfall SWE, as a percentage, on north and northeast aspects, and remove most or all snowpack SWE from south and southwest aspects. It got worse if the pixel was, by aspect, already hot and then was tilted (slope angle) towards the sun as well. And, the antithesis was true in pixels with north and northeast aspects. Those aspects got to keep most of their snowfall SWE and even more of if the slope was steeper than gentle sloping. Carey made model runs of the Oquirrh Mountains, west of Salt Lake City, Utah with good effect (Carey et al., 1998).

Mizukami et al. (2003)ran these same rules in Excel for the Parrish Creek drainage. Parrish Creek drains a west facing watershed of the Wasatch Front above Centerville, Utah. Mizukami then grid sampled the upper portion of the watershed, deploying several teams on skis on a single day utilizing helicopter support from the NRCS. Mizukami's aggregate model estimates of snowpack SWE compared well with integral of the observations. Both Carey and Mizukami's models used pixel aspect and slope angle as indexes of solar radiation on that pixel, and hence ablation. Modern GIS, including those used in this latest version of the model, can provide solar wattage directly on a per pixel basis.

More recently Heffelfinger (2010), building on programing efforts of Werbylo, (Bringhurst et a., 2011) found useful investigative capabilities for the Excel model's snow accumulation rule. He painted snowpack SWE unto the White Mountain summit highland of eastern Arizona at a time near the seasonal SWE maximum for the 2009 water year utilizing two SNOTEL observations at different elevations, and then distributed snow by elevation, taking nothing away anywhere, preferentially or not. He then laid-out three virtual cloud-seeding generator plumes in an effort to answer the question; how much of an increase, relatively speaking, in snowpack SWE might be realized if these generators where actually put in place. For each individual pixel in each of the three plumes, an additional 10% percent increase in snowpack SWE was added to each pixel's existing snowpack SWE value. Heffelfinger used the plume geometries of Bruntjes et al. (1995) and deployed his virtual generators on high, upwind ridges where the plumes would cover the high snowpack SWE accumulating summit cap of the mountains. His modeled results indicate that three cloud-seeding generators would add an additional 630 acre-feet of snowpack SWE in this mountain highland.

Also of note, Heffelfinger (2010) utilized the mountain highland as a whole for analysis purposes, as opposed to the much more common watershed/single outfall perspective. Snowline is available by remotely sensed imaging almost anywhere in the world, and snowline is highly uniform in elevation around a given mountain highland on any given date and especially late in the season when the snowpack SWE maximum is approached. All elevations above snowline define the resource boundary and footprint for analysis. It has a ring of value to it if remote, poorly or un-instrument watersheds in a mountain highland are to be investigated with this model.

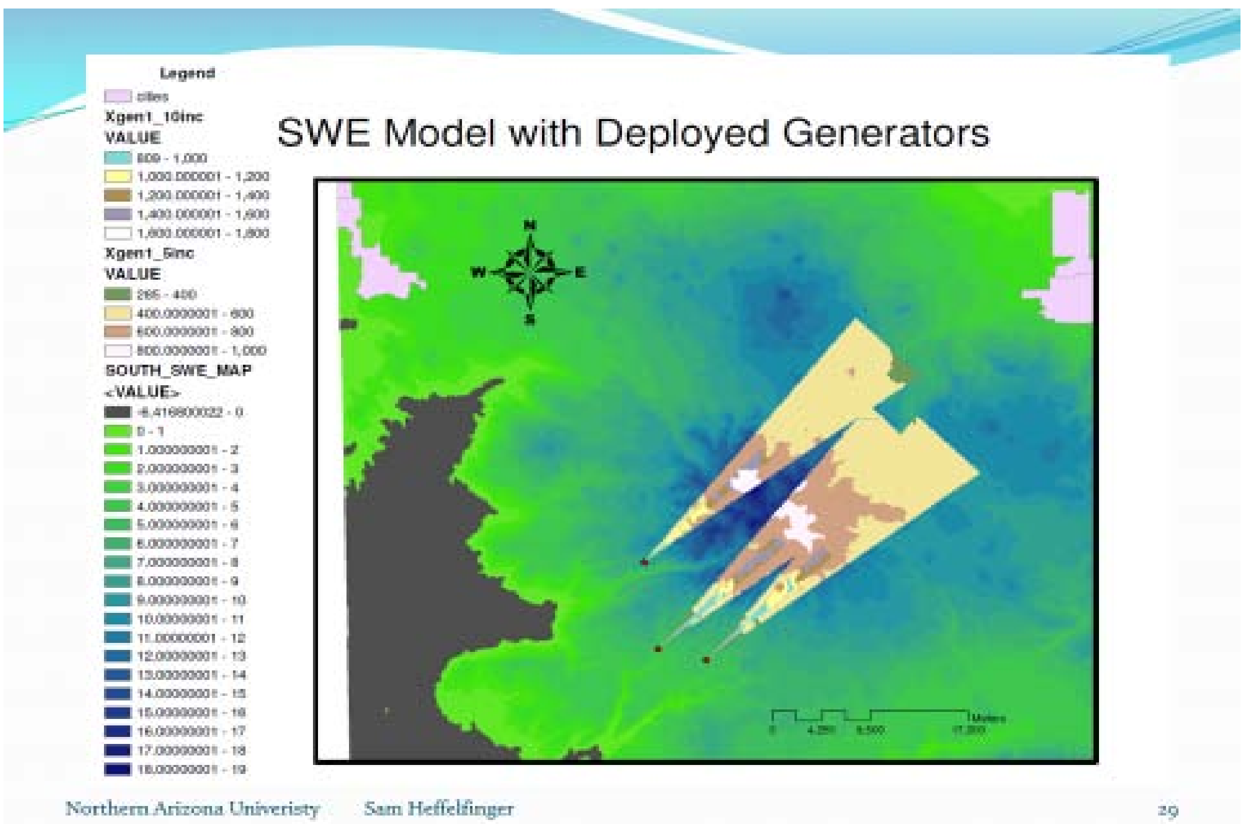

Figure 1. Snowpack SWE distributed by elevation with ground based cloud-seeding generator plumes overlaid on the White Mountains, eastern Arizona [from: 13].

RESULTS

The model runs of Stackhouse (Rohde et al., 2012) are repeated for this investigation utilizing the tools of the Spatial Analyst toolbox of ArcGIS. The watershed areas are delineated using the Hydrology tools. Snowpack SWE values, per pixel, are determined using a linear expression whose slope is derived from two SNOTEL observations at different elevations. Snowpack SWE ablation is indexed to solar radiation, which is provided by the Solar Radiation Area tool and then applied, per pixel, as a percent of the accumulated snowpack. The percent ablation ranges from 90% at the highest solar gains to 30% at the lowest, and varies in “silos” of 10% each between these ranges. The results of this method compared well, within a few percent, of Stackhouse’s aggregate snowpack SWE estimates for the same watersheds initialized with the same snowpack SWE observations, specifically paired SNOTEL observations for each watersheds’ spring snowpack SWE maximum for water year 2011 (Rohde et al., 2012). Snowpack accumulation and ablation is modeled to the DEM pixel scale, in all of cases 30m by 30m. Snowpack SWE in storage, per pixel, is then integrated for an estimate of watershed aggregate snowpack SWE storage.

This capability allows for the comparison of snowpack SWE volumes in a given watershed to the area of the watershed; a measure of the watershed’s snow water volume to area efficiency. For example and from the modeled results, it is estimated that the high elevation Jones Peak and Mount Elbert mountain tributaries in Colorado accumulate 0.64 and 0.51 hectare-meters of snowpack storage per hectare of watershed, respectively. The more southerly facing Kings Peak tributary in Utah accumulated 0.22 hectare-meters of snowpack storage per hectare of watershed. Doyle Peak in Arizona, only 0.09. In addition, for Kings Peak, Utah and Jones Peak, Colorado, total runoff volume from proximal USGS stream gauges is compared with total snowpack storage volume estimates from the model. The estimate of snowpack storage volume at Kings Peak compares well, at 10%, with its tributary gauge measurement. The difference on Jones Peak was 30%.

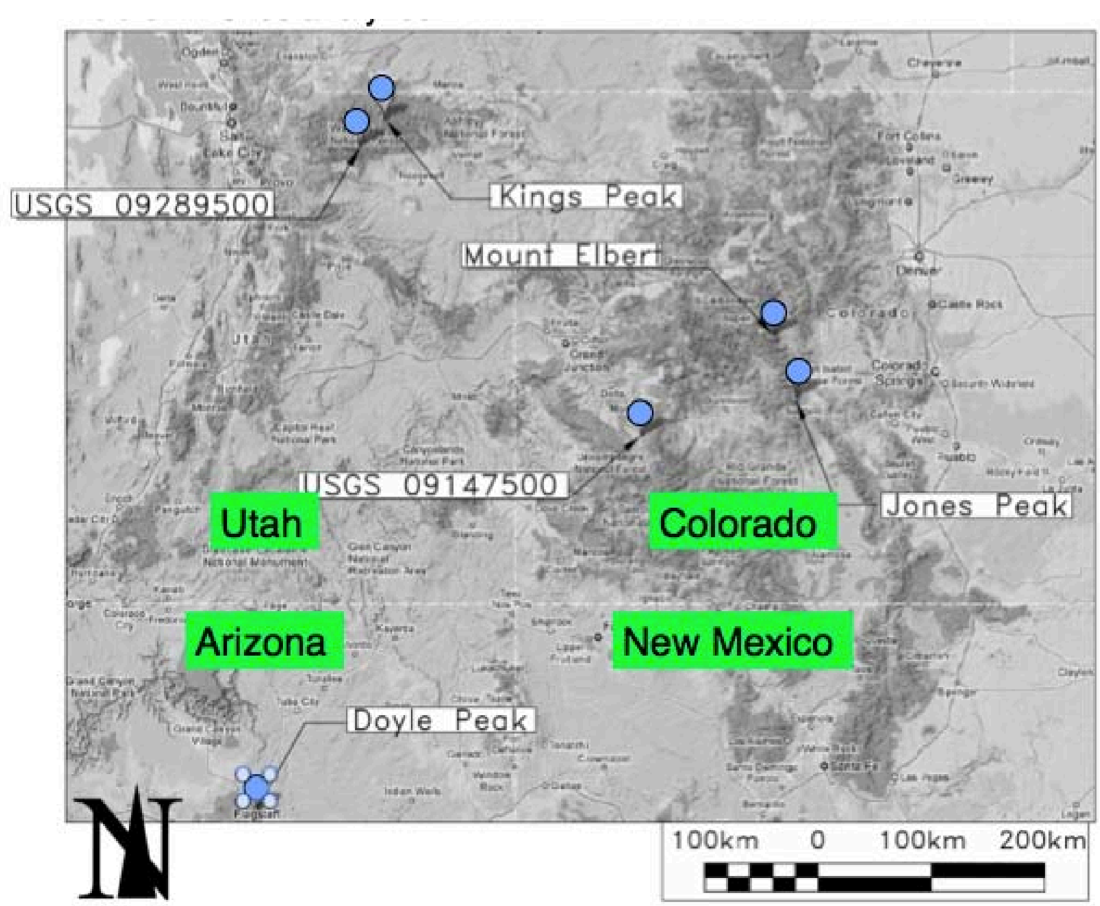

Figure 2. Location map of tributary watersheds and attendant USGS stream flow gauges.

Watershed Location	SWE Volume		Watershed Area		Watershed Efficiency	
	m^3	acre-feet	m^2	Acre	ha-m/ha	acre-ft/acre
Doyle	7,924,853	6,425	92,943,900	22,967	0.09	0.28
Elbert	44,838,316	36,351	88,135,200	21,779	0.51	1.67
Jones	97,280,865	78,867	151,405,200	37,413	0.64	2.11
Kings	45,610,054	36,977	210,015,900	51,896	0.22	0.71

Table 1. Modeled watershed aggregate snowpack SWE, and SWE volume to watershed area efficiency [from: 1].

Clearly, this model can be initialized and overlaps well with aggregate snowpack SWE observations from the domestic SNOTEL SWE reporting system. Moreover, the model is also sufficiently simple in guise that it can also be initialized with little or no snowpack SWE observation infrastructure. It is sufficient to have, even from a distance, snowline elevation and then one more ground observation or "best guess" of snowpack SWE at a higher elevation, in the latter case, hopefully from a local personality with cause to watch winters and snowpacks in the vicinity of the watersheds being investigated.

Another valuable attribute of the model is a detailed mapping of snowpack SWE storage within the watershed, at the pixel scale. This information can be used in a variety of ways, and there are surely many more than those imagined by the authors alone. As an example of the decision support capabilities of the model, three water resource decision space challenges are investigated in an effort to further demonstrate the utility of the model. These included the following:

1.) Tributary watershed target identification and ground based cloud-seeding generator siting for snowpack augmentation, including estimates of snowpack storage volume increases to be realized.

Cloud seeding generator plumes for the purpose of increasing or augmenting snowpack SWE in storage are virtually placed in the Jones Peak watershed in two different deployment schemes. In one guise, the generators are placed "manually" along obvious ridge tops, and in the second they were placed optimally by the model itself. In the latter case, every pixel in the watershed is given a cloud-seeding plume, and only the top ten that produce the greatest snowpack SWE increase are retained for further analysis. In Figure 3, below, the snowpack SWE is largest where the shading is darkest. The model optimized cloud-seeding generator placement increased snowpack SWE by 44% over the increase realized by manual placement of the generators on ridge tops. SWE increases or augmentation, per pixel, for each generator plume is set at 10%.

2.) Forest reclamation (thinning) target areas at fine scales within a given watershed, that have the highest potential to increase net ground snow accumulation.

Mechanized forest thinning for the purpose of reducing fuel volumes for wildland fire management, along with other assets, including water resources is now common practice (Heffelfinger et al., 2011). If the goal is to increase ground snow accumulation by reducing the amount of snowfall intercepted by forest canopy and sublimated back into the air, then forest thinning would best be conducted where there is significant overlap between areas of high snowpack SWE accumulation and forested areas within the watershed. The map of these overlapping attributes is particularly easy to achieve with this model and commonly available modern GIS overlays of forest cover. An example of this is shown for Kings Peak, Utah in Figure 4, below. The value of this decision support product can be further refined with the integration of additional asset maps, such as roads, sensitive or unstable soils, wildlife habitat, scenic assets, etc.

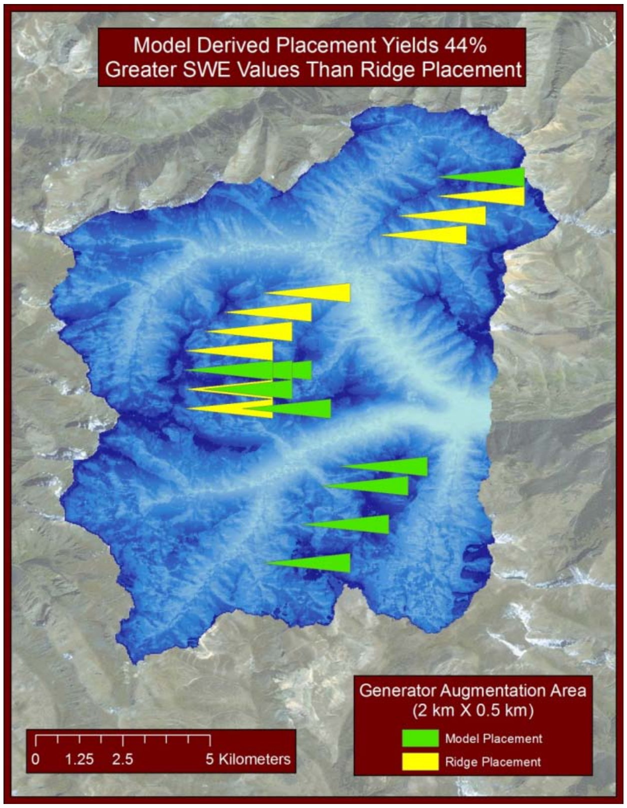

Figure 3. Jones Peak, Colorado snowpack SWE distribution (SWE increases with increased blue shading) and the impact of optimal ground based cloud seeding generator siting over manual siting on ridge tops alone.

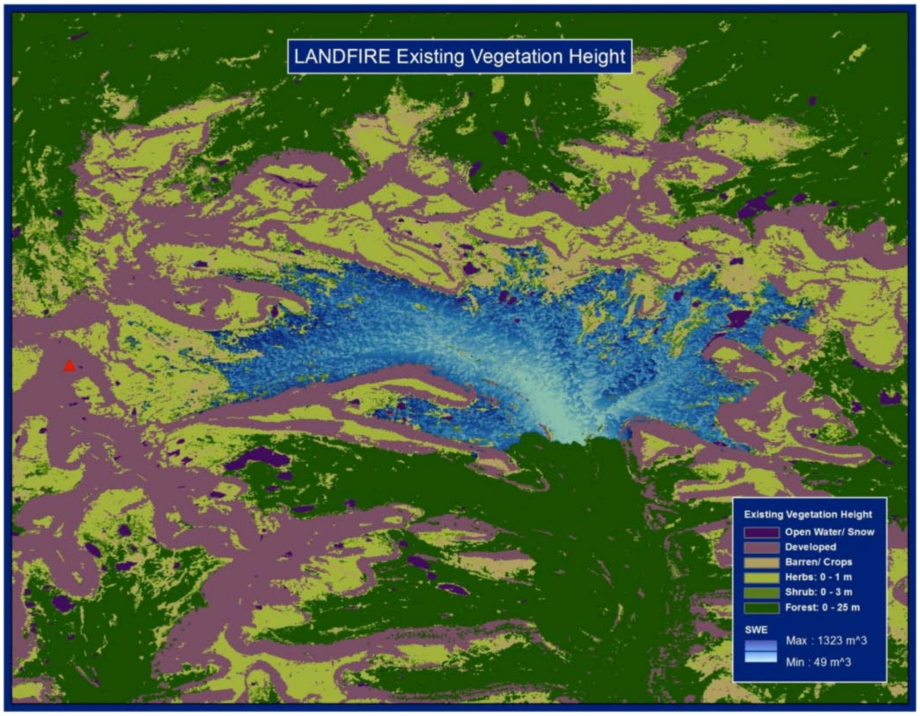

Figure 4. The intersection (overlap) of existing forest canopy and the high snowpack SWE areas of the Kings Peak, Utah watershed.

3.) Point locations within a watershed where the snowpack SWE storage properties at the pixel scale are indicative of the watershed averages.

Consider the challenge, especially in a remote and poorly or un-instrumented watershed, of establishing new ground based snowpack SWE observation stations which are indicative of and can be used to extrapolate the watershed's aggregate snowpack SWE storage from one or only a few observation sites. In Figure 5., the model pixels that have snowpack SWE indicative of the average for the Mount Elbert watershed are shown. When the SWE value in these pixels is multiplied by the watershed area, they provide an estimate of the aggregate snowpack SWE in the watershed. The decision support capability of the modeled ground based snowpack SWE locations indicative of the watershed SWE average can be further refined with overlays of transportation assets such as roads, ski areas or helicopter landing zones that would ease access to the observation sites chosen.

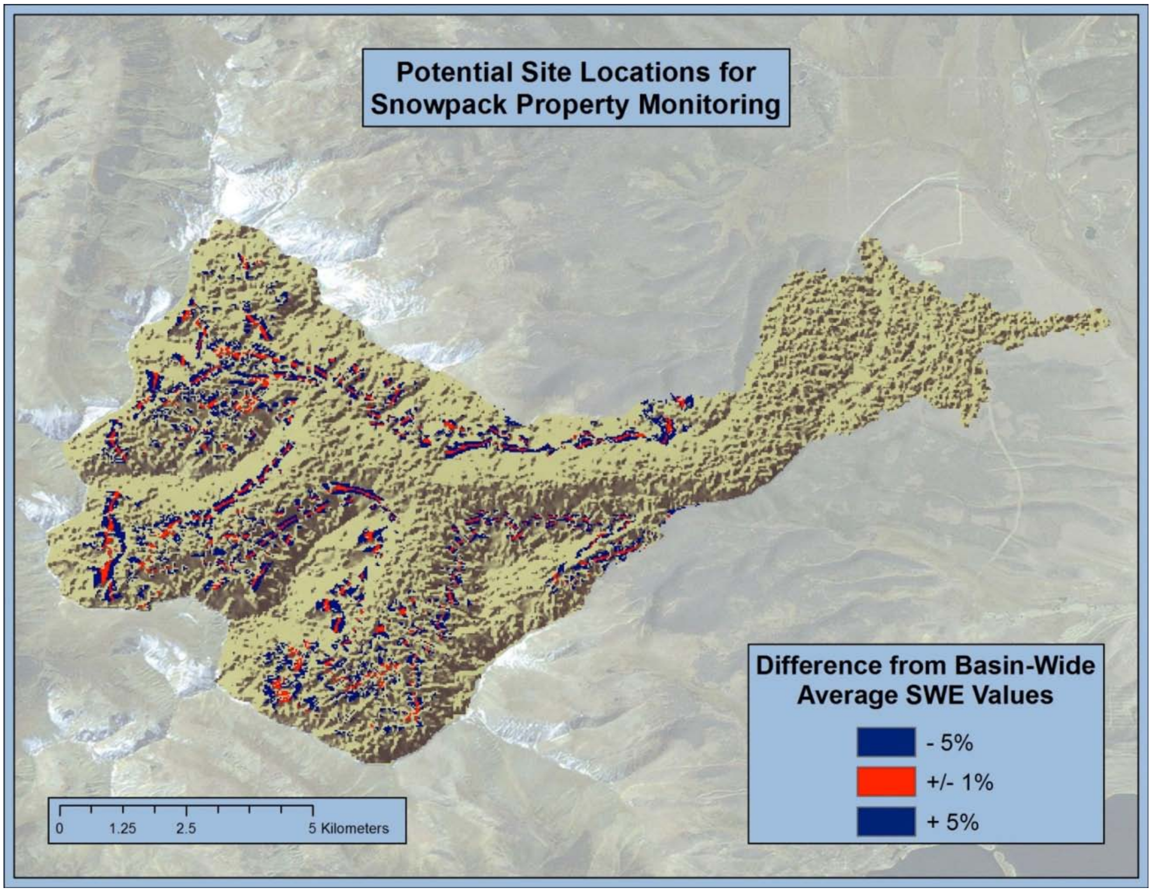

Figure 5. Modeled pixels that have snowpack SWE indicative of the watershed average for the Mount Elbert, Colorado watershed.

CONCLUSIONS

This evolutionary snowpack SWE model, under development since 1998, continues to show promise as a tool that can integrate with and support aggregate watershed SWE estimates and measurements from existing SWE observing and reporting systems. Additionally, the model also extends on the capability to inform water and other natural resource decision making by mapping the distribution of snowpack SWE in detail at the model's pixel scale. Whether being utilized for watershed aggregate SWE estimates or for more detailed investigations where the question of "where's the snow" is critical, the model requires a minimum amount of data and observations to initialize. Hence, the model may be of particular value where there is little, if any, snowpack observational infrastructure.

There remains room for improvement in the development of ablation rules for this snowpack model, and includes the need to account for differential (and much higher) sublimation losses for that snowfall intercepted by timber canopies and then sublimated away, compared to adjacent ground snow sublimation losses (Hagberg et al. 2012). This becomes a practical question if timber thinning is an on-going activity and one goal is to cut back (by cutting down) on snowfall canopy intercept and losses through mechanized thinning (Heffelfinger et al, 2011; Masek-Lopez et al., 2011). Additionally, the recent work of Wetlaufer points clearly to the need to better account for sublimation in the high alpine zones where the primary ablation mechanism during the cold months is sublimation, often in the presence of strong winds (Wetlaufer, 2103). Snowpack accumulation is overestimated by allowing it to continue to increase with elevation all the way to the summit peaks.

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