METHODS FOR QUANTIFYING THE EFFECT OF PHYSIOGRAPHIC PARAMETERS ON THE SPATIAL DISTRIBUTION OF SNOW WATER EQUIVALENT IN MOUNTAINOUS BASINS

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ABSTRACT

This paper presents a set of methods for quantifying the effect of various physiographic parameters on the spatial distribution of snow water equivalent (SWE) in mountainous terrain. These methods were designed to be robust over a wide range of spatial scales and landscape types, while remaining effective by measures of data quality as well as efficient use of time and money. Understanding the factors that influence how and why SWE is distributed throughout the landscape can allow for greatly improved estimates of total basin SWE as well as the timing and volume of streamflow. This increased knowledge of snow as a water resource can have many positive impacts on the accuracy of water supply forecasting for use in activities including agricultural planning, reservoir management, municipal water supply planning, and flood forecasting. These methods provide an easily replicable framework that will produce a strong and versatile data set that can be used in a wide range of applications.

KEYWORDS: snow hydrology, spatial distribution, GIS, runoff forecasting

INTRODUCTION

A precise and well quantified understanding of the effect that physiographic parameters (e.g. elevation, land cover, solar radiation, slope angle, aspect, and wind exposure) have on the spatial distribution of snow water equivalent (SWE) throughout large and physiographically complex watersheds is an aspect of snow hydrology that needs to be understood. By undertaking research that improves the understanding of how and why SWE is distributed throughout the landscapes of the Western United States, much of which critically depends on the winter snowpack for the livelihood of its' inhabitants, the sustainability and quality of life in these regions can be greatly improved. This knowledge and understanding can potentially be used to estimate parameters such as total basin SWE, and how it is spatially distributed by using only limited point data from sources such as snow courses and SNOTEL sites.

This paper presents a set of methods that were developed for a research project that was designed for a master's degree thesis project at Montana State University in Bozeman, MT. This project is seeking to precisely quantify the effect of physiographic parameters on the spatial distribution of SWE in a large (207 km^2) and physiographically diverse drainage basin. While these methods were developed specifically for this research project, they were designed to also provide a framework for designing a similar study that can be replicated in a wide variety of landscape types and over a large range of spatial scales. This paper describes the framework in detail from the initial planning stages, comprehensive field data collection, and data processing. Terrain analysis using geographic information science (GIS) is first used for defining which portions of the basin to sample based on how well they will represent the physiography of the basin as a whole. Then, by adhering to a pre-determined field sampling plan, a researcher can obtain a high quality dataset that is representative of the spatial distribution of SWE throughout an entire basin based on its' physiography while only having to sample a portion of the basin. In addition, the dataset will provide all of the necessary information to be able to quantify the precise effects of various physiographic parameters (and combinations of parameters) on the spatial distribution of SWE near the time of maximum accumulation and do so in a timely and cost effective manner.

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Some of the potential advantages that could result from the information derived from these methods include improved estimates of total annual stream runoff volume as well as increased accuracy in estimates of the timing and discharge of spring peak flow events. Increased accuracy in these two aspects of water supply forecasting can potentially have a very positive effect on the way of life in the Western United States in several ways. Among others, these include improved agricultural planning based on estimated available water supply, more efficient reservoir management, increased accuracy and lead time of flood forecasts, and better estimates of the potential severity of a summer wildfire season due to the moisture input into the forest system from the winter snowpack. The aforementioned items are examples of just a few of the positive societal impacts that can come from an improved understanding of the effect of physiographic parameters on the spatial distribution of SWE. Considering the critical importance of snow as the primary water resource for much of the Western United States, continued research as to precisely how and why SWE is distributed throughout the landscape is currently, and will continue to be very important to the sustainability of living in the snow dependent West. The methods described in this paper provide a broadly applicable framework for conducting such research.

OBJECTIVES

There were several primary objectives in the development of these methods. First was to provide a structured and easily replicable means for obtaining a representative sample of how SWE is distributed throughout a basin, based on its' physiography, while only sampling a portion of it. Second, these methods were developed to provide a framework that could be easily applied to a wide variety of basin types and sizes across the country and the world while still obtaining the highest quality results. Lastly, these methods were developed to be able to obtain a dataset on which many different types of statistical and spatial analyses can be performed. The primary objective of this research was to obtain a data set that would allow for the precise quantification of the effect that various physiographic parameters, such as elevation, incoming solar radiation, and land cover, to name a few, have on the spatial distribution of SWE throughout diverse and complex mountainous terrain.

LOCATION OF CASE STUDY

The research took place in was the West Fork of the Gallatin River basin in Southwest Montana (West Fork Basin). This basin was chosen for a variety of reasons which are primarily related to its' unique and diverse physiographic characteristics as a way to test the methods in a large and physiographically complex watershed. The terrain includes low elevation grassy meadows and sagebrush covered rolling hills, heavily forested rolling hills, and high elevation steep, rocky terrain. The elevation range is from 1830m at the confluence of the West Fork of the Gallatin River with the Gallatin River to 3405m at the top of Lone Peak (1575m of total vertical relief). The basin covers a total area of 207 km^2. The elevation range and spatial extent are greater than most previous studies of SWE by field data collection (Clark et al. 2011) as can be seen in figure 1. Roughly 52% of the basin is forested and the primary forest type is Lodgepole pine although there are many other types of conifers present as well.

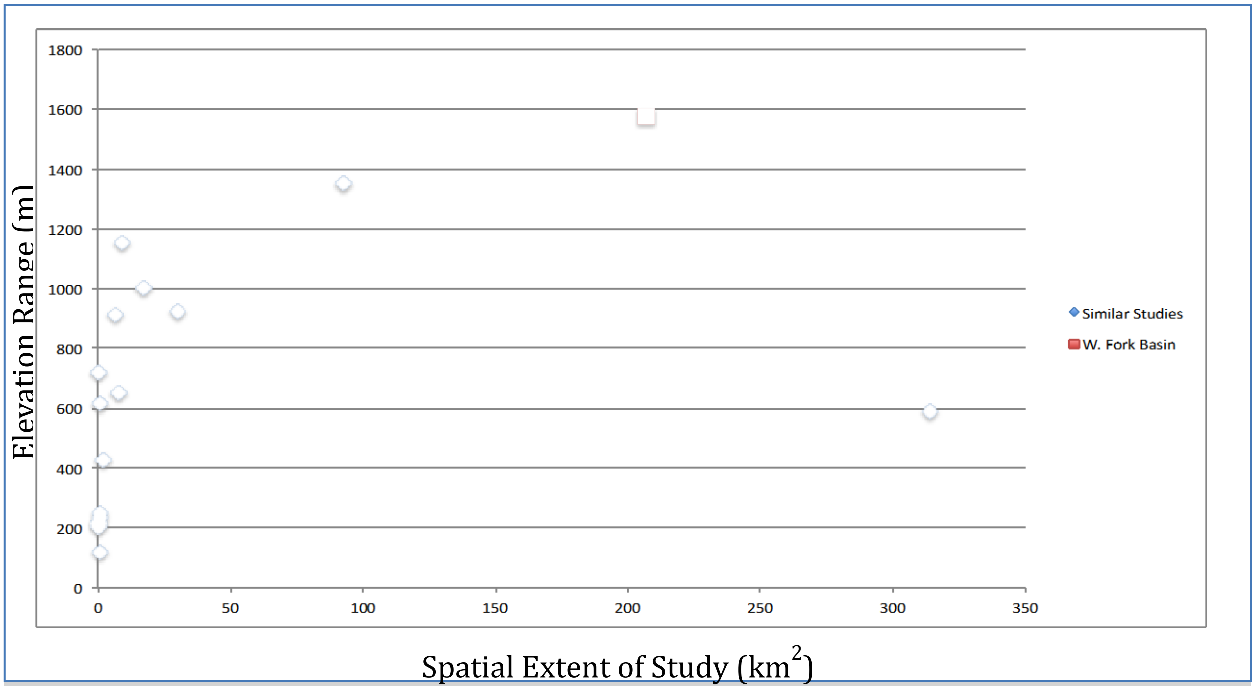

Figure 1. The spatial extent and elevation ranges of similar studies of the spatial distribution or spatial variability of SWE in mid-latitude mountainous basins, compared to that of the West Fork basin. This figure displays the power of these methods in being able to quantify the spatial distribution of SWE in large and physiographically complex basins (data from Clark et al. 2011).

The physiography is spatially distributed as follows:, The low elevation grasslands and sagebrush covered areas primarily occur in the eastern most portion of the basin in the relatively flat "meadow area" near the confluence with the main fork of the Gallatin River. The central portion of the basin is the most heavily forested and is moderately developed while the northern and southern edges of the basin are far less developed. The west and northwest portions of the basin contain some of the highest elevation alpine terrain, including three ski resorts (Big Sky, Moonlight Basin, and the Yellowstone Club). This large spatial extent and high level of physiographic diversity made the West Fork basin an ideal location to both develop and test the methods for this unique type of study.

DETERMINING WHERE TO SAMPLE

One of the most important steps in defining an effective sampling plan is determining what areas within the basin to sample in order to obtain a data set that is most representative of the basin as a whole. The goal of this step is to define small portions of the basin to sample that are physiographically proportional to the basin as a whole. First, the criteria on which the determination of representativeness can be made must be developed. The determination of physiographic representativeness is made by defining physiographic strata that can be used to compare the proportionality of the strata within the potential sampling areas to that of the whole basin. These strata are unique combinations of physiographic parameters that are distributed across the landscape and can be used to ensure that the basin is being proportionally sampled.

Strata can be defined by any combination of parameters that the researcher may choose but for the purpose of this study strata were defined by unique combinations of elevation, potential incoming solar radiation, and land cover. These three parameters were chosen because it is well accepted in the scientific literature that they have a strong influence on the spatial distribution of SWE (Clark et al. 2011). The elevation data is already embedded in the 30 meter digital elevation model (DEM) that is readily available online. Values of potential incoming solar radiation for each pixel in the DEM can be calculated in a GIS program (ArcGIS was used for this study). For this particular study total accumulated potential solar radiation was calculated for the time period of December 1st to April 1st. The range of unique values that exist in the elevation and radiation datasets were reclassified into five and four distinct categories, respectively (table 1). The land cover data, which is also generally available for free download was reclassified simply as forested or un-forested (table 1). Each parameter was reclassified on a different order of magnitude. This allows the researcher to add the raster layers together in the GIS program to create the strata while still maintaining unique identifiers of which combination of parameters each strata is comprised of. For example, if a particular strata had an identifier of 1410 one could tell that that strata is in the lowest elevation band (1000), receives the highest levels of solar radiation (0400), and is forested (0010). In the West Fork case study 36 unique strata were developed that were used to define and justify the areas to be sampled as well as used as parameters in the analysis portion of the project.

Table 1. Reclassification Scheme

Elevation (m)
1826-2139=1000
2139-2453=2000
2453-2767=3000
2767-3081=4000
3081-3395=5000
Solar Radiation
Lowest=100
Medium-Low=200
Medium-High=300
Highest=400
Land Cover
Forested=10
Other=0

The next step is to use the strata to define areas of the basin to sample that are collectively physiographically proportional to the basin as a whole. The initial consideration is which areas of the basin are likely to be the most representative of the whole basin, as well as which of these are practical to access to maximize the efficient use of time and money. Once several possible sampling areas are defined they can be clipped out of the strata raster layer in the GIS program and the percentage of pixels in each strata can be compared between the sampling areas and the whole basin (Fig. 2). This comparison can be used to justify that the areas in which samples are being taken are physiographically proportional to the basin as a whole. This coupled with an appropriate field sampling plan will allow a researcher to gain a strong inference about the likely spatial distribution of SWE in the basin as a whole as well as the influence of the physiography of the basin on that distribution. If the proportions are not deemed to be adequate for the purpose of the study the sampling areas can be redefined and analyzed again until an appropriate set of sampling areas is determined.

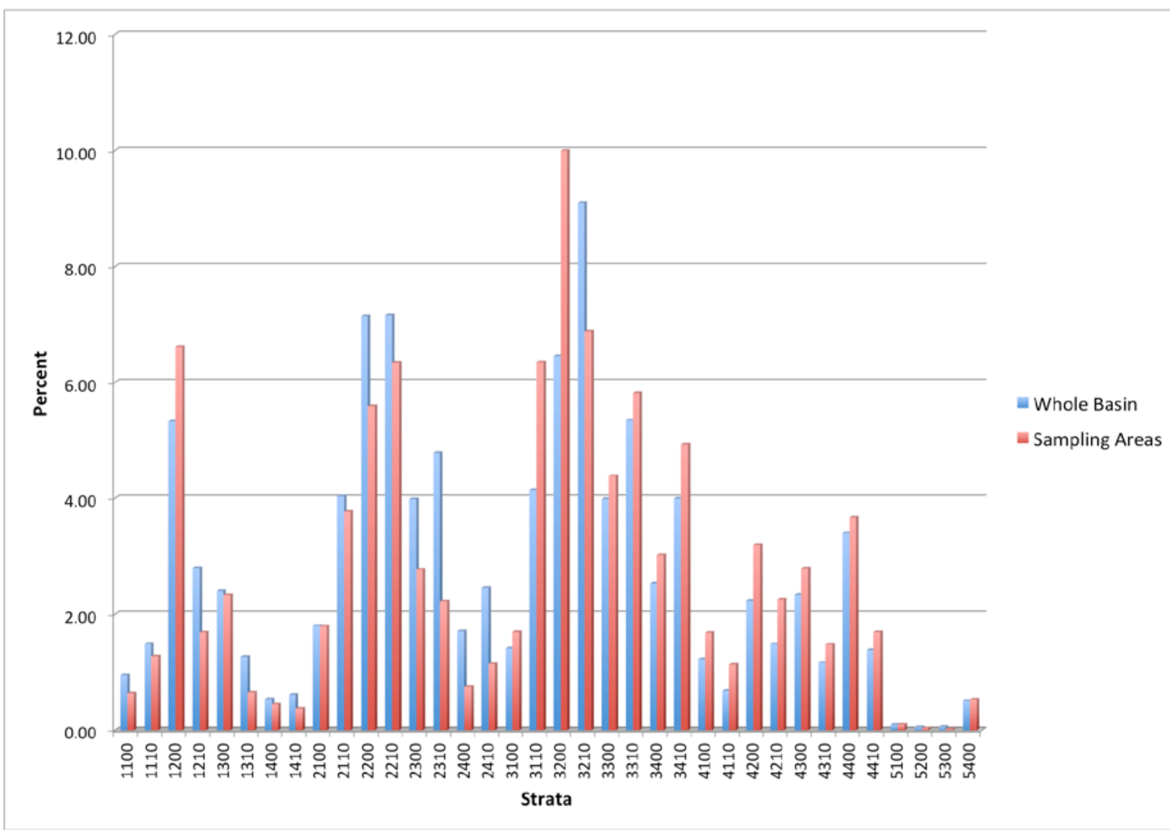

Figure 2. Comparison of the percentages of the various strata (by number of pixels) within the proposed sampling areas to the percentage of each strata within the whole basin.

SAMPLING PLAN

Once the areas that are to be sampled have been defined, the next step is to define how the field data is to be collected. There are several primary goals for the collection of the field data. The first goal is to take samples in as many of the strata within each pre-defined sampling area as possible. The second goal is to maintain as much randomization as possible in where the SWE samples will be taken so as to maximize the statistical viability of the data. The final goal is to obtain samples at a variety of spatial scales to account for spatial variability in SWE depth at a wide range of spatial scales as well as reduce any bias that could be introduced from a more systematic approach. Much of this sampling theory was influenced by the importance of the scale triplet in spatial sampling, where spacing, extent, and support are used to define the spatial dimensions of a field study (Blöschl and Skøien, 2006 and Blöschl and Sivapalan, 1995).

Sampling the Strata

To gather data that is most representative of the basin as a whole it is ideal to sample within as many strata as possible while traveling through the sampling area. This allows the final data set to be most representative of the whole basin as was determined during the definition of the sampling areas. As the sampler travels throughout the sampling area 3 SWE samples are taken in 10 meter equilateral triangles at pre-defined random distances and snow depth, SWE, and geographic coordinates are recorded in a mapping grade (sub-meter accuracy) global positioning system (GPS) unit. The randomized distances at which samples were taken varied from 30m to 400m for the West Fork basin study, but can be defined over any spatial scale depending on the size of the sampling area, the mode of travel of the samplers, or the specific purpose of a study. By sampling between distances of 10m and 400m the sampling plan accounts for both small and large scale variability in the spatial distribution of SWE. Also, the randomization of the distances at which samples are taken allows for a more robust statistical inference into how SWE is likely to be distributed throughout the greater landscape and is recommended to be included in the sampling plan (Kronholm and Birkeland, 2007). Using this method of sampling at randomized distances, if done appropriately, increases the amount of inference that can be made about SWE depth in similar but un-sampled strata across the basin that were not actually sampled.

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Field Sampling Process

Once the sampling areas and the manner in which the data is going to be collected has been defined, the next step is to go into the field to collect the data. Aside from the standard equipment necessary to travel safely and efficiently in the winter backcountry, the following equipment is needed to collect the field data. First is a U.S. Federal SWE sampler, which takes a core of the snowpack that is weighed with a spring scale specially calibrated to measure inches of SWE contained in the core. A direct measurement of SWE contained in the snowpack at that exact point can be obtained by simply removing any dirt or litter from the bottom end of the tube portion of the sampler, weighing the sample while still in the tube, and subtracting out the dry weight of the sampler. This method provides a very quick and easy means of obtaining SWE measurements in the backcountry. By using the federal SWE sampler a sampling team in the field is able to quickly collect samples and cover large portions of terrain.

The second piece of equipment that is needed is a GPS receiver to note the exact point where each sample is taken and store the associated SWE and snow depth data. When selecting a GPS receiver to use, a high accuracy unit is most desirable. By using a high accuracy GPS receiver the researcher is able to most accurately relate SWE depth to the physiographic parameters of that exact point (with fine scale variability in solar radiation being of primary concern). For this case study Trimble GeoXH mapping grade receivers were used. A mapping grade GPS is ideal because it allows the researcher to be sure that SWE samples are most precisely matched to the physiographic parameters of the landscape, particularly if a 1m resolution DEM derived using light detection and ranging (LiDAR) technology data is available for the analysis. Another primary advantage to using a mapping grade GPS receiver is a data dictionary that is programmed to quickly and easily enter data specific to the project into the receiver. By using a pre-defined data dictionary SWE depth and snow depth measurements are easily attached to each point feature created by the GPS. Also, when the data is exported into the GIS program SWE depth and snow depth values are automatically entered as attribute values for each sampling point.

To collect the field data teams of two travel throughout the defined sampling areas (by the most appropriate means for the area, but most likely on skis or snowshoes) and attempt to pass through as many different strata within the area as possible. This is accomplished by travelling through as many different combinations of elevations, slope angles, aspects, and land cover types while stopping at the pre-determined random distances to take three SWE samples in a triangular pattern using the federal sampler. Because it is difficult to know exactly which strata one is in at any given time this process can be used as a proxy for ensuring that samples are taken in as many of the strata within the sampling area as possible. At the location where each sample is taken the total snow depth and SWE depth are recorded in the data dictionary on the GPS unit. In this study, depending on the nature of the terrain in the sampling area, in this study a team of two was generally able to cover an entire sampling area and collect 80-120 SWE samples per day.

RESULTING DATASET

In this case study a "snapshot" of how SWE was distributed throughout the West Fork basin was taken during the period of March 29th through April 2nd, 2012. These dates were chosen for the study both as an estimate of maximum SWE accumulation as well as for possible comparisons that could be made to other April 1st SWE measurements that are made annually throughout the country. During this period over 1000 SWE measurements were collected throughout the sampling areas in the West Fork Basin with the help of 10 field assistants as well as logistical assistance from the Yellowstone Club Ski Patrol. The distribution of how the sampled points are spatially distributed throughout the basin can be seen below in Figure 3.

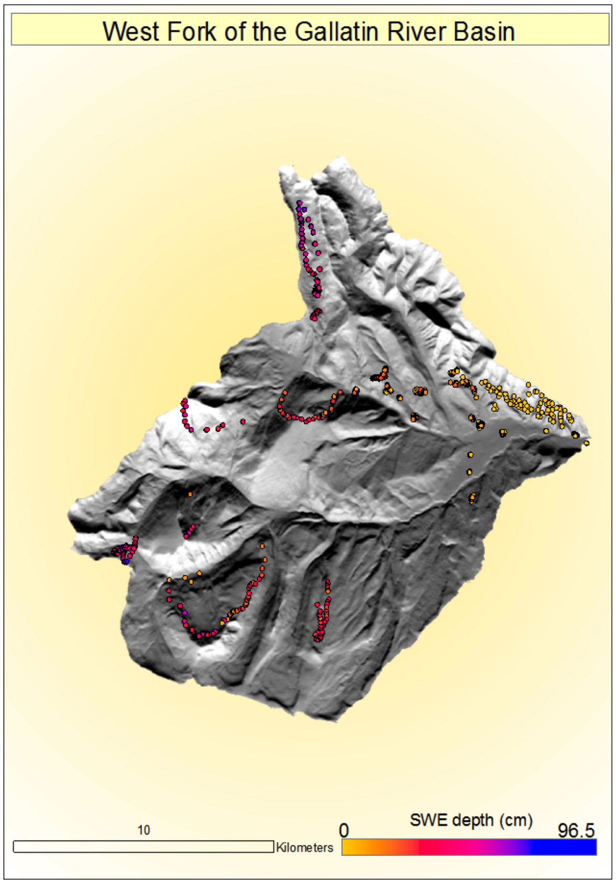

Figure 3. The points on the map represent where SWE samples were collected and recorded, displaying how the SWE samples were spatially distributed throughout the West Fork basin.

DATA PREPARATION

Once the field data has been collected and recorded in the data dictionaries of the GPS receivers the next step is to prepare the data for analysis. First the data is uploaded off of the receiver and imported into an appropriate software package (in the case of this study *Trimble Pathfinder Office*) on a computer where it can be post-processed to increase the positional accuracy of the points that were taken in the field. The software makes these changes by analyzing positional inaccuracies experienced by a nearby “base station” that has a precisely known location. Corrections can then be made to the GPS data due to errors that would be common to both the base station and the GPS receiver. Post-processing allows the vast majority of the sampled points to have sub-meter positional accuracy.

After the post processing is complete the GPS points are then converted into a usable format for analysis in the GIS program . In the case of this particular study this conversion was made in *Pathfinder Office* and all of the data was exported as one comprehensive shapefile containing the data collected on all of the receivers that can then be imported into the GIS program. The ability to directly import the precise locations of the sampling points into the GIS with SWE depth, snow depth, and precise elevation already imbedded in the shapefile’s attribute table is a powerful tool to maximize the analyses with the data set. The precise values of any additional physiographic parameters that can be calculated or imported into the GIS can then also be added to the attribute table for the SWE depth layer and associated with each individual sampled point. By using spatial overlay techniques in the GIS values of parameters such as potential received solar radiation, land cover, slope angle, aspect, the strata that the point lies within, degree of convexity or concavity, and wind exposure can be attached to each SWE depth point. Using this information, the effect that individual parameters as well as any number of combinations of parameters can be used to quantify the effect they have on SWE distribution throughout the landscape. Many types of analysis can be done directly in the GIS program, but for more advanced statistical analysis of the data the attribute table can be exported as a text file that can be used for analysis in a statistical package such as *Matlab* or *R*.

RESULTS AND DISCUSSION OF THE SAMPLING PLAN

After the data has been collected and values of the various physiographic parameters have been attached to each individual sampled point, the effectiveness of how well the sampled points represent the physiography of the whole basin can be assessed. This section discusses how well the sampled points represent the physiography of the whole basin as a test of the effectiveness of both the pre-planning and the field sampling plan. Overall, based on the case study of the West Fork Basin, this method appears to be a very effective and efficient (by measures of data quality, quantity, and versatility, as well as time and money) way to assess the spatial distribution of SWE in complex terrain based on physiographic parameters. Roughly 25% of the basin was sampled and the collected samples were sufficiently representative of the physiography of the basin as a whole. To determine this, the locations of the sampled points were compared to the whole basin based on physiography. Figures 4-7 display the comparison of percentage of sampled points within each strata to the percentage of the whole basin that lies within each strata, elevation band, radiation band, and land cover class. A representative data set was obtained over the course of five days (could have been done in two if availability of the 10 field assistants could have been better aligned) and with a cost of roughly including travel and equipment costs (primarily GPS rental fees) as well as payment to field assistants.

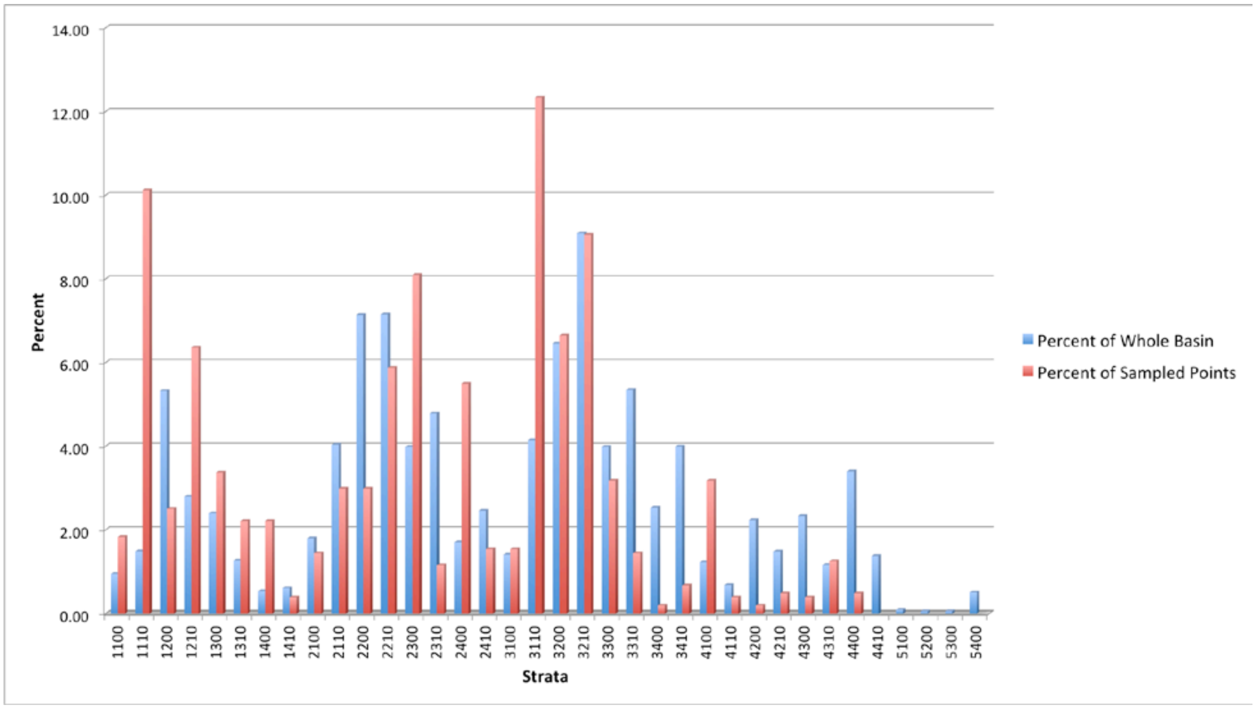

Figure 4. Comparison of the percent of samples collected in each strata compared to the percent of the whole basin that each strata encompasses. The largest discrepancies can be seen in the higher elevation strata, located on the right side of the graph, can be explained by the inability to sample in avalanche terrain due to a high hazard level during the sampling campaign.

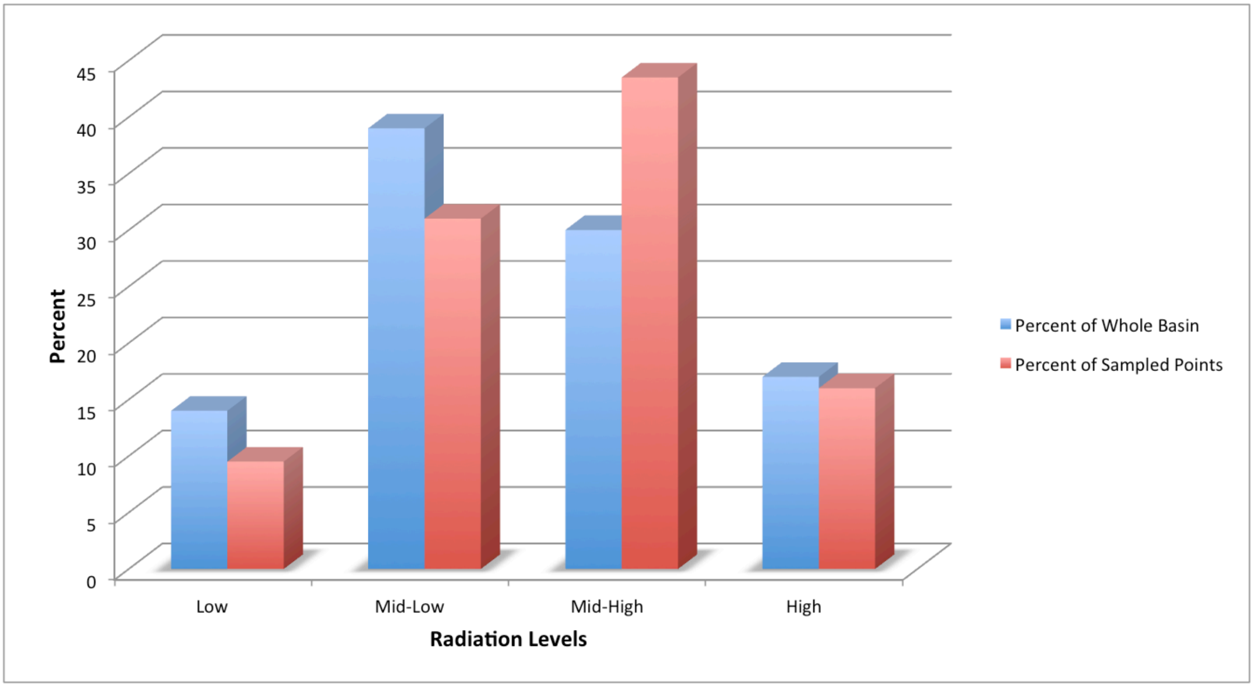

Figure 5. Comparison of the percent of sampled points in each of the five elevation bands that were used to define the strata compared to the percentage of the basin that lies within each elevation band

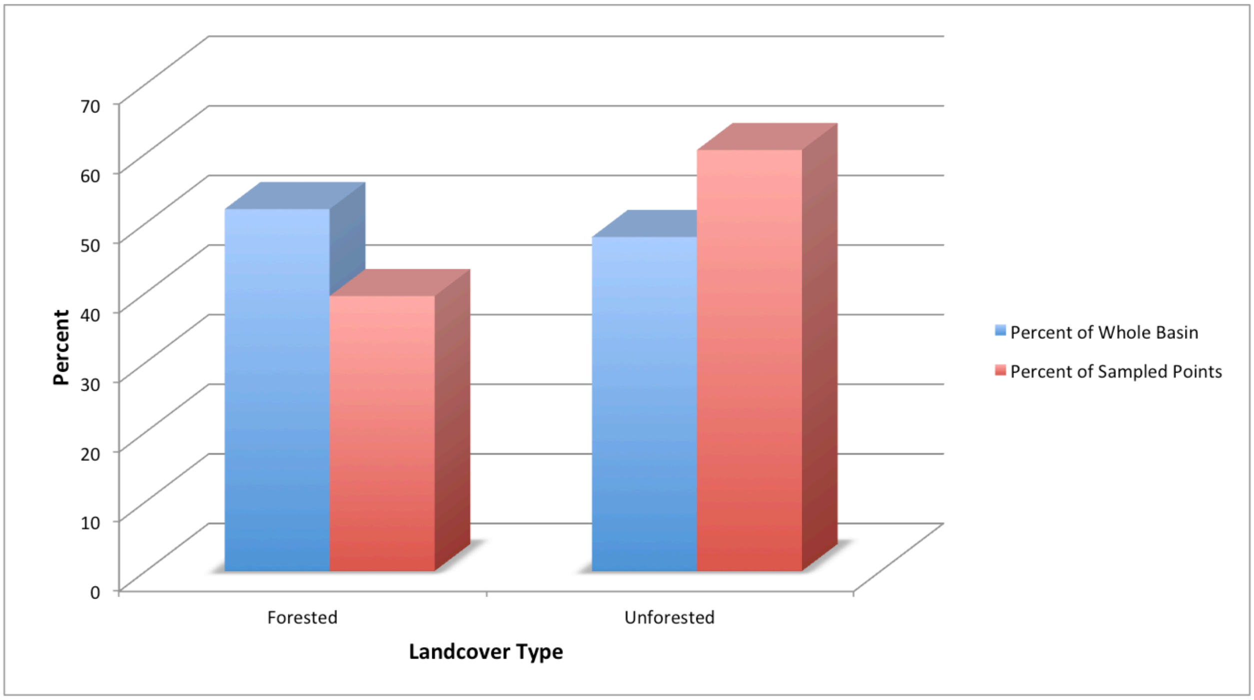

Figure 6. Comparison of the percent of sampled points in each land cover class that was used to define the strata compared to the percentage of the basin that lies within each class.

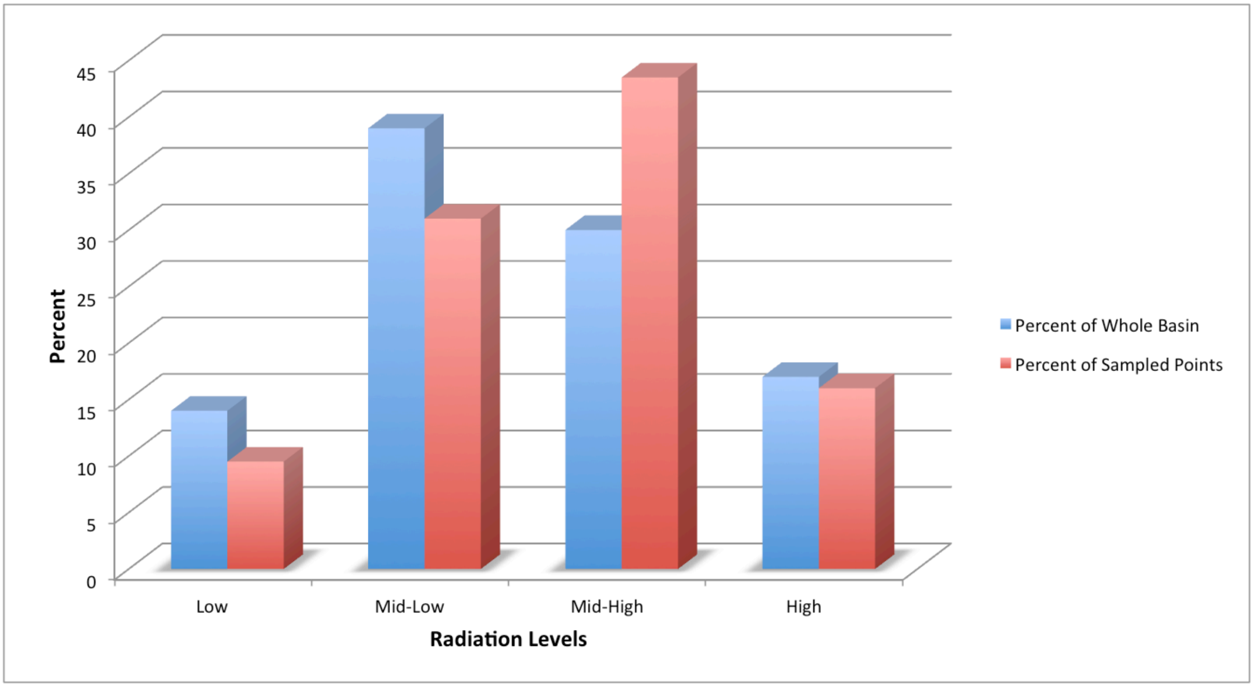

Figure 7. Comparison of the percent of sampled points in each of the four bands of potential incoming solar radiation that were used to define the strata compared to the percentage of the basin that lies within each band.

CHALLENGES AND IMPROVEMENTS

There are many challenges that arise in conducting field based snow research, particularly when working with predetermined dates and a short timeline. This section addresses many of the challenges experienced during the case study of the West Fork basin as well as suggestions and improvements that can make such a study operate more efficiently and effectively in the future.

Lack of Access Due to Low Snow

In this study, certain areas in the northern portion of the basin were minimally accessible due to below average snow cover for that time of year. Challenges due to lack of access can be addressed in several ways. First, the risk of this occurring can be minimized through obtaining as much knowledge of the area as possible during the planning stages. This can be done by either the researcher observing patterns of snow cover distribution over many different snowpack conditions, or through accessing local knowledge from individuals who have observed a wide range of conditions. This process would allow the researcher to identify which sampling areas are at risk of minimal access if snow depths happen to be less than ideal during the data collection campaign. With this knowledge alternate sampling areas can be identified which have similar physiographic characteristics but would still be accessible during low snow conditions. If this information is gathered early enough, the definition of alternate sampling areas can easily be identified and analyzed during the planning stages of the project.

Avalanche Hazard

A second major challenge that was faced was the inability to access certain areas due to safety concerns, primarily avalanche hazard. In the West Fork study all avalanche terrain and runout zones outside of controlled ski resorts were avoided due to very dangerous conditions during the sampling campaign. While this is more challenging to plan for due to the fact that avalanche terrain likely comprises unique strata and may be difficult to replace, a similar strategy as mentioned for the lack of access due to low snow can be employed to ensure a quality data set is still obtained regardless of avalanche hazard. By using GIS to identify avalanche terrain (primarily by slope angle) alternate sampling areas can then be identified that are not in avalanche terrain but in strata that are as similar as possible to the ideal sampling areas.

Access to Sample On Private Land

Another major issue that was well addressed in this study, but must be heavily considered in the planning stages of any similar study is the ability to legally access private land for sampling. During the initial planning stages portions of the basin that are potential sampling areas that lie in private land must be identified. If any private land lies within a proposed sampling area access must be requested from the landowner as early as possible to ensure that legal access can be obtained or if an alternate sampling areas must be considered. In the case of the West Fork study various resorts owned much of the large tracts of private land that were in ideal sampling areas and access was granted through contact with these owners. This however may not always be the case and this process should be started well in advance as it may require significant amounts of time.

Weather

One of the most significant challenges to be considered is variable weather during the sampling campaign. Ideally, a “snapshot” of how SWE is distributed throughout the basin near maximum accumulation will be obtained. If a multi-day data collection campaign is to be undertaken, any significant precipitation or ablation that takes place during the middle of the data collection process can potentially negatively impact the accuracy of the results of the study. In the case of the West Fork study weather did not have an impact of the collection of an unbiased “snapshot” of the basin. Throughout the data collection process temperatures remained near freezing and only traces of precipitation occurred throughout the basin. Measures can however be taken to minimize the potential of a weather related bias being introduced into the data. First, the data should be collected throughout the basin in as short of a time period as possible. By utilizing numerous field assistants in a short period of time to collect the data the researcher can have increased confidence that a true “snapshot” of how SWE is distributed is obtained and trends in how SWE is distributed can be more easily and confidently attributed to the physiographic characteristics of the basin without impact from changing conditions during data collection. Also, in case there is a weather related bias introduced, the researcher must know in advance all of the available resources (i.e. all available weather and precipitation data throughout the basin for the time period that data is collected) to be able to quantify how and when these changes may have occurred throughout the basin to be able to explain as much variability due to weather as possible during data analysis.

Well Defined Sampling Areas

One final consideration for the planning stages is to be able to define the areas to be sampled as narrowly as possible to ensure the data that is collected is most representative of the basin as a whole. In this study, the points that were sampled were representative of the physiography of the whole basin. Regardless, the more narrowly the sampling areas are defined during the planning stages (primarily the analysis of representativeness) the higher confidence the researcher can have that the resulting data set will be as physiographically representative of the whole basin as possible.

CONCLUSIONS

These methods provided a reliable and replicable framework for planning and executing a study of the effect of physiographic parameters on the spatial distribution of SWE in complex terrain that is robust over a wide range of spatial scales. Through the use of thoughtful preplanning and GIS analysis this study was able to obtain a dataset that is physiographically representative of how SWE is distributed throughout the West Fork of the Gallatin River basin while only sampling a relatively small portion of the basin. With the use of GIS, these methods allow a researcher to obtain a very thorough, robust, and statistically versatile dataset in a manner that is very efficient by measures of both time and money. The methods were developed around being able to collect a dataset that is representative of how SWE is spatially distributed throughout complex mountainous terrain but the same framework can be employed throughout virtually any type of snow covered landscape and over a wide variety of spatial scales.

Considering the critical importance of snow as a water resource for the Western United States, an enhanced understanding of how and why SWE is distributed throughout the landscape is and will continue to be of utmost importance to regions that depend on water from the winter snowpack. Continuing research, using methods such as these can provide valuable insight into this vital resource and how the data can best be utilized to better the sustainability of living in regions that are dependent on the winter snowpack for water supplies throughout the year. Continuing to further the knowledge base of how SWE is distributed throughout snow covered landscapes through the use of robust, flexible, and cost effective methods can have significant positive impacts on the sustainability of the society and culture of the Western United States. These impacts range from ensuring there is adequate water supply for municipal and agricultural purposes every year, to improved flood forecasting, wildfire management, and recreation.

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