DISSERTATION

# GIS-BASED RESERVOIR PLANNING WITH LIMITED DATA IN DEVELOPING NATIONS: A CASE STUDY OF THE LOWER MEKONG RIVER BASIN

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ABSTRACT

GIS-BASED RESERVOIR PLANNING WITH LIMITED DATA IN DEVELOPING NATIONS: A CASE STUDY OF THE LOWER MEKONG RIVER BASIN

Planning for construction and operation of water resources infrastructure requires high quality data to explain water demands, environmental conditions, and a range of impacts on economic, social, and natural systems. Where the required data are scarce or of low quality, poor decisions are often made and this has been the case in developing nations for many years. For past infrastructure planning, paper copies of maps, aerial imagery, aerial topography, and field data were required, but in developing nations these might not be available. Now, however, the situation has changed as global-scale geospatial data combined with the powerful capabilities of a geographic information system such as ArcGIS (by ESRI) have created the potential to assist greatly in water resources planning.

The potential of the new data systems has been recognized by international water planning organizations and has led to the research question: "Now that the data is available, how can we effectively tap into it and utilize it for water resource planning in developing nations?"

The new information technologies actually create a new paradigm for the water resource planning process and bypass the arduous and expensive task of collecting the massive amounts of data required in traditional approaches. Also, the new information technologies

will enable decision makers to anticipate and mitigate natural disasters, and will offer resources for training and educational purposes.

The study probes the use of the new technologies to enable decision makers to explore more alternatives, achieve better decisions, and identify the impacts of planning decisions. It addresses two facets of the data revolution as it applies to water resources planning. First, because of the vastly expanded accessibility of data via the Internet, the study identifies the types of data and new channels for data availability and analyzes their suitability for planning purposes. The second part of the study explores how the expanded availability of data can transform traditional planning processes and improve transparency, as demonstrated in an example case of reservoir system development in developing nations.

To identify the types of data and channels for data availability, the study created a system to transform global geospatial data into packaged "Data Products" for reservoir planning. This was accomplished by creating tools and models that provide decision support for key reservoir planning questions, such as annual yield or hydropower production expected at a potential site, irrigable areas, and related questions. These tools and models allow the decision maker to manipulate and extract geospatial data required for planning from a geographic information system. Some of the tools and models will process data for export into a spreadsheet.

To address how the expanded availability of data can change traditional planning processes and improve transparency, a model planning process was formulated to conduct reservoir planning tasks on a regional scale. It is now recognized that the planning process for a new reservoir must take into consideration potential adverse impacts alongside the perceived benefits of a planned reservoir. History gives us many examples of reservoirs which have been planned with only the benefits being considered, resulting in devastating human and environmental costs. Cross-border impacts also have not in many cases been considered in the traditional planning process, and examples are also given here of significant turmoil, both environmental and social. The planning process proposed in this research provides a platform for more open communication of these potential adverse impacts, as well as the potential benefits of alternative project proposals.

To test the data platforms and planning methods, two case studies in the Lower Mekong River Basin were conducted. The first case study screens potential reservoir sites and answers fundamental reservoir planning questions for each site using the data products, tools and models. The second case study takes the planning questions further to assess the flood control benefits of a potential reservoir. It shows how, in addition to assessing site feasibility, the data products, tools, and models can provide a decision maker in estimating the benefits of flood control scenarios.

The efficiency of the methodology is demonstrated in the screening activities conducted within the first case study. Potential reservoir sites were evaluated, and fundamental reservoir planning questions were answered for each potential site in a matter of hours, once the data products, tools and models were set up for the case study area. The tools and models also enable the consideration of potential adverse impacts as well as potential benefits of alternate sites. The spatial framework of GIS facilitates a decision support method where stakeholders can visualize the tradeoffs. This will improve communication of positive and negative aspects of alternative sites and show the prioritization of evaluation criteria to expose any pre-disposed bias towards potential benefits or adverse impacts. This communication will enhance decision makers' understanding, as well as facilitate public forums, presentations, and information campaigns.

The new and innovative aspects of this research are to combine and utilize multiple data sets to create more efficient and effective planning and decision support systems. As seen in the literature review, the primary focus of many past studies on the subject of reservoir planning and decision support has been on single data sets. This research aspires to provide a more inclusive perspective, showing the multiple data sets now available, and the advantage of combining these data. In a sense, this research proposes a means for synthesizing data sets for the purpose of reservoir planning and decision support in data limited areas and developing nations. In addition to combining data sets, the study demonstrated how to utilize the increasing power of raster DEM's to carry out specific planning study elements, such as rapidly estimating reservoir stage-storage curves.

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# 1.0 INTRODUCTION

## 1.1 Problem Statement

With rising expectations and needs of their citizens, developing countries are turning to more water resources development to provide water supplies, energy, and other benefits. For example, in the Lower Mekong Basin, which is used as the main data source for this research, ten major reservoirs are under construction, eleven main-stem reservoirs are under consideration, and an additional 50 reservoirs are being planned for the next 20 years (Mekong River Commission, 2009). If traditional planning processes continue to be used, exploring alternatives and finding feasible solutions for these new projects will be difficult.

The traditional process of reservoir planning typically begins with the identification of needs and goal setting. From this point, the process progresses into the exploration of alternatives and testing of site feasibility. Often however, in developing nations, the planning process would be limited or hindered by a lack of information. Fortunately, new information technologies based on geospatial data are available to improve the planning process, and the United Nations World Water Assessment Programme has identified the need to tap this data to assist developing nations in planning their water resources. The availability of new information technologies offers an alternative paradigm for the water resource planning process to assist these nations in their quest to create sustainable projects instead of simply pursuing traditional approaches.

Where data are scarce or of poor quality, poor decisions are often made and this has been the case for water resource planning in developing nations for many years where adequate paper copies of maps, aerial imagery, aerial topography, and field data have not been available. Now however, global-scale geospatial data combined with the powerful capabilities of a Geographic Information System such as ArcGIS (by ESRI) has the potential to assist greatly in the water resources planning process in developing nations.

This capability was acknowledged several years ago by the World Water Assessment Programme (2003):

*"The capacity of the earth systems science community to generate data sets from high technology observing systems and modeling is enormous and growing…major efforts need to be initiated to effectively 'drink from the fire hose' in order to sensibly exploit the information contained in these data streams. Collectively, these represent an enormously important contribution to the water resources community, a contribution that has yet to be productively tapped."*

This quote from the UN World Water Assessment Programme frames the intent of this research, to explore means by which to "drink from the fire hose" of digital data that is now available. The quote also sets the context of the problem statement governing this research, which can be stated: "The data is now available, but how can we effectively tap into it and utilize it for water resource planning in developing nations?"

Three predominant research questions originate from this governing problem statement:

- What data are of value, in the context of reservoir planning and decision support in developing nations, within the multitude of geospatial data sources that are now available?

- How can we package the geospatial data for utilization in reservoir planning and decision support in developing nations?
- How do we set up tools and models to transform and manipulate the geospatial data for the purpose of reservoir planning and decision support in developing nations, looking at both the potential impacts as well as benefits of a reservoir?

This research focuses on the use of Geographic Information Systems (GIS) to manage and effectively utilize this digital data for water resource planning in developing nations with a focus on reservoir planning and decision support in developing nations. The Lower Mekong Basin is used as a case study in this research. The Lower Mekong Basin is an example of the need for tapping into the planning resources that the newly available geospatial data and GIS have to offer for the purpose of reservoir planning and decision support.

This research focuses on the trade-offs between potential impacts and benefits resulting from a new reservoir. Without any doubt, this is an extremely complicated and controversial topic. Many examples are available of the traditional process of reservoir planning, where focus was placed on the potential benefits of a new reservoir and little consideration was given to the consequences in the area immediate to the reservoir, as well as upstream and downstream of the reservoir. Baird & Wyatt (2007) note the Yali Falls Dam, in the Kon Tum Province of Vietnam, as such an example. The Yali Falls project began in 1993, and by May of 2000 the dam had caused large-scale environmental, social and economic impacts to the communities living along the Sesan River. Baird (2011) uses the Don Sahong Dam as a more current example of a reservoir in the planning stage which is following suite. The Don Sahong Dam is proposed as a single use project, focused solely on the sale of electricity. The project is to be located on the main stem of the Mekong River in Laos, very near to the Laos-Cambodia border. The project's impacts on Mekong fisheries are the focus of Baird's paper, and he notes that the Mekong inland fisheries are among the most productive in the world. Baird concludes "Fisheries losses in the Mekong Region from the DSD (Don Sahong Dam) would negatively affect the nutrition of hundreds of thousands or even millions of people, especially in parts of Laos, Cambodia, and Thailand where nutritional standards are already low."

### 1.2 Introduction to Research Hypotheses

Three research hypotheses are presented in this research. These three hypotheses thread together with a common theme: better water resource planning can be achieved in developing nations through more effective use of newly available geospatial data and contemporary Geographic Information Systems (GIS).

Current literature demonstrates a growing trend towards the utilization of GIS and geospatial data to aid in water resource planning. As noted in the Literature Review section of this study, there are many examples of how GIS and geospatial data are being used to create very effective planning tools, decision support systems, and other resources for water resource planners and managers in both the United States and abroad. The focus of this work is on one aspect of water resource planning, which is the planning of reservoirs. However, the broader implications of this research relate to water resource planning as a whole.

The first hypothesis is stated as:

"Geospatial data are now available to fill the data gaps that have existed in the past for regional scale reservoir planning and decision support in developing nations."

In the past, considerable manpower and funding would have been required to gather and process data. The new data in combination with both the data management and analytic capabilities of contemporary Geographic Information Systems are hypothesized to be the source by which the data gaps can be filled for regional scale reservoir planning and decision support in developing nations and other data-limited regions of the world.

The second hypothesis is stated as:

"The geospatial data now available are readily managed and manipulated in contemporary GIS Software for the purpose of regional scale reservoir planning and decision support in developing nations."

Simply stated, the data are ready to be put to use. The abilities of a contemporary Geographic Information Systems allow the geospatial data to be readily utilized for water resource planning in developing nations, and specifically reservoir planning/decision support.

The third hypothesis is stated as:

"The newly available geospatial data, and the utilization of capabilities in contemporary Geographic Information Systems can provide new means of regional scale assessment of the flood controlling benefits of reservoirs in developing nations."

This research hypothesis states that the data and the systems are now available to lay the foundation for assessment of flood controlling reservoirs in developing nations and other data limited areas. In the U.S., the HAZUS program has been developed which allows for efficient evaluation of the impacts of flooding and other natural disasters. It is hypothesized that the foundation of a similar evaluation methodology can now be established in developing nations with the newly available data and capabilities of contemporary Geographic Information Systems.

### 1.3 Summary of Data Sources Researched

How do we extract what is useful from the multitude of geospatial data sources that are now available? There is a vast array of global data sets now available through the internet. Many data sources were researched by the author over a period of several years in order to find those data sets and data sources of value for the purposes of this study. It was found that there is a multitude of data with potential uses. However most data are of a lower resolution than what would be required to fulfill the purposes of this study. A very popular and well known data set, MODIS, for example provides data, at best, on a 250 meter grid. This spatial resolution is not adequate for utilization within the tools and models created in this research.

Tools and models have been created in this study with the purpose of answering fundamental reservoir planning questions on a regional scale. These tools and models rely on geospatial terrain data, land cover data, population data, and satellite imagery which are discussed in Chapter 3.

All of the data sets researched are global in nature; hence, the methodologies created in this research could be applied to any developing nation or data limited area of the globe.

Chapter 3 provides discussion of the four data sources that have been concluded to be the best available data for the focus of this study, which is reservoir planning and decision support in developing nations. In Chapter 3.1, the Shuttle Radar Topography Mission (SRTM) data set is explored and discussed. The SRTM data set provides a nearly global digital elevation model of the earth on a 90-meter grid. The data set was produced on an 11-day mission flown in February of 2000 aboard the space shuttle Endeavor (NASA, 2011). This data set is freely available through U.S. Geological Survey (USGS), Consultative Group on International Agricultural Research (CGIAR) and other websites. This data set was generated using active radar remote sensing devices; thus, clouds and vegetation canopy are much less of an issue compared with passive remote sensing devices. The data is very efficiently managed and manipulated in contemporary Geographic Information Systems.

In Chapter 3.2 the Landsat data set is explored and discussed. This data set provides land cover scenes for nearly the entire globe. The data is freely accessible at the Landsat website and is available typically on a 30 meter grid (30 m x 30 m pixels). Scenes are available on a temporal resolution typically of 1 month (however, not all scenes are clear due to cloud cover, etc.); thus, studies such as vegetation change over time can be conducted on a month by month basis. This data is also very efficiently managed and manipulated in contemporary Geographic Information Systems, as the data is provided in a grid raster format.

Chapter 3.3 focuses on the LandScan global population data set. LandScan is a global population data set that is readily imported in a Geographic Information System as a grid raster. The raster is on a 1 kilometer grid, with each grid cell listing population within that one kilometer grid cell. The data was freely obtained through the Oak Ridge National Laboratory website in 2009. As of 2010, however, nominal fees are now applied to the distribution of data.

Finally in Chapter 3.4, the research explores high resolution satellite imagery. High resolution satellite imagery is now available for most of the planet. Several commercial providers currently offer satellite imagery products that have up to 0.5m pixel resolution. At this level of resolution, natural and man-made features can be clearly identified. Google Earth is, in a sense, a repository of this aerial imagery. The imagery Google Earth offers is taken from commercial sources, and is free of charge. Methodologies for georeferencing and utilizing this imagery are presented in Chapter 3.4.

It is noted that this research places a significant emphasis on the Shuttle Radar Topography Mission (SRTM) data set. Much work has gone into the exploration of this data set and comparison with several other data sets has been performed in this research. The emphasis that has been placed on the SRTM data is due to the fact many of the decision support “Data Products”, “Tools”, and “Models” created with this research utilize the SRTM data set as their base data set.

**1.4 Summary of Research**

The path of research followed with this study maintained a strong emphasis on exploring the data available and the utilization of the data in creating data products, tools, and models. The research first looked at the vast array of geospatial data now available through the internet, and the capabilities of contemporary geographic information systems to manage this data. In a sense, the initial phase of the research was to try to mine out data sources of value to developing nations and water resource planning. Chapter 3 summarizes this phase of the research.

The second phase of the research explored how to take the data from the four sources found in the initial phase, and package it into data products. Out of the four data sources, several packaged data products were created. These data products are set up in such a way that they can be quickly imported into both proprietary (such as ArcGIS by ESRI), or non-proprietary (such as Quantum GIS) geographic information systems. These data products represent a complete database that is then built upon in the third phase of the research. Chapter 4 summarizes this phase of the research.

The third phase of the research involved the creation of several tools and models which allow for the export of GIS data to a spreadsheet environment. Geospatial data are taken into a singular reservoir planning spreadsheet in which the tools and models reside. These tools and models are based on the data products created in the second phase of the research, and allow a user to extract information related to reservoir planning and decision support. Chapter 5 summarizes this phase of the research.

Chapter 6 provides case studies demonstrating the use of the tools and models created. The case studies were conducted using the Lower Mekong Basin, in Southeast Asia, as a testing ground. Data products were set up for the entirety of the Lower Mekong Basin (652,000 square kilometers), within the nations of Laos, Vietnam, Thailand, and Cambodia. The first case study involved the use of the tools and models in the reservoir planning spreadsheet. This, in conjunction with the data products, was used to conduct a screening study of multiple reservoir sites. The second case study involved the tools, models and data products to assess flood control effects of a potential reservoir with a flood control component.

The fourth and final phase of the research lays out a methodology for evaluation of adverse impacts alongside the potential benefits. This final phase could be considered as more of a preliminary work of research, with the potential to build upon the concepts presented. The architecture for a type of multi-criteria decision analysis tool is presented which would weigh the adverse impacts of a potential reservoir against the benefits for potential reservoir sites. A comprehensive evaluation of possible adverse impacts would require consultation with a multi-disciplinary panel of experts, and this study does not intend to create information that could only result from such consultation. Rather, this phase of the study seeks to set up the framework that would allow for input from the experts. The data products, tools and models created in this research provide the impact and benefit information which is then input into a proposed multi-criteria decision analysis tool with user interface set up in a spreadsheet environment. Chapter 7 summarizes this final phase of the research.

As previously stated, the central theme of this research was to explore the geospatial data that is now available and to find ways to utilize this data for reservoir planning and decision support in developing nations. The research plan followed in this work maintains this theme.

# 2.0 LITERATURE REVIEW AND MEKONG RIVER BASIN BACKGROUND

## 2.1 Digital Data and GIS

A wealth of information is now available to resource managers around the globe. The flood of geospatial data now available via the internet has created a world that is much more understandable and manageable. With such a great deal of information now available, it seems that wise resource planning and management should be much more of a possibility for those areas of the globe that have in the past had very limited data to work with.

The Center for Earth Resources Observation Systems Data Center(EDC) was established in the 1970's as the principal archive of remotely sensed data for the US Geological Survey. Some of the products available from the EDC relevant to water resources planning are (Qu, 2006):

- Global 30-Arc Second Elevation Dataset (GTOPO30), a global 1-kilometer digital raster data derived from a variety of sources.
- HYDRO1K, a global hydrologic database derived from 1996 GTOPO30 data.
- Advanced Very High Resolution Radiometer (AVHRR), 1-kilometer multispectral data from the NOAA satellite series (1979 to present).
- Declassified Satellite imagery – 1, photographic imagery from the CORONA, ARGON, and LANYARD satellites (1959 to 1972).
- Declassified Satellite imagery – 2, photographic imagery from the KH-7 surveillance, and KH-9 mapping system (1963 to 1980).

- Global Land Cover Characterization (GLCC), a global land cover database primarily derived from 1992 to 1993 AVHRR data.
- Miscellaneous Aerial photography, elevation data sets and derivatives, and satellite data products.

Good water resource planning and management is becoming increasingly essential for natural resources in all nations and particularly in developing nations (Lyon, 2003). The Geographic Information System (GIS) is a key tool in utilizing, interpreting, and transforming this newly available data into meaningful forms, and placing the information into useful formats.

In developing nations, management tools are needed that can be used by laymen in water resource management. Such tools need to be transparent and provide information that is open and easily accessed by stakeholders involved with various water projects. The tools need to be easily manipulated and readily "re-tooled" to represent sets of changing parameters.

GIS seems to have evolved to a stage where it could be this tool, or at least provide a platform for such a tool. GIS has the qualities that are essential for a transparent and readily changed management tool in the sense that it is visual, and readily manipulated. GIS allows for the management of a common database of files and geographic information. Also, GIS can be utilized with web applications, making it much more open and transparent to stakeholders. The layer concepts utilized by GIS are readily explained and easily understood by an audience of stakeholders.

## 2.2 Contemporary Geospatial Data Sources

Discussion of contemporary geospatial data sources logically begins with some explanation of the remote sensing devices utilized in the creation of the data. These devices can be lumped into three general categories based on the spatial resolution of the data produced. It is important to note that there are derivative data sets available that have been created from base data sets of lower spatial resolution by means of interpolation. These data sets can be useful for some applications; however, these are sometimes misinterpreted as being a better data set because they have a higher spatial resolution. An example of this would be the National Elevation Dataset. This data set is available at a very high resolution (up to 3 meters). Upon inspection it is very apparent that these high resolution digital elevation models are merely interpolated from much more coarse data. The high spatial resolution of the data can mislead the user to conclude that he or she has a very detailed terrain model when this is actually not the case.

High spatial resolution data could be considered as data on a 1 to 10 meter grid; medium spatial resolution data could be considered as that with a resolution of 10 to 250 meters; low spatial resolution data could be considered as that with a resolution of 250 meters to 10 kilometers.

This being said, the figure below, taken from Lefsky (2011), summarizes the remote sensing devices from which the prime geospatial data sets available today are derived, grouped into the three categories.

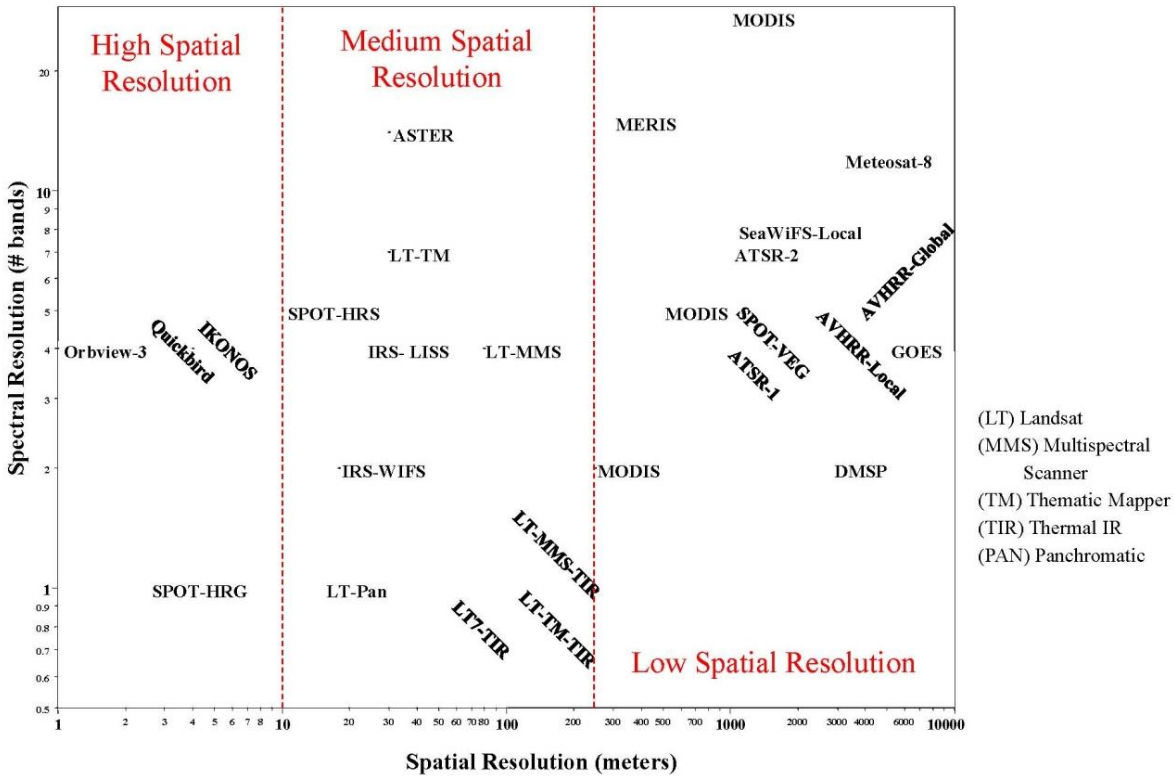



**FIGURE 2.2.1** – Spaceborne remote sensing devices and their spatial / spectral resolutions.

Source: Professor Michael Lefsky class notes (Physical Basis of Remote Sensing), Fall Semester 2011, Colorado State University.

There is a plethora of data available through the internet, and one of the purposes of this research was to search out data sets of value for reservoir planning and decision support in developing nations.

Four categories of data were explored, which were:

- Geospatial terrain data, which can be applied to reservoir planning for hydrologic studies, feasibility assessments, elevation comparisons for determining serviceable areas, etc.
- Geospatial land cover data, which can be applied to land cover studies and identification / inventory of streams, rivers, lakes, etc. Land cover information also applies to hydrologic studies.
- Geospatial population data, which can be utilized in estimation of the population within a certain radius or vicinity of feasible reservoir sites.
- Satellite imagery, which can be used to give decision makers and stakeholders an immediate visual sense of land cover, land features, populated areas, infrastructure, etc.

### 2.3 GIS in Water Resource Applications

Current literature indicates a growing trend to utilize GIS in water resource applications. In developing nations, the value of water is developing into a key issue, and GIS can be a key instrument in assisting with the planning and management of this resource. How nations invest in planning to sustain water availability and the quality water supplies may prove to be much more vital than ever in the face of increasing global scarcity of fresh water supplies.

When speaking of the value of water, discussion can very quickly turn to conflicting opinions of core values. Water resource decisions often involve human needs and ecological impacts. Some may argue that human needs should take precedence over those of the environment; others would argue that the environment which humans depend on should be respected and considered as a higher priority. According to the AWWA Research Foundation (2005):

*"It is no wonder then that even though values are an important consideration for sound water resource management, integrating water values into these deliberations is a significant challenge. Often, the accounting of values is incomplete-or may appear to be incomplete to some parties concerned about the water decision. Thus it is important to try to identify and account for all types of values-and reflect them as fully and clearly as possible-when water resource management options are evaluated and decisions made."*

Water's value is dependent on many factors. The cost to provide water, the quality of the water provided, and the reliability of water delivery are all factors which influence the "value" of water. Water availability is increasingly becoming a global issue. The public's perceived value of water will inevitably rise as water becomes less abundant and shifts towards the category of a limited resource.

Clarity in the decision making process for water resources will become more and more of a vital issue for all nations; developing nations are not an exception. In this context, wise water resource planning and management is becoming essential. Data limited areas of the globe, such as developing nations, are in need of methodologies and tools to extract and utilize the geospatial that is now available to support decisions revolving around water.

The ways in which GIS can bring clarity to the decision process are numerous. GIS allows for improved database organization and storage. Water resource studies often require the gathering of multiple base maps and extracting data such as land cover, terrain slope, drainage channels and networks. Creation of this data can be time consuming and laborious with paper maps and aerial photographs, especially when base mapping can be from different sources and at different scales. With the use of GIS, the creation of this data is much more easily done and is much less time consuming to manage (Lyon, 2003).

Nguyen, et. al. (2011) utilized GIS and remote sensing data as a tool for change detection in the Lower Mekong Basin, specifically in the Mekong delta in southern Vietnam. Remote sensing data sources including Landsat, SPOT, and Radarsat, were utilized to conduct studies of land use change focused on the decline of mangrove areas near the southern coast of Vietnam which are critical to maintaining a protective barrier. Additionally, these data were utilized to study riverbank erosion along the Mekong River in the delta area. This study showed dramatic loss of mangrove areas, and significant riverbank erosion at key locations over the time period studied extending from 1989 to 2009. The primary cause of mangrove reduction was identified as the conversion of mangrove land to shrimp farming. Causes of riverbank erosion were not expounded. The study concluded that the utilization of remote sensing techniques and GIS provide a useful tool when applied at a large scale, giving a synoptic view to monitor changes and also predict future changes in a large region.

The potential for GIS and remote sensing data to be utilized for watershed analysis with minimal cost, efforts and time compared to the traditional methods is recognized by Mohamed, et. al. (2011). A case study of the Al-Kanjar Watershed in Sudan was conducted comparing traditional watershed analysis techniques with GIS and remote sensing data. The main objective of the study was to implement new information technologies to determine hydrologic parameters based on remotely sensed terrain data, and apply these new technologies to the planning of water harvesting projects in the Al-Kanjar Watershed. A digital elevation model (DEM) was managed in GIS, and based on this DEM, analysis of watershed parameters such as flow path lengths, stream networks, sub-catchment centroids, etc. was conducted. The study concluded that GIS and remote sensing data can greatly enhance the planning process of water harvesting projects, providing efficient access to the data and effective data modeling capabilities.

Anderson, et. al. (2010) utilized remote sensing data and GIS to conduct analysis of floodplain forests in the Connecticut River watershed which contains more stands of floodplain than any other watershed in the United States. The Connecticut River mainstem is 660 km long and drains an area 2,918,277 ha. The scale of basin required the use of contemporary GIS in conjunction with remote sensing data in order to efficiently conduct this study. A model was developed using GIS and remote sensing techniques in order to provide a unifying floodplain assessment for the study area. The study identified patches of remnant floodplain forests, identified suitable conservation areas, and highlighted watershed-scale patterns. The study used geospatial data from a variety sources including Landsat data, National Elevation Dataset (NED), and the National Hydrography Dataset (NHD). From the Landsat data set, an additive index was developed using Landsat band 4 (near infrared) and band 7 (mid-infrared) to distinguish flooded and non-flooded areas. Inundation changes between spring flood season and the autumn dry season were quantified by generating a composite image combining three bands. Bands 1 and 2 were derived from the addition of Landsat bands 4 and 7 for spring and autumn. The third band was derived from a 30-meter slope map created using terrain data from the National Elevation Dataset (NED). The results of the study were compared with a digital 1 meter pixel orthophoto available for one area of the watershed, and showed surprising accuracy. One hundred-fifty random reference flooded points and an equal number of non-flooded points were extracted from the orthophoto and overlayed on the flood map that was generated in the study and found to have a pixel class accuracy of over 96 percent.

Wienand, I., et. al. (2009) demonstrate the effectiveness of GIS as an instrument of water resource management with a case study involving a water safety plan in the state of North Rhine-Westphalia in Germany. The objective of the study was the practical implementation of a water safety plan for a single potable water supplier with the primary focus on application of GIS through every step of formulation of the water safety plan. The development of the plan included hazard identification, risk assessment, effective operational monitoring, management, and communication. A variety of spatial analysis techniques were applied in this study ranging from very simple tasks in GIS (clip, merge, reclassification), to more complex tasks such as spatial interpolation techniques applied to predict the values of a variable distributed in space at unsampled locations from measurements made at sampled locations within the same area. Population data was utilized within GIS in order to determine vulnerable population clusters in a spatial context. Landsat data on a 30 meter grid was used in GIS to perform spatial analysis of land use. Land use characterization was conducted for the purpose of assessment of potential groundwater contamination as correlated with land use patterns.

Alexakis, D.G., et. Al. (2012) studied the hydrological effect of land use changes and flood risk in the Yialias River Basin in Cyprus utilizing GIS. The study utilized a hydrologic model that was set up using ArcSWAT (Soil Water Assessment Tool), a companion program within

ArcGIS, to study land and soil use parameterization and their effect on runoff processes. A prime focus of the study was to highlight the potential of remote sensing in providing GIS-based hydrologic software with adequate, reliable and updated land use data. A digital elevation model (DEM) on a 25 meter grid was obtained from the ASTER data set, which was utilized to delineate individual sub-basins within the watershed. Additionally, ASTER imagery was obtained for a 10-year time interval for the catchment area. The first three spectral bands from ASTER, with a spatial resolution of 15 meters, were used to analyze land use change. A base hydrologic model was set up and results were compared to a flood which occurred within the basin in 2003. From this base model, increase in urbanization was simulated. The study concluded that the role of urbanization is crucial to the increase in flood runoff rates. The study's focus on showing the potential for remote sensing data and GIS in hydrologic analysis was also fulfilled, in that the study showed the "importance of searching land use regime with the use of satellite remote sensing imageries".

Labadie and Triana (2007) have created a GIS based decision support system "GEO-MODSIM". This river basin management model integrates the stand alone model "MODSIM" with GIS for spatial database management, analysis and display. The model allows input of spatially oriented data layers including precipitation data, topography, soil maps, land use, and other data layers. This data is processed in the model to delineate watershed boundaries, and create hydro-networks.

GEO-MODSIM utilizes ArcGIS (by ESRI) as a user interface platform. The model is a custom ArcMap extension, so that the user can access full functionality through ArcMap. The model allows full utilization of the available spatial data processing, display, and analysis tools in ArcGIS.  Georeferenced MODSIM networks are developed by the creation of an ESRI geometric network in ArcGIS using imported feature classes such as the National Hydrologic Dataset stream and canal layers, reservoirs, gauging stations, and other pertinent features.

River GeoDSS (Gates et al. 2009) is another example of a GIS based decision support system.  This model can be utilized to design and assess basin-wide strategies for water management that promote sustainable irrigation.  Coordinated operation of multipurpose reservoir systems, conjunctive surface and groundwater management, and water quality management can be simulated in the model.  The model is designed to operate within ArcGIS, and information is spatially referenced in the model.

Fontane et al. (2002) integrated GIS with a real-time meteorological and hydrological data monitoring system in order to achieve a real-time flood forecasting and flood control model.  The model allows for spatially distributed forecasted flood flows that are updated as a flood event progresses.  This information is then input to a flood control model which provides optimal flood gate control strategies which are updated in real-time.  GIS allowed for the efficient use of spatially oriented hydrometeorological data in the model.

GIS was applied to the generation of rainfall isohyets for a river basin over hourly time increments.  Spatial analysis tools in GIS were applied to each 1-hour isohyet in order to obtain aerial estimates of rainfall over watershed sub-basins.  GIS proved to be essential in minimizing computational time requirements for spatial analysis of precipitation data over the watershed.

Mahmoud et al. (2002) presents a GIS based methodology for determination of locations and sizing of desalinization facilities.  The methodology integrates GIS with multi-criteria decision analysis for locating and sizing such facilities.  An optimal cost-distance routing algorithm was embedded in GIS which allowed consideration of complex terrain on locating facilities.

A multi-criteria decision analysis procedure was applied with utilized a 0 – 1 integer programming model for the selection of sites to be served under specified budget allocations. A second 0 – 1 integer programming model was utilized which found minimum cost selection and sizing of facilities serving only those cities selected from the first integer programming model.

A feature map of a region to be considered is developed as a grid raster in GIS. A raster terrain map is overlaid onto this feature map, which reveals areas to be considered as barriers. Then a least cost optimal routing procedure is utilized in GIS to calculate the optimal route from every cell in the raster feature map. The cell in the resulting final processed map with the lowest attribute value is the solution and best location for the desalinization facility.

### 2.4 Decision Support Systems

In a general sense, decision support systems provide support for the decision making process in many disciplines of study. Decision support systems allow decision makers easy access to information vital to the decision making process. Mittra (1986) notes four levels of support typically provided by a decision support system:

- Access to facts/information retrieval. The ability to find relevant information within a mass of data is key for a decision maker.
- Filters and pattern recognition ability. The decision maker can query databases and utilize the decision support system for determination of patterns and trends in the data.

- Ability to perform computations, comparisons, and projections.
- Development of useful models for the decision maker.

According to Mittra, S. (1986):

*"A decision support system, DSS for short, is a computer-based information system that helps the manager make decisions by providing him or her with all the relevant data in an easily understandable form. As the user of DSS, the manager formulates the problem by using an interactive and probably menu-driven front end. The system then accesses a database to locate the necessary data, utilizes a repertoire of mathematical and/or statistical models, and finally produces the desired information at the user's terminal The user can explore several "what if" scenarios in order to arrive at a decision. The DSS thus merely helps the manager make a decision; it does not and cannot make the decision for the manager."*

Decision support systems come in many varieties and as noted above, are multi-disciplinary. However, Labadie (2010) notes that there are three basic components which any decision support system must have:

- A database management subsystem, which allows for the coordination, integration, integrity, storage, and extraction of information
- A user display and dialog system, which allows the user to manipulate models, input data during model execution, and define display preferences.
- A problem analysis and modeling component, which may include statistical data analysis, forecasting algorithms, simulation capabilities, and optimization capabilities.

Specific to water resource planning, decision support systems can provide assistance to decision makers in the frequently ill-structured and complex issues posed in this discipline of study.  As water resource decision making often has a significant spatial component, a geographic information system (GIS) is a very appropriate platform for such a decision support system.

GIS seems to be an appropriate platform for decision support systems for water resources planning and management.  Decision support systems are, as their name implies, a means of supporting decisions related to a system composed of variables.  Water resources planning and management decisions are often characterized by a number of complex and dynamic variables.  Stakeholder participation is often a significant component in the decision process, and can greatly increase the complexity of decision making.

Bajracharya, Birendra, et. al. (2010) created what they term a "Decision Support Toolbox" for the purpose of decision support in the context of a pilot study focused on the management of mountain protected areas within the Sagamartha National Park in Nepal.  They evaluated current decision support systems and tools and arrived at their concept of a decision support toolbox which is a collection of tools an methods created to address the needs of different stakeholders to support key components of the decision making process. Management of a national park is highly complex, and the project promoted a systemic approach as an appropriate frame of reference for conservation and management of protected areas.  It was noted that the fundamental assumption behind systemic thinking is that everything interacts with, affects, and is affected by the things around it.  Because of this complexity, a spatial oriented decision support system was found to be very beneficial.  The capabilities of GIS allowed for viewing, creating, editing and analyzing spatial data. GIS allows users to query and find attributes of spatial data and prepare maps for display and printing. The study concluded that, in general, the linking of GIS and systemic thinking has opened new possibilities for developing models, and specific to the pilot study, allowed for dynamic modeling with spatial components that previously would not have been possible.

Ballofet (1992) describes the complexity of the water resources decision making process as being commonly characterized by uncertainty, scarcity of causal evidence on which to base a plan or policy, requiring consideration of multiple objectives, and having multi-institutional involvement. Water resource planning tends to be an iterative, and explorative learning process that redefines the problems as much as it seeks solutions to them. Often water resources planning is a complex and unstructured process which incrementally arrives at a solution with the participation of a large number of stakeholders whose strategies, perceptions of the problem, power and responsibilities vary greatly.

The subdivision of information by layers that can overlay one another creates new understanding, and a visual means of interpreting how a system works. This concept facilitates a visual problem solving process. Also, the visual nature of GIS creates a good platform for decision maker involvement.

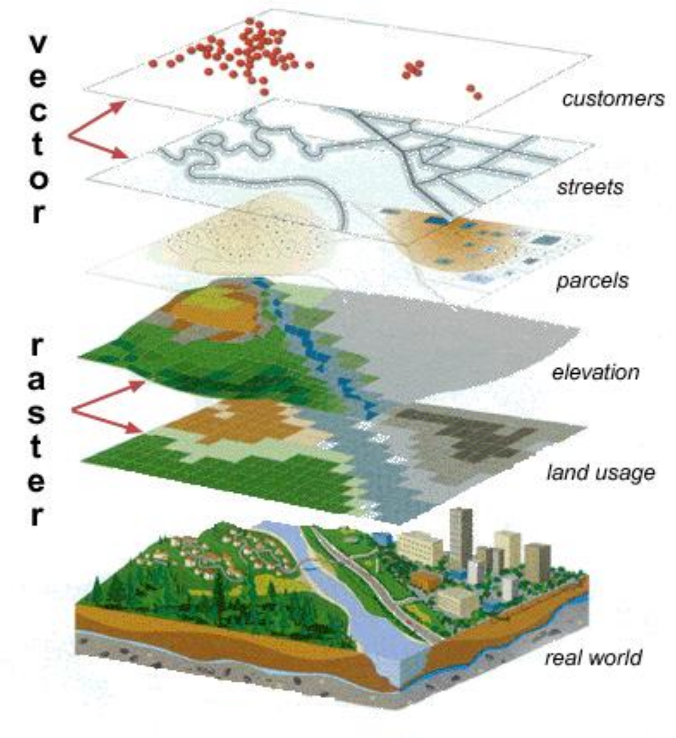



**FIGURE 2.4.1** - The Geographic Information Systems Layer Concept

Source: http://www.geom.unimelb.edu.au/gisweb/GISModule/GISTheory.htm

With the use of GIS, the creation of this data is much more easily done and is much less time consuming to manage (Lyon, 2003). Peters (2002) notes that water resource planning is often a complex and unstructured process which incrementally arrives at a solution with participation of a large number of stakeholders whose strategies, and view of the problems surrounding an issue vary greatly. Narrowly focused, rigid models will seldom produce a result that is useful. Peters notes that as early as 1970, broad based, flexible models were recognized as being necessary for effective water resource planning. Peters notes the 1970 ASCE water resource council recommendation for future research of interactive computerized systems which decision makers could use to evaluate the consequences of their decisions in terms that that are easily understood.

Peters states that water resource conflicts throughout the world are characterized by unclear objectives, disagreement as to the relative importance of the objective, disagreement between reputable scientists, and the desire that the decision be fair and ethical. These characteristics demand public participation in order to determine true values, and acceptable levels of risk. Decision makers must be provided enough information in order to create and implement sound water policy and water projects. The use of a decision support system allows decision makers to reach consensus about the decision making process.

Peters goes on to quote Simpson (1998), " The consensus building that will be necessary can only be accomplished if full and transparent information is available to both decision makers and stakeholders within the basin. This will require the establishment of a comprehensive and accessible database for the basin that reflects the hydrology, meteorology, geomorphology, ecology, sociology, and economic parameters of the basin."

The call for computer based models that would allow for interactive decision making, and provide understandable results for stakeholders with limited modeling experience still resounds today, particularly for water resource planning and decision making in developing nations. A geographic information systems (GIS) approach could be an effective means of achieving a decision support system that is user friendly, visual, and spatially oriented decision support system for water resource planning, particularly for application in developing nations.

## 2.5 Flood Risk Assessment and GIS

As stated by Akmalah (2010), worldwide flood disaster impacts are increasing due to population growth, pressures for land, and economic development in urbanized areas. During the 20th century, floods were the number-one natural disaster in the United States in terms of number of lives lost and property damage. Roughly 200 million people in over 90 countries are exposed to catastrophic flooding every year. Asian countries are among the most affected, with the highest number of people exposed.

Akmalah observed that less than half of all flood disasters worldwide occurred in Asia; however, over 80% of the people killed, affected, or displaced occurred in Asia. Akmalah notes that in general, due to water scarcity in developing countries, large populations live along major rivers, resulting in flood impacts that are more devastating.

Disaster preparedness by structural measures is costly and usually out of reach for developing countries, where disaster mitigation funding must compete with other priorities. Planning and flood management strategies require a clear understanding and awareness of the risk.

Akmalah goes on to emphasize the need not only for clear assessment of risk, but also the necessity for developing nations to take an integrated approach to flood management. This would entail a mixture of structural and non-structural flood response measures to be implemented. Integrated flood management should involve a holistic approach to hazard, exposure, vulnerability analysis, and mitigation.

VanOosterom et al. (2005) states that Geo-information technologies offer a variety of opportunities to aid management and recovery in the aftermath of disasters. Effective disaster management depends on large volumes of accurate, relevant, on-time geo-information. The challenge is to bring the information together in a common format.

Bonn et al. (2005) developed a prototype GIS based emergency response system for the district of Kandal, Cambodia. Their prototype system focused on a list of questions requiring answers of the “where” type, requiring a geographic location answer. These questions and associated information requirements could be divided into five subcategories:

- Location of and access to health services
- Location of and access to flood safe areas
- Needs related to evacuation roads and waterways
- Inventory and location of infrastructures at risk
- Access to food security

A geographic information systems approach lends itself well to providing information necessary for answering these questions. Geospatial data and GIS technologies have reached a point these questions can be addressed with exceptional efficiency.

A concept referred to as Extreme Events Engineering and Monitoring (EEEM), was developed in 2002 by the Institute of Geomatics Business Park, in the Netherlands. EEEM utilizes geo-spatial data to assess disaster vulnerability and risk. Minh Hien et al. (2005) discusses the application of EEEM to Vietnam as a means of flood vulnerability assessment in the country.

Vietnam is one of the most disaster prone countries in the world. Over the last 25 years, flooding disasters have become a growing threat in Vietnam, killing hundreds of people each year. Many locations in Vietnam are hit by disasters while they have not yet recovered from the consequences of the previous year's disaster(Minh Hien et al., 2005). The EEEM concept has been applied in Vietnam, producing flood vulnerability maps of the area around the City of Hue, and of the area between Can Tho and Chau Doc in the Mekong River delta. ERS, ENVISAT and RADARSAT imagery was utilized for analysis of historic flooding and was utilized as a reference for determination of flood extent. Topographic data was obtained from Shuttle Radar Topography Mission (SRTM) on a 90 meter grid. Additionally, ASTER data on a 15 meter grid was used for the area around the city of Hue. This information combined with satellite imagery was utilized within a GIS environment to create flood vulnerability maps.

In the United States, FEMA and the National Institute of Building Sciences has created HAZUS-MH (FEMA, 2011). HAZUS is a decision support system that can be used to conduct loss estimation for flooding, earthquakes, and hurricanes. It utilizes ArcMap (by ESRI) as a platform, and provides standardized methodologies for estimating potential disaster losses in the United States. The HAZUS flood model can be applied to both riverine and coastal flooding.

HAZUS uses the relationship between depth of flooding and annual chance of inundation of to that depth to define flood risk. Flood depth, duration, and velocity are considered as the predominant factors contributing to flood losses. Flood hazard is defined by a relationship between depth of flooding and the annual chance of inundation to that depth. Depth, duration and velocity of water in the floodplain are the primary factors contributing to flood losses. Other hazards associated with flooding that contribute to flood losses include channel erosion and migration, sediment deposition, bridge scour and the impact of flood-born debris.

A component of HAZUS is the flood information tool (FIT). The FIT is an ArcGIS extension that is separate from HAZUS. The FIT is utilized to process user supplied flood data (ground elevations, flood elevations, and floodplain boundary information). The FIT computes extent, depth, and elevation of flooding based on this user supplied data.

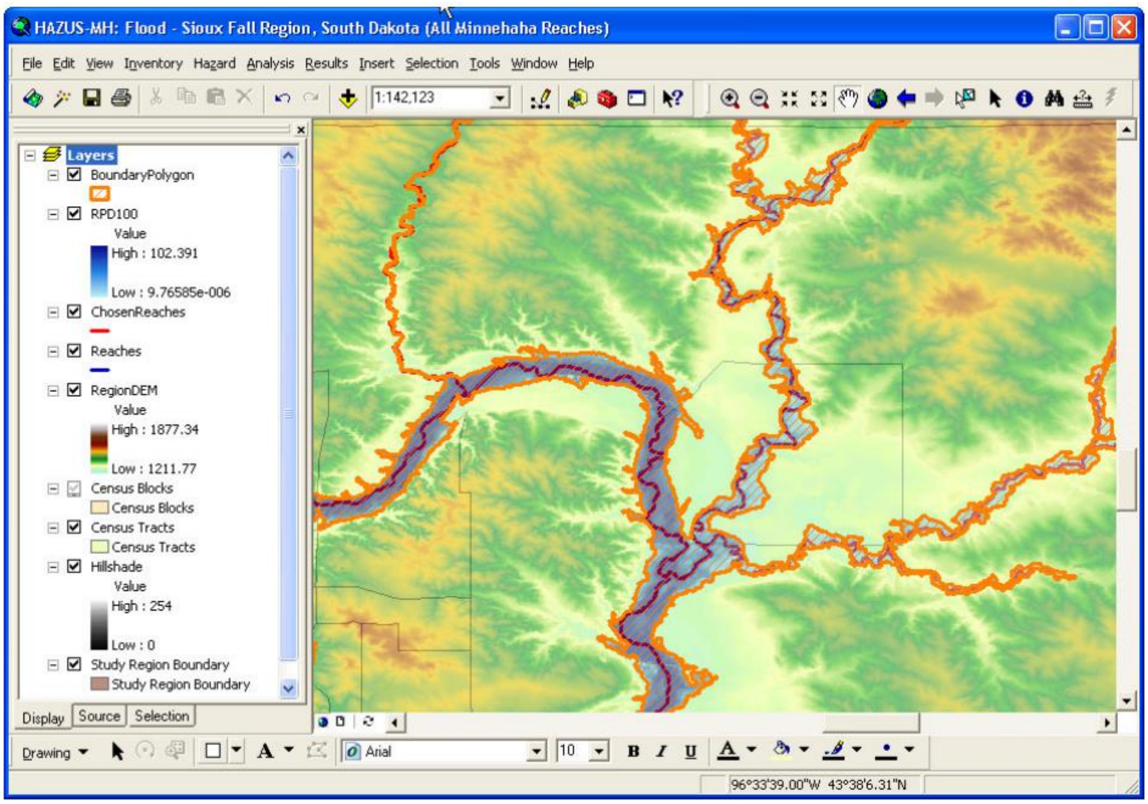



**FIGURE 2.5.1** - HAZUS-MH Graphic Output Flood Depth Grid for a 100-year Flood

Source: HAZUS MR4 User Manual, FEMA (2011)

There is a great deal of flexibility in displaying output. Tables of social and economic losses can be displayed on the screen, printed, or pasted into electronic documents. Most outputs can also be mapped. Colors, legends, and titles can be easily altered. Results can be compiled to create electronic presentations, or as inserts to a community project report.

### 2.6 Lower Mekong River Basin

This research uses the Lower Mekong river basin as a case study for how the decision process for water resource planning occurs within a river basin encompassed by developing nations. Over 55 million people live in the Mekong River Basin and depend on the water resources of the basin for basic needs and livelihood (Mekong River Commission, 2003).

The Lower Mekong Basin is encompassed by the developing nations of Laos, Cambodia, Thailand, and Vietnam. The Lower Mekong Basin encompasses 82% of the overall Mekong Basin, with an area of roughly 652,000 square kilometers.

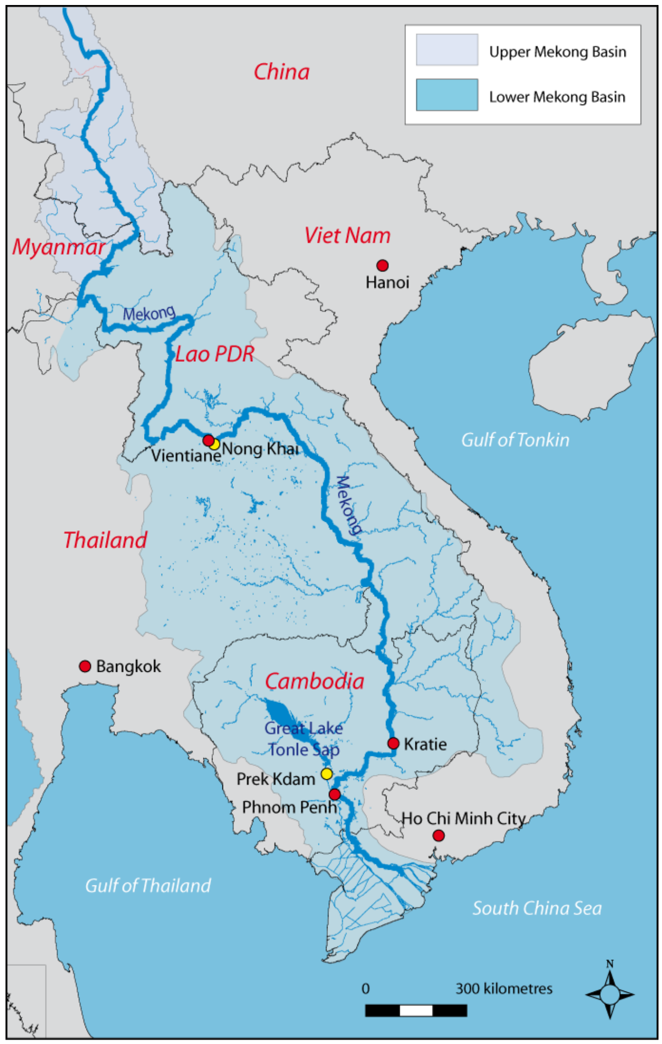



**FIGURE 2.6.1** - Mekong River Basin

Reference: Mekong River Commission (2009)

There are currently 10 major reservoirs under construction and 11 main-stem Mekong River reservoirs under consideration in the Lower Mekong Basin. An additional 50 reservoirs are being planned for construction during the next 20 years. There is a significant need for transparency, and clear representation of impacts, both positive and negative, related to water resource planning in this basin.

Annual flooding is an important issue in the Lower Mekong River Basin. Flooding occurs along both tributaries and the main-stem of the Mekong River. The Mekong River Basin is broken into two regions: the Lower Mekong Basin, and the Upper Mekong Basin. The Lower Mekong Basin is considered to be the portion of the Mekong basin within the nations of Thailand, Lao PDR, Cambodia, and Vietnam. The Upper Mekong Basin lies within the nations of Myanmar and China. Roughly 80% of the Mekong River's flow is generated within the watershed of the Lower Mekong Basin.

Mean annual rainfall in the Lower Mekong Basin ranges from 1000 mm near North Central Thailand to 4000 mm in the Truong Son Mountain Range between Lao PDR and Vietnam. The wet season extends approximately seven months out of the year, typically lasting from April to November. Wet season rain accounts for 80 to 90 percent of annual rainfall and is sufficient to grow the region's main crop, which is rice. However, rainfall is unevenly distributed during the growing season, causing drought damage throughout the region almost every year (Le-Huu, Ti; Nguyen-Duc, Lien, 2003).

The Mekong River carries a very large volume of excess water during the wet season. Typically, severe flooding occurs every wet season, and substantial damage is experienced along the river's main stream and major tributaries. In its flood stage, high water in the Mekong causes flow reversal of one of its major tributaries, the Tonle Sap River.

During the wet season flow reversal in the Tonle Sap River, a large volume of Mekong water is transported to and stored within the Tonle Sap Lake. The Tonle Sap lake is considered the great lake of Cambodia, and is located northwest of the nation's capital, Phnom Pehn. In the dry season, flow reversal of the Tonle Sap River subsides and the river then becomes the outlet for the Tonle Sap Lake. The annual flow reversal in the Tonle Sap is very significant as it plays an important role in the ecology of the regional fishery.

On a large scale, the resources of the Mekong River have yet to be wisely planned and utilized for the benefit of surrounding populations. According to the Mekong River Commission (2009):

*"Average annual withdrawals for agricultural, industrial and other consumptive uses in the LMB are estimated at around 60,000 mcm, or 12% of average annual discharge of the Mekong. The most downstream end of the Mekong Basin, the Vietnamese Delta, is by far the largest water using area in the Basin. Diversions from the mainstream upstream the Vietnamese Delta are so far negligible. Lao PDR, Cambodia use about 1% of their annual renewable water resources. Consumptive uses of water resources in the Upper Mekong Basin are insignificant. Existing storage of water resources behind dams corresponds to less than 5% of the average annual flow, and does not significantly redistribute water between seasons. Agriculture is the most dominant water-related sector, particularly in Thailand and Vietnam. In the dry season, the irrigated area is less than 10% of the agricultural area (1.3 million hectares). Expansion of the present levels of irrigation is limited by the availability of dry season flows. The water flows*

*that reach the Vietnam Delta in the dry season are fully used for economic, environmental and social purposes, including combating seawater intrusion. The hydropower potential of the Mekong Basin is estimated at over 60,000 MW and about 10% of this potential has been developed to date. Navigation is an important sector but is largely undeveloped in the sense that it is occurring naturally and, so far, not as an integrated transport sector. To reduce damage by major floods, the emphasis so far has been on the reduction of vulnerability to floods by flood proofing and non-structural measures. Water resources have been developed on a small scale for the improvement of wetlands and aquaculture.*

*While millions of poor people use the natural resources of the Mekong River Basin for their food security and livelihoods, the Mekong's water and related resources are largely undeveloped."*

### 2.7 Mekong River Commission

The Mekong River Commission was formed as a river basin commission with the goal of creating regional cooperation at a basin scale. The countries of Lao PDR, Cambodia, Thailand, and Vietnam entered into the "Agreement on the Cooperation for Sustainable Development of the Mekong River Basin" on April 5, 1995 to form the Mekong River Commission. These countries border what is considered the "Lower" Mekong River Basin. The countries of China and Myanmar border the "Upper" Mekong River Basin; however, these two countries currently are considered as dialogue partners only, and have no representation within the commission.

The Mekong River Commission seeks to promote sustainable development and regional cooperation within the river basin. Sustainable development of the river system for potable water, irrigation, sanitation, power generation, transportation and tourism are considered to be key in fighting poverty, and bettering the lives of the peoples in the region. Regional cooperation is recognized as a key aspect of making development goals a reality. The Commission realizes that development in one country may have consequences in another country, and thus, there is a need for joint planning and management of the river basin. (www.mrcmekong.org, 2010)

### 2.8 Water Resource Planning and Management Challenges Faced by the MRC

The Mekong River Basin faces many water resource planning and management issues. Regional cooperation is a common theme throughout the Commission's publications. The Mekong River is vital to the livelihood of so many people groups within the river basin, and the need for regional cooperation with regards to water resource management in the Mekong River Basin was recognized very early on in the Lower Mekong Basin. The Mekong River Commission seems to recognize that the lack of cooperation, which would undoubtedly lead to dangerous conflict between nations, cannot be afforded in this struggling area of the world.

It appears that the four member nations dialogue effectively with regards water management within the Lower Mekong River Basin. Cambodia, Lao PDR, and Vietnam have seen tumultuous times in very recent history; the peoples and economy of this area are only recently recovering. The cooperation achieved by the Mekong River Commission within this transboundary river basin can be considered a significant victory for these struggling nations.

China and Myanmar, which border the Upper Mekong River Basin, pose a difficult issue in that these nations directly affect the quality and quantity of water flowing into the Lower Mekong River Basin. These two countries have yet to commit to a position within the Commission. They have recently taken a position of "Dialogue Partners", which seems to be a step towards a more cooperative position with the Commission. Still, these nations create a serious issue for the Lower Basin nations. China has constructed several upstream mainstem dams, and has plans for several more. The new dams have already created changes in the flow characteristics of the Mekong River. It is a great concern of the Lower Basin nations that the future planned dams will have an even greater impact which could disrupt the very important ecology and fishery of the river. How to bring China and Myanmar to the table and into a cooperative position is probably one of the hardest questions for the Mekong River Commission. As of yet, there seems to be no answer for this question.

Hydropower and main-stem dams are also very challenging issues for the Mekong River Commission. There is a growing need for new sources of electric power in the region, and there is a strong desire to provide this power by tapping into the resources of the Mekong River. However, the fishery provided by the river is also vital to the peoples of the region. There is a severe conflict of interest between the desire to build main stem dams, which will have serious effects on the fisheries of the river, and the desire to protect this very much needed source of food and livelihood for the region. It seems that there is no easy answer to this conflict.

According to R. Friend, R. Arthur, Marko Keskinen (2009):

*"Framing hydropower and fisheries in terms of trade-offs has an immediate appeal of reasonableness and balance. But at the same time, it reduces complex societal choices based on values of what development means to simplistic choices to be determined by an inferred technical, neutral decision. It simplifies complex options to a set of polar choices, as if these were the only options available, and as if the choice between dams and fish were comparable…*

*For as much as it is a choice between fish and people, it is also a choice between food and air conditioning, and to who these benefits accrue."*

There appears to be a shift in thought from focusing on the value of the natural fishery to the value of "progress", i.e. hydropower. Dams for hydropower seems to be perceived as a step towards progress. While fishing seems to be portrayed as a dying means of livelihood. Aquaculture and fish farms are proposed as the alternative to wild capture fisheries. In addition to the notion that wild capture fishing is a backwards form of maintaining a livelihood, it is also being portrayed as naturally declining due to lack of good management

Who truly benefits from the development of dams and hydropower is a very valid question in this area. The mostly rural population surrounding the Mekong River and its tributaries seem to have little to gain and very much to lose with the development of strictly hydropower projects.

A current example of the quandary presented by hydropower development is the Don Sahong Dam being planned for the mainstream of the Mekong within Lao PDR in the Khone

Falls area, which is just north of the border between Lao PDR and Cambodia. This area of the Mekong River is key to the regional fishery. Multiple studies have been conducted which show the unique role this area plays in fish migration. The proposed dam at this location would block the only deep channel that allows fish to migrate through Khone Falls year round (J. Dore, K. Lazarus, 2009).

The country of Lao PDR has undertaken environmental studies which have shown the Don Sahong project to be viable. However, this conclusion is highly disputed, and the Lao PDR government has not made their study public. The Mekong River Commission is put in a very difficult position as an analysis and campaigner for International Rivers, Carl Middleton, stated in a 2008 interview:

*"If the MRC provides advice to government agencies that is perceived as critical of proposed hydropower projects, this advice could be unwelcome, ignored and then no longer sought, undermining the MRC's relevance in the eyes of the government agencies it considers itself primarily answerable to. Yet, by not providing this objective analysis and releasing it into the public domain, as it should do, the MRC faces a crisis of legitimacy in the eyes of the wider public that it is also intended to serve."*

(J. Dore, K. Lazarus , 2009)

The issue of hydropower and mainstream dams has catalyzed questioning of the legitimacy of the Mekong River Commission. De-marginalization of the Commission has become an interesting problem. There have been several well publicized issues in recent years, besides hydropower and mainstream dam projects, where the Mekong River Commission has been silent or ineffective. In these instances the Commission has been portrayed as hesitant to step into situations and issues which have the potential for bringing countries into conflict. The role of the mediator and facilitator of solutions seems to be traded for a “look the other way” position for fear that the Commission may offend member countries. This attitude has disappointed many and brought questioning of the Commission’s legitimacy. The Commission is working to improve this tarnished image.

Flood protection is a key issue for the region. The area is subject to the Asian Monsoon which results in annual flooding of the Lower Mekong Basin. Many flood protection projects have focused on major cities. However, the benefits of protecting these cities has come at the cost of enhancing flood problems in rural areas. There are many examples of diversions and levees have resulted in sending water into rural areas that had little previous flooding or have risen flooding significantly above historic levels.

According to **L.** Lebel et all (2009:

*“Instances where flood protection intervention measures have made things worse are multiplying. More and more people are becoming aware of the unanticipated side effects of urban flood protection measures for wetlands, river ecosystems, and the livelihoods of people who depend on them. Across the region people are asking questions about who really benefits, who is paying for protection, and whether there are alternative ways of managing risks from floods.”*

## 2.9 Mekong River Commission Framework

The Mekong River Commission is structured with a council, a joint committee, and an office of the Secretariat. The Council is made up of one member from each participating country that holds a ministerial or cabinet level. The Council meets once a year, and makes policy decisions, provides other necessary guidance. The Council has overall governance of the Mekong River Commission.

The Joint Committee is also made up of one member from each participating country a least at the rank of department head. The Joint Committee is responsible for implementing policies and decisions of the Council. The Joint committee holds at least two sessions per year, and when necessary, special sessions are held in addition to the 2 mandatory sessions. The Joint Committee also supervises the office of the Secretariat, and functions as a board of management over the Secretariat.

The office of the Secretariat is made up of a Chief Executive Officer, Assistant Chief Executive Officer, and a staff typically consisting of over 150 persons. The Secretariat carries out tasks assigned by the Council and Joint Committee, but is directly responsible to the Joint Committee. The Secretariat formulates the Mekong River Commission's annual work program and serves to prepare all other plans, project and program documents, studies and assessments as may be required. The Secretariat also maintains information databases for the Mekong River Commission. In a sense, the office of the Secretariat is the operational arm of the Mekong River Commission. (www.mrcmekong.org, 2010)

## 2.10 Basin Planning and Development Philosophy

The river basin planning process for a transboundary basin must take into account a multitude of conflicting interests, ecological issues, social impacts, and seek to achieve a point of balance. The Mekong River Commission has embraced the Integrated Water Resources Management (IWRM) approach to basin planning in the hope of achieving a point of balance as much as possible in its planning process.

According to the Mekong River Commission (2009):

*"A key part of the 1995 Mekong Agreement is the need for the four riparian countries to cooperate in 'the formulation of a basin development plan that would be used to identify, categorize and prioritize the projects and programs to seek assistance for and to implement at the basin level'. …*

*The Mekong basin cooperation model is built on 'cooperation, coordination and mutual respect'. So developing a common understanding of the IWRM transboundary issues, and of the importance of the environmental and social values and assets of the basin, and how these can be used and managed in the future development, is the essential supporting foundation for basin wide sustainability."*

There appear to be general guidelines for development projects on the main stem and tributaries of the Mekong River. However, as planning and development processes must account for a transboundary basin inclusive of several sovereign nations, it is clear that it would be very challenging to develop rigid review and approval processes for such projects. In a sense, the 1995 "Agreement on the Cooperation for Sustainable Development of the Mekong River Basin", which is the basis of the current Commission's existence, is a river compact or treaty. In a very general sense, the 1995 agreement guides planning and development projects within the basin.

Based upon the 1995 agreement, the “Procedures for Prior Notification, Prior Consultation, and Agreement” was ratified in 2003 by the member nations. These procedures affirm the member nation’s commitment to cooperative use and planning of the resources of the river basin. The procedures provide further definition and clarity to expectations for individual nations when seeking to develop within the basin. Among these expectations are prior notification submitted to the Mekong River Commission for any development project. Also, a process is outlined within the 2003 procedures for prior consultation with the Mekong River Commission concerning any development project.

**2.11 Brief Summary of Regional History**

It is important to grasp the political history of this region to fully appreciate the Mekong River Commission. Water resource planning and management cannot be conducted in a vacuum, isolated from the political and social environment within which it occurs. The Lower Mekong Basin is most certainly an example of the dynamic and challenging environment in which water management in developing nations must occur.

The Mekong River Commission had its beginnings much earlier than 1995. In the mid-1950’s the Mekong River Committee was initially formed, and was active in conducting surveys and studies of the Mekong River Basin.

Looking back to 1958, U.S. Lieutenant General Raymond A. Wheeler surveyed the development potential of the Mekong River. His conclusions were that the Mekong River had great potential for development of navigation, hydropower generation, irrigation, and other related water uses. He believed that if developed properly,

*"…this river could easily rank with southeast Asia's greatest natural resources. Wise conservation and utilization of its waters will contribute more towards improving human welfare in this area than any other single undertaking."*

(C. Schaaf, R. Fifield , 1963)

In the 1960's the region sank into major conflict: the Second Indochina War (also referred to as the Vietnam War). The United States saw development of the Mekong as a means of bringing peace to this troubled area of the world, and sought to maintain its role as a key player in the region. In April of 1965, President Lyndon Johnson, in a speech at Johns Hopkins University stated:

*"Fort what do the people of North Vietnam want? They want what their neighbors also desire – food for their hungers, health for their bodies…and they would find all these things far more readily in peaceful association with others than in the endless course of battle…The first step is for the countries of Southeast Asia to associate themselves in a greatly expanded cooperative effort for development…For our part I will ask the Congress to join in a billion dollar American investment in this effort… The vast Mekong River can provide food and water and power on a scale to dwarf even our TVA."*

(Nguyen Thi Dieu, 1999)

Lack of stability in the area caused interruption of committee sessions in the late 1970's, and in 1977 Cambodia withdrew from the committee. The result of Cambodia's withdrawal was the formation of the Interim Mekong Committee, consisting of Lao PDR, Thailand, and Vietnam. In 1991, Cambodia requested readmission, which over four years led to the 1995 agreement which was the basis of the current Mekong River Commission.

### 2.12 Conclusions

This chapter concludes that there is a large body of research on the topic of GIS, remote sensing and the potential for exploiting these relatively new information technologies for utilization in the arena of water resources planning and management. However, work on synthesizing the data sets for the purpose of water resource decision support is limited. Based on the literature review conducted, which included a thorough search of digital doctoral dissertations nationwide, dissertations in print and available through local library sources , books on the subject, and scholarly papers and articles, the author has found little work to date done to synthesize the growing body of geospatial data for the purpose of water resource planning.

Moreover, even less work was found relating synthesis of geospatial data sources for the purpose of water resource planning in developing nations. Possibly, there is not the funding available for this type of research in developing countries. It is likely that funding in these areas is focused more on immediate and basic needs. Although water certainly is a basic need, planning for the future and management of this resource likely does not take priority over more immediate issues.

Also this chapter concludes that a multitude of geospatial data sources are currently available. Many of these data sources provide excellent temporal resolution, with time intervals of 15 days or less. These data are exceptional for analysis of global conditions and monitoring temporal changes on a broad scale. However, most of these data sets have a very coarse spatial resolution, ranging from a 500-meter to an 8 kilometer grid. Such data, although exceptional for analysis of say, global land use change, to not provide the utility necessary the intent of this study. This research is focused on water resource planning in developing nations, particularly decision support revolving around the planning of new reservoirs. What is important for the purposes of this research is spatial resolution. The data sets that have been identified in this research have a much higher spatial resolution, ranging from 30-meters to 90-meters. The one exception is the ASTER data set and the global digital elevation model (DEM) offered by ASTER. This data set would, upon initial examination, appear to be better than the SRTM digital elevation model which was identified as the data set of choice in this research. However, as is discussed in Chapter 3, the ASTER data set exhibits exaggerated and sometimes erratic characteristics. This can be seen very clearly in the cross-section comparisons provided. ASTER data has been generated utilizing a passive remote sensing device based on optical sensors, whereas STRM data has been generated with an active remote sensing device using radar. Because of this, the SRTM data set would be the more trustworthy data set, and it is for this reason that the SRTM data set was selected in this research.

# 3.0 DATA RESEARCH

## 3.0.1 Introduction

The advent of Geographic Information Systems and greater accessibility of geospatial data have expanded the data resources to plan water resource projects, and have created a flood of global information through the world wide web. The United Nations World Water Assessment Programme has identified the need for tapping into the mass of geospatial data now available to assist developing nations in their growing need for wise planning of water resources. The Lower Mekong Basin will see the development of multiple new reservoirs and has been used as a case study in this research.

The study proposes methodologies for transforming the newly available global geospatial data into packaged “Data Products” for reservoir planning in developing nations, which is further discussed in Chapter 4. This chapter explores the geospatial data that is currently available, and how manageable it is in contemporary geographic information systems.

As discussed in previous sections of this research, there is a vast array of global data sets now available through the internet, and many data sources were researched by the author in order to find those data sets and data sources of value for the purposes of this study. Most data currently available are of a lower resolution than what would be required to fulfill the purposes of this study. A very popular and well known data set, MODIS, for example provides data, at best, on a 250 meter grid. This spatial resolution is not adequate for utilization within the tools and models created in this research. Four data sources were found to be of the most value for this study, and suit the purposes of this research. These four data sources are now examined in the following sections.

## 3.1 - GEOSPATIAL TERRAIN DATA

### 3.1.1 Shuttle Radar Topography Mission Data Research

This section of the research explores the Shuttle Radar Topography Mission (SRTM) data set, which provides geospatial terrain data for the majority of the globe. First, the means for obtaining the data is discussed. Following this discussion, background for the SRTM data is expounded. Finally, comparison of the SRTM data set to several other sources of data including the National Elevation Dataset (NED), local data sets (aerial topographic data), and the ASTER data sets is provided. Some of these comparative data sets provide global coverage, and some provide coverage only for the United States. Point datasets within the Lower Mekong Basin have also been compared to the SRTM dataset.

### 3.1.2 Obtaining SRTM Data

The SRTM data set provides global elevations on a 90-meter grid, and was produced using an active remote sensing device, in contrast to many spaceborne remote sensing devices, which are passive. Passive remote sensing devices only receive electromagnetic energy, either reflected or emitted; whereas active remote sensing devices both emit and receive energy.

The SRTM data set was produced on an 11-day mission flown in February of 2000 aboard the space shuttle Endeavor (NASA, 2011). The SRTM data is referenced to the 1996 Earth Gravitational Model (EGM96), which is a geoid-based model.

SRTM data can be obtained from a number of sources. The USGS Earth Explorer website (http://earthexplorer.usgs.gov/) is the preferred choice of the author. Alternate websites from which SRTM data can be obtained are:

- Global Data Explorer (http://gdex.cr.usgs.gov/gdex/)
- Consultive Group on International Agricultural Research (CGIAR) ( http://www.cgiar-csi.org/2010/03/108/)

### 3.1.3 USGS Earth Explorer

Once logged in to the USGS Earth Explorer website (http://earthexplorer.usgs.gov/), the user is provided a map-based user interface. The User can identify an area of interest by picking vertices which create a boundary for the area of interest.

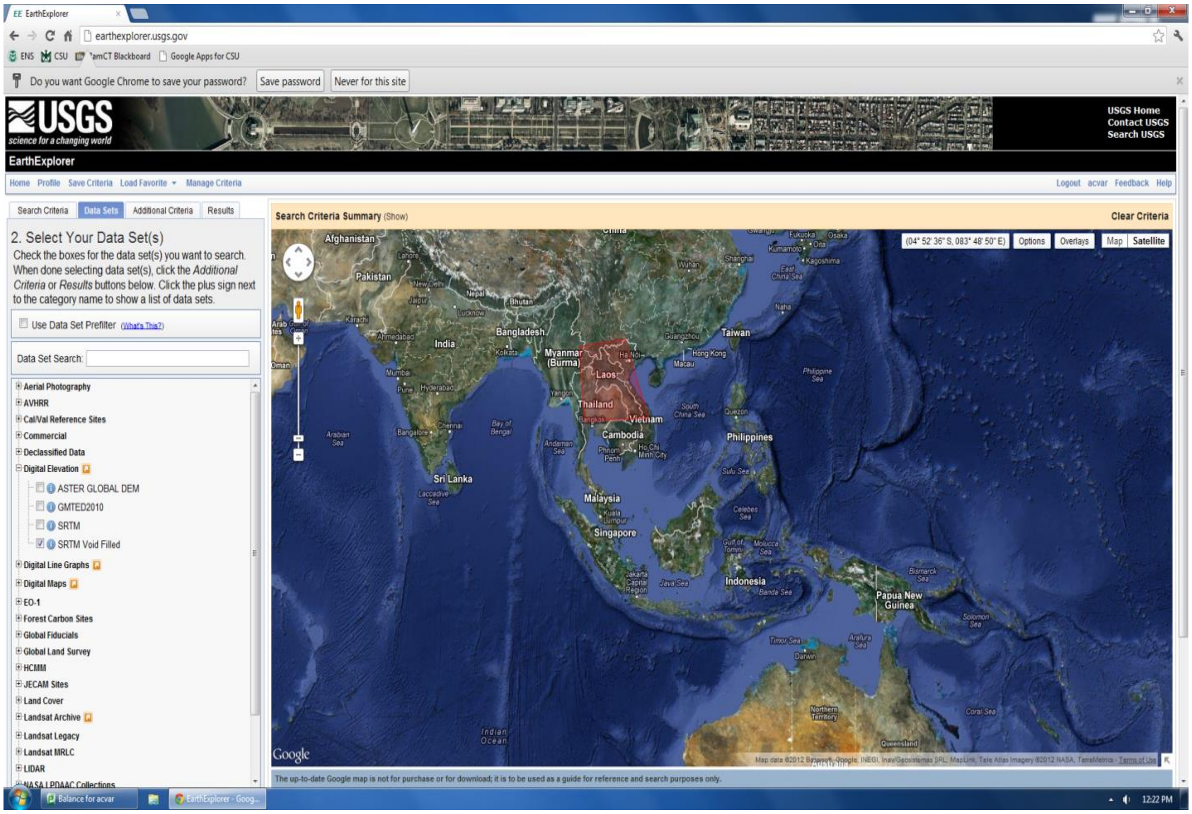



**FIGURE 3.1.1** – USGS Earth Explorer map-based user interface. User selected area of interest hatched in red.

The user is given the option to select the desired data sets to obtain within the area of interest. In this case the SRTM Void Filled Digital Elevation data set was selected.

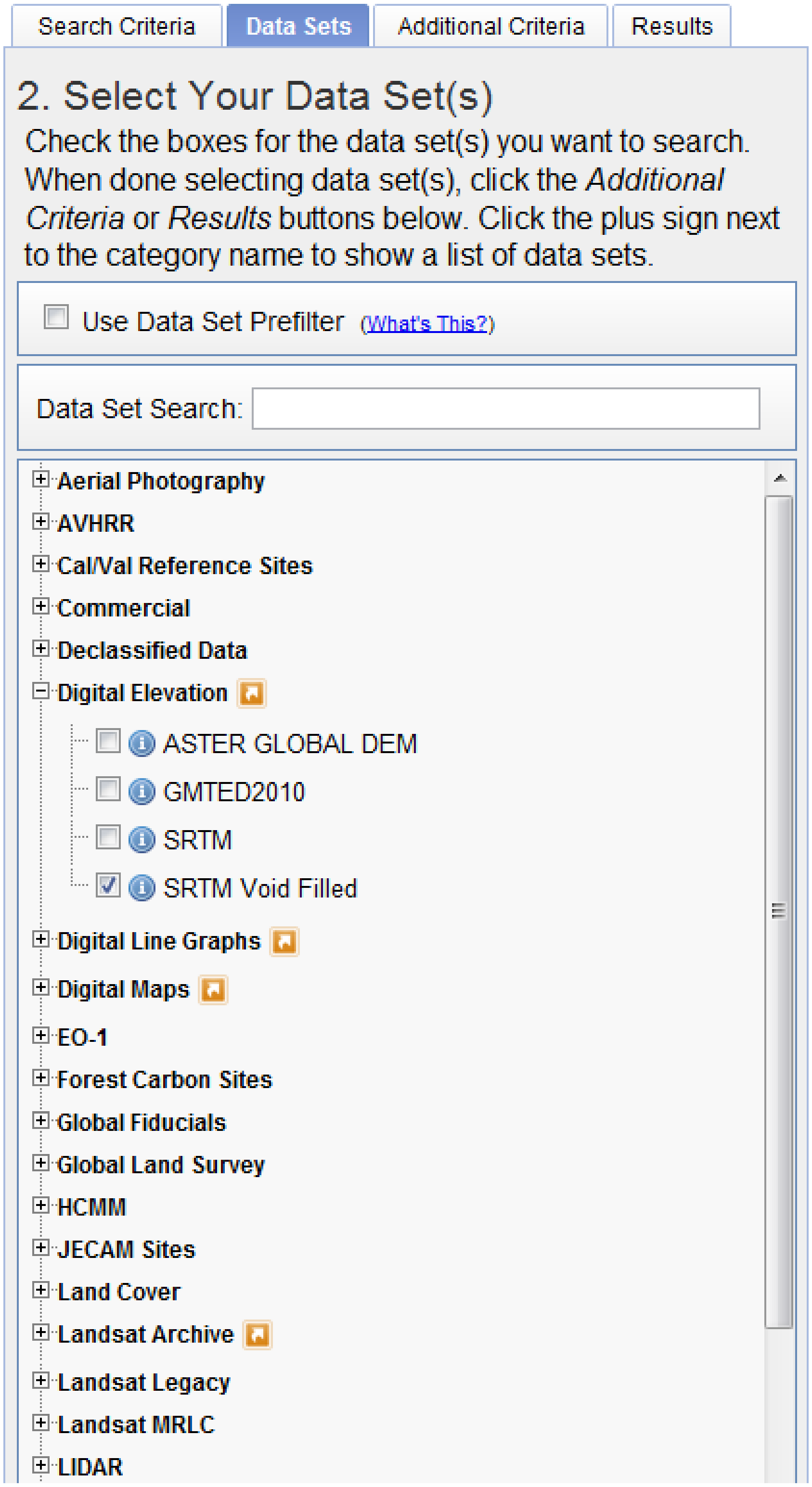



**FIGURE 3.1.2** – USGS Earth Explorer data selection.

The results of the data query bring out a series of SRTM panels which the user can choose to download in a BIL format, DTED format, or GEOTIFF format.  The author's preference was to download the data in a GEOTIFF format.

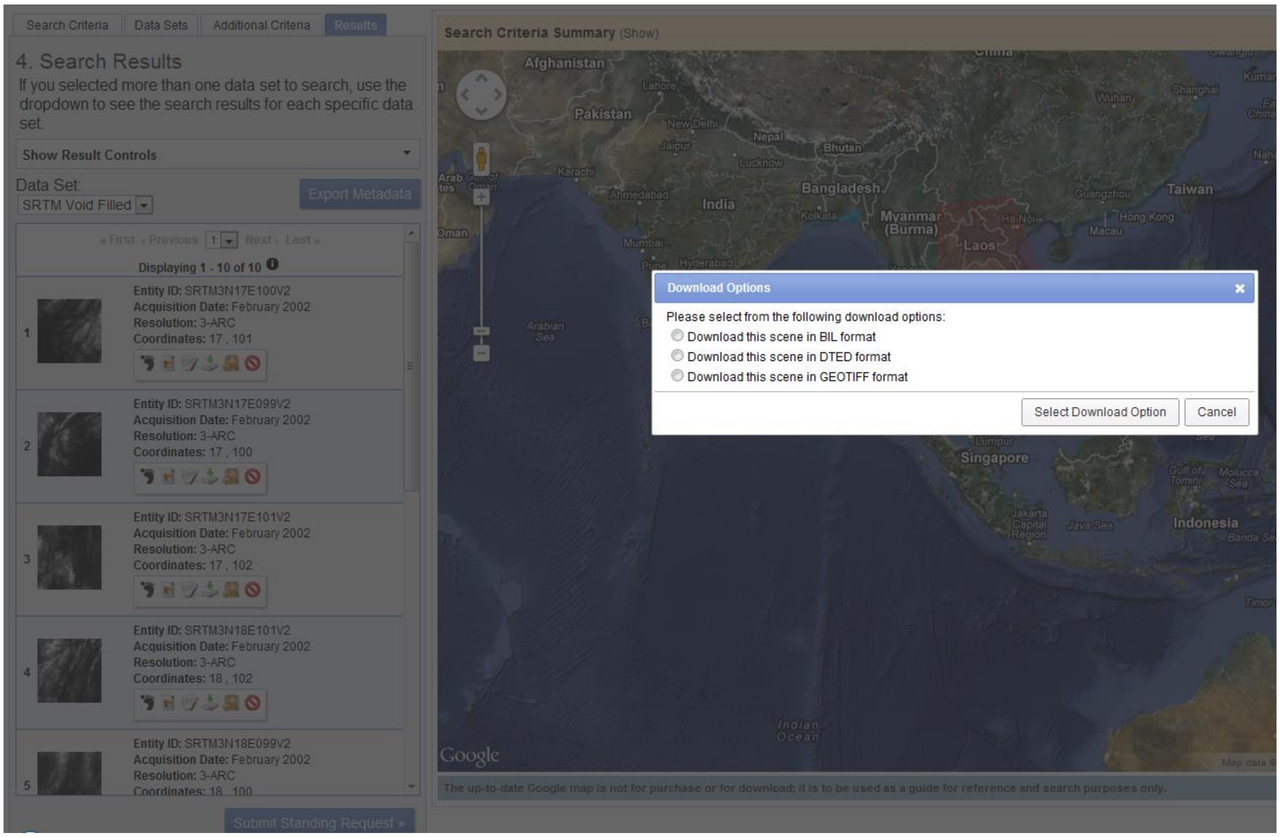



**FIGURE 3.1.3** – USGS Earth Explorer download format selection

SRTM data was downloaded as 105 x 105 kilometer panels with a file size of roughly 3 MB each.  When downloaded initially SRTM panels are in a  georeferenced TIFF raster format.  SRTM panels must then be converted to a GRID format in order to be manipulated within ArcGIS (by ESRI).  Eighty nine SRTM panels were required to cover the Lower Mekong Basin.

### 3.1.4 Comparison of SRTM Data With the National Elevation Dataset (NED)

This section compares SRTM with the National Elevation Dataset. The NED data was freely downloaded at the USGS Seamless website (www.seamless.usgs.gov). This data is downloaded as a raster grid that is readily utilized in ArcMap. As with the SRTM data, the data comes on a geographic coordinate system. ArcMap was utilized to re-project the data into a projected coordinate system. Consistent with the processing done for the SRTM data, all NED data was re-projected into the Universal Transverse Mercator (UTM) system.

According to the USGS (2012), http://ned.usgs.gov/Ned/about.asp#:

*"The National Elevation Dataset (NED) is a new raster product assembled by the U.S. Geological Survey. NED is designed to provide National elevation data in a seamless form with a consistent datum, elevation unit, and projection. Data corrections were made in the NED assembly process to minimize artifacts, perform edge matching, and fill sliver areas of missing data. NED has a resolution of one arc-second (approximately 30 meters) for the conterminous United States, Hawaii, Puerto Rico and the island territories and a resolution of two arc-seconds for Alaska. NED data sources have a variety of elevation units, horizontal datums, and map projections. In the NED assembly process the elevation values are converted to decimal meters as a consistent unit of measure, NAD83 is consistently used as horizontal datum, and all the data are recast in a geographic projection. Older DEM's produced by methods that are now obsolete have been filtered during the NED assembly process to minimize artifacts that are commonly found in data produced by these methods. Artifact removal greatly improves the quality of the slope, shaded-relief, and synthetic drainage information that can be derived from the elevation data….These processing steps ensure that NED has no void areas and artificial*

*discontinuities have been minimized. The artifact removal filtering process does not eliminate all of the artifacts. In areas where the only available DEM is produced by older methods, then "striping" may still occur.”*

### 3.1.5 Comparison of SRTM Data With Local Data Sets

Local data sets were also utilized to conduct comparison with the SRTM Data. Local data sets originated from various sources. Local 2-foot interval topographic data for Greeley, Colorado was obtained through the City of Greeley GIS department. The topographic data came as an ArcMap shapefile on a projected coordinate system. ArcMap was utilized to transform this shapefile (consisting of topographic lines/contours) into a digital elevation model. This data has been used for graphical comparison against the SRTM data set. Greeley was chosen for a comparison data set because the author was already familiar with this data. The author had utilized data from this area in previous professional experience.

A second data set, 2-foot interval topographic data for La Veta, Colorado was obtained through the report entitled “Floodplain Information-Cucharas River and Tributaries, La Veta, Colorado”, by the U.S. Army Corps of Engineers, 1977. This topographic data was based on aerial photogrammetric methods. A Paper copy of the topographic mapping was scanned and imported into ArcMap. Georeferencing tools in ArcMap were utilized to align the scanned map with the base mapping already set up in ArcMap.

### 3.1.6 Comparison of SRTM Data With Aster Data

The ASTER remote sensing device was launched in December of 1999. This device provides global elevations on a 30-meter grid. ASTER is a cooperative effort between NASA and Japan's Ministry of Economy and Trade and Industry. The ASTER device is a passive remote sensing device, only receiving reflected energy. ASTER digital elevation models are derived by stereographic means. The ASTER device has dual optical devices, one of which is turned at an angle to the other, allowing stereographic imagery. As with the SRTM data set, the ASTER global digital elevation model is referenced to the 1996 Earth Gravitational Model (EGM96). (NASA, 2011).

The data sets used for comparison against the SRTM and ASTER data were either based on the North American Vertical Datum (NAVD88) vertical datum or the National Geodedic Vertical Datum (NGVD29). Further discussion of the geoid model of the earth, and orthometric elevation systems is provided in the following sections.

### 3.1.7 Small Scale and Large Scale Data Comparisons

Large scale data analysis of the SRTM and ASTER data was conducted by comparison of SRTM and ASTER data to well-established data sources. The national elevation database (NED) by the US Geological Survey was used for a baseline data source. Also different local topographic datasets were utilized for comparison.

Small scale data sets were analyzed throughout the Lower Mekong Basin. Data analysis of the SRTM and ASTER data was conducted by comparison of SRTM and ASTER data to one another on a large scale. Ten cross-sections have been analyzed throughout Laos, Thailand, Cambodia, and Vietnam. Cross-sectional information has been displayed graphically to provide the reader with a visual sense of how the SRTM data compares to the ASTER data.

### 3.1.8 Comparison of SRTM Data with Point Data

Point data has also been compared in order to gain a sense of the validity of the SRTM dataset within the case study area. Professor Stephen Leisz, Colorado State University Geography Department, provided ground elevations which he personally surveyed in Northwestern Vietnam in 2001 through 2005. These ground elevations have been imported in GIS with the SRTM dataset. As a background, the ASTER dataset has also been overlayed on a common projection and coordinate basis (UTM Zone 48 North, WGS 1984), for further comparison.

### 3.1.9 Geiod Model of the Earth

The SRTM dataset is provided on a vertical datum referred to as the EGM96 (1996 Earth Gravitational Model), which is a geoid-based model of the earth. Many of the local datasets utilized for comparison to the SRTM, as well as the National Elevation Dataset (NED) are referenced to the NGVD29 or the NAVD88, which are orthometric models.

The earth is an irregular body, and with the irregularity comes the difficulty of computing elevation across its surface. It is convenient to utilize a shape close to sea level as a datum for measuring elevation (Iliffe, Lott, 2008).

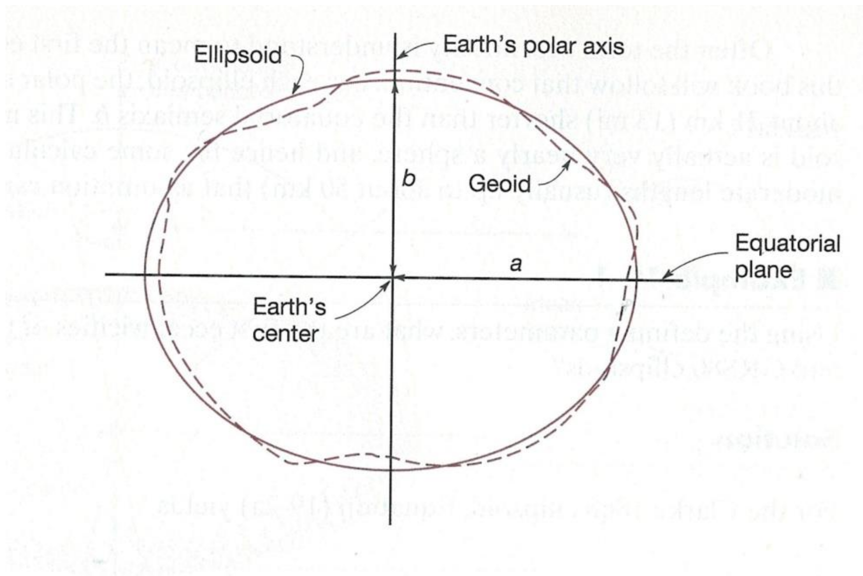



**FIGURE 3.1.4 -** Ellipsoid and Geoid. Reference: Paul Wolf, Charles Ghilani (2002), "Elementary Surveying An Introduction to Geomatics", Prentice Hall.

The geiod represents an equipotential gravitational surface located at mean sea level. This surface is drawn perpendicular to the direction of gravity at every point. The surface is not a consistent shape however. The geoid is irregular in shape due to the fact that there are variations in the earth's mass distribution (Wolf, Ghilani, 2002).

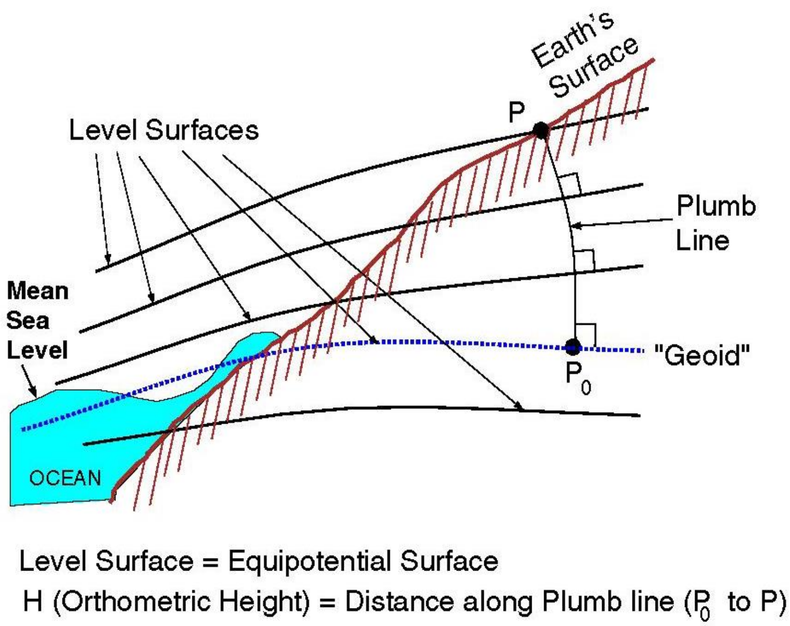



**FIGURE 3.1.5 -** Illustration of the Geoid.

Reference: www.ngs.noaa.gov/GEOID/geoid_def.html

The ellipsoid is a mathematical surface created by revolving an ellipse about the earth's polar axis. The dimensions of the ellipse are selected to, as much as possible, create consistency between the geoid and the ellipsoid. Surveys of large areas are typically conducted, and an ellipsoid is "fit" to represent the geoid for large areas of the earth's surface. The Clarke Ellipsoid of 1866, as an example, was created to approximate the geoid for North America (Wolf, Ghilani, 2002).

The size and shape of an ellipsoid is defined by two parameters "a" and "b". the parameter "a" is the semi-major axis of the ellipsoid. The parameter "b" is the semi-minor axis of the ellipsoid. These two parameters are illustrated below.

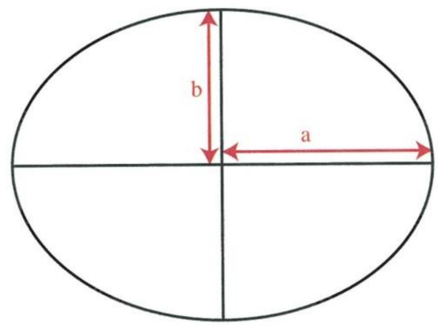



**FIGURE 3.1.6 -** Defining the parameters of an ellipsoid. Reference: Athan Iliffe, Roger Lott (2008), "Datums and Map Projections For Remote Sensing , GIS and Surveying", 2nd Edition. Whittles Publishing.

Historically, the ellipsoidal models of the Earth were completely defined by a and b. Additional parameters (Flattening, Inverse Flattening, and Eccentricity) have been defined and are more commonly utilized. These parameters are defined as follows (Iliffe, Lott, 2008):

Flatting is defined by the relationship:

Flattening, f = (a-b)/a

Inverse flattening is defined as:

Inverse Flattening = 1/f

Eccentricity is defined by the relationship:

Eccentricity, E^2 = (a^2 – b^2)/a^2

It is most common to use the parameter a, and inverse flattening (1/f) to define the ellipsoidal models of the Earth. The figure below from (Illiffe, Lott, 2008) summarizes parameters for some frequently used ellipsoidal models.

| Ellipsoid name | Semi-major axis (a) | Flattening (f) | Comment |
|---|---|---|---|
| GRS 1980 | 6 378 137 m | 1 / 298.257222101 | The international standard. |
| International 1924 | 6 378 388 m | 1 / 297.0 | A former international standard. |
| GRS 1980 Authalic Sphere | 6 371 007 m | 0 | An authalic sphere is one with a surface area equal to the surface area of the ellipsoid. |
| WGS 84 | 6 378 137 m | 1 / 298.257223563 | Used by the GPS satellite navigation system. |

**FIGURE 3.1.7 -** Defining ellipsoidal parameters. Reference: Athan Iliffe, Roger Lott (2008), "Datums and Map Projections For Remote Sensing , GIS and Surveying", 2nd Edition, Whittles Publishing.

It is helpful to provide a sense of how a common ellipsoidal model, the WGS 84, compares to the geoid model of the Earth. Illiffe and Lott (2008) compared the height of the geoid (obtained from the EGM96 model of the geoid) to the WGS 84 ellipsoid. The figure below depicts the height differences in this comparison.

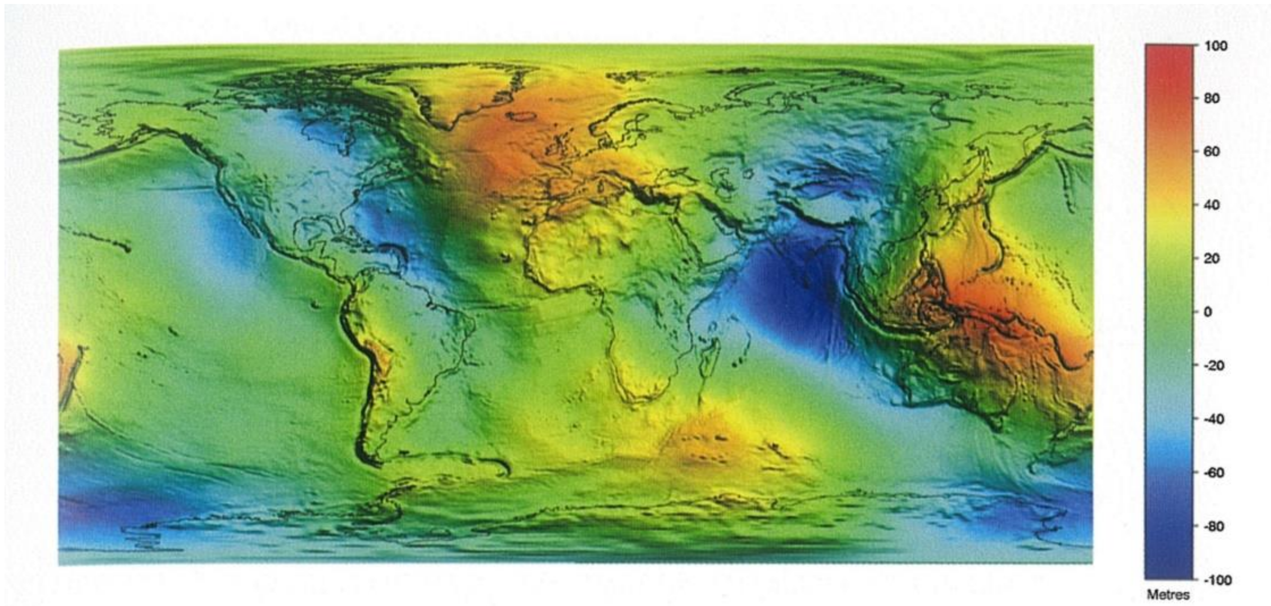



**FIGURE 3.1.8 -** The geoid with respect to the WGS 84 ellipsoid. Reference: Athan Iliffe, Roger Lott (2008), " Datums and Map Projections For Remote Sensing , GIS and Surveying", 2nd Edition, Whittles Publishing.

Height differences ranged from positive (meaning that the geoid is above the ellipsoid) 100 meters to negative (meaning that the geoid is below the surface of the ellipsoid) 100 meters. The root mean squared difference was roughly 30 meters.

### 3.1.10 Orthometric Models of the Earth

The data sets utilized in this research are based upon the North American Vertical Datum (NAVD88) and the National Geodedic Vertical Datum (NGVD29). The NGVD29 was established in the United States by the U.S. Coast and Geodetic Survey (USC & GS). The USC & GS set thousands of bench marks throughout the United States using an incremental leveling procedure. The leveling and setting of this system of benchmarks began in the 1850's, and went through 1929. In 1929 the USC & GS began a general least squares adjustment of all leveling completed to that point in the U.S. and Canada. Long term data from 26 tidal gaging stations was incorporated into this 1929 adjustment in order to relate all bench marks in the USC & GS network of benchmarks to mean sea level. The end product of this adjustment was a system of interrelated benchmarks across the U.S. and Canada. These benchmarks were all considered to accurately reflect elevations related to mean sea level, and were all said to be related to the National Geodetic Vertical Datum of 1929 (Wolf, Ghilani, 2002).

Over the years the 1929 system of benchmarks deteriorated due to shifting of the earth's crust, and changes in sea level. In order to adjust to these changes, the U.S. National Geodetic Survey performed a new general readjustment. Work on this readjustment began in 1978 and included more that 1.3 million observed elevation differences in the U.S. and Canada. The resulting readjustment to all benchmarks in the system concluded in 1991; however, since the planned completion date was 1988, the readjusted system of leveled benchmarks was named the "North American Vertical Datum of 1988" (NAVD88). The NAVD88 shifted the position of the reference surface from the mean of the 26 tidal gage stations originally utilized or the NGVD29 to a single tidal gage bench mark known as "Father Point/Rimouski" in Quebec, Canada.

The readjustment from the NGVD29 to the NAVD88 involved elevation differences that were relatively small throughout the Midwest and the east coast of the U.S. and range generally from .1 to .3 meters. More significant adjustments occurred throughout the Rocky Mountains and the west coast, and range generally from .5 to 1.5 meters (Wolf, Ghilani, 2002).

### 3.1.11 Large Scale Data Analysis

Large scale data analysis of the SRTM and ASTER data was conducted by comparison of SRTM and ASTER data to well-established data sources. These comparisons were done in order to establish a sense of the accuracy and quality of the SRTM data set.

The national elevation database (NED) by the US Geological Survey was used for a baseline data source. Also different local topographic datasets were utilized for comparison. The NED data is referenced to the North American Vertical Datum of 1988 vertical datum, which is an orthometric elevation model. Local data sources were referenced to either the NAVD88 or the National Geodedic Vertical Datum of 1929, which is also an orthometric elevation model.

As seen in the following results section, there is good consistency between the EGM96 geoid model of the earth and the orthometric elevation models upon which the study data sets were based.

Large scale data sets were analyzed at Greeley, Colorado, and La Veta, Colorado. Cross-sectional information was extracted from the SRTM dataset as well as the NED and local datasets. Cross-sectional data was used to create flood models with computer program HEC-RAS in order to estimate flood elevations. Flood elevations in the form of water surface profiles were compared for the different data sets with the intent of establishing a sense of how digital elevation model data accuracy affects the results of flood analysis. Cross-sectional information and water surface profiles have been displayed graphically to provide a visual sense of how the SRTM data compares to the NED and local data sets.

### 3.1.12 Methodology-Large Scale Data Analysis

Data was managed and manipulated using the Geographic Information System ArcMap by ESRI. The SRTM data was freely downloaded at the Earth Explorer website (www.earthexplorer.usgs.gov). When downloaded, the SRTM data comes as a raster grid that is readily utilized in ArcMap. The data is on a geographic coordinate system. ArcMap was utilized to re-project the data into a projected coordinate system. All SRTM data sets were re-projected into the UTM (Universal Transverse Mercator) system.

The NED data was freely downloaded at the USGS Seamless website (www.seamless.usgs.gov). This data is downloaded as a raster grid that is readily utilized in ArcMap. As with the SRTM data, the data comes on a geographic coordinate system. ArcMap was utilized to re-project the data into a projected coordinate system for ease of use. Consistent with the processing done for the SRTM data, all NED data was re-projected into the UTM system.

Local topographic data sets were obtained from various sources. Local 2-foot interval topographic data for Greeley, Colorado was obtained through a personal contact at the City of Greeley GIS department. This data is available to the public for a fee. The topographic data came as an ArcMap shapefile on a projected coordinate system. ArcMap was utilized to transform this shapefile (consisting of topographic lines/contours) into a digital elevation model.

Local 2-foot interval topographic data for La Veta, Colorado was obtained through the report entitled “Floodplain Information-Cucharas River and Tributaries, La Veta, Colorado”, by the U.S. Army Corps of Engineers, 1977. This topographic data was based on aerial photogrammetric methods. A Paper copy of the topographic mapping was scanned and imported into ArcMap. Georeferencing tools in ArcMap were utilized to align the scanned map with the base mapping already set up in ArcMap.

USGS quadrangle mapping of the area was added in ArcMap as a background layer. The USGS quadrangle mapping was used to establish common reference points. These reference points were then used to rotate and translate the scanned 2-foot contour interval topographic map. Once the scanned map was properly aligned in ArcMap, contours were traced/digitized. The attribute table in ArcMap housing the data for contour lines was edited in order to associate elevations with the contour lines. Once digitizing of the contour lines was completed, ArcMap was utilized to transform the contour lines with associated elevations into a digital elevation model.

The digital elevation models for the SRTM, ASTER, NED and local data sets were incorporated into a single ArcMap document in order for comparative analysis of river cross-section to be performed. The program HEC-geoRAS, which is a companion program that works within ArcMap, was utilized to create river cross-sections and to create hydraulic models. The Cache La Poudre River was modeled with the Greeley data set, and the Cucharas River was modeled with the La Veta data set.

Using HEC-geoRAS, river cross-sections were cut through the digital elevation models (DEMs). River cross-sections based on the DEMs are shown in the following Results section. River cross-sections based on the NED data as a dashed black line, data from a local source (2-foot interval aerial topographic mapping) as a solid black line, ASTER as a solid green line, and SRTM data as a solid red line. Cross-sections have been displayed graphically for visual comparison. For the purposes of this study, it was felt that graphical plots of the cross-sections would provide the most meaningful comparison. The graphical plots have been exaggerated vertically such that the vertical scale is ten times that of the horizontal.

Upon completion of the creation of river cross-sections from the various data sets, hydraulic models were built in the river analysis software package HEC-geoRAS, by the U.S. Army Corps of Engineers. The program HEC-geoRAS works within the ArcMap environment to extract the necessary data to build a hydraulic model. HEC-geoRAS then allows for the creation of an export file which can be imported directly into HEC-RAS for hydraulic modeling of a river or floodplain.

All hydraulic modeling was done in a manner that would allow accurate comparison of the affect that the data sets had on 100-year flood water surface profiles. Manning-n values, overbank and channel reach lengths, channel and overbank stationing were all held consistent between the data sets being compared.

The intent of these comparative hydraulic models was to compare the affect that the various data sets would have on modeling 100-year floodplain water surface elevations. In the United States, 100-year water surface elevations are typically utilized for flood planning and preparedness, as well as aiding in regulation of flood zones. At the conclusion of a flood study, water surface profiles and 100-year flood elevations are utilized by communities for regulatory purposes. This portion of the research sought to understand how the accuracy of the SRTM data would affect the end product of a flood study done utilizing SRTM data.

Water surface profiles for the Cache La Poudre and Cucharas Rivers are provided in the following Results section. Water surface profiles based on the NED data are shown as a dashed black line, those based on data from a local source (2-foot interval aerial topographic mapping) as a solid black line, and those based on SRTM data as a solid red line.

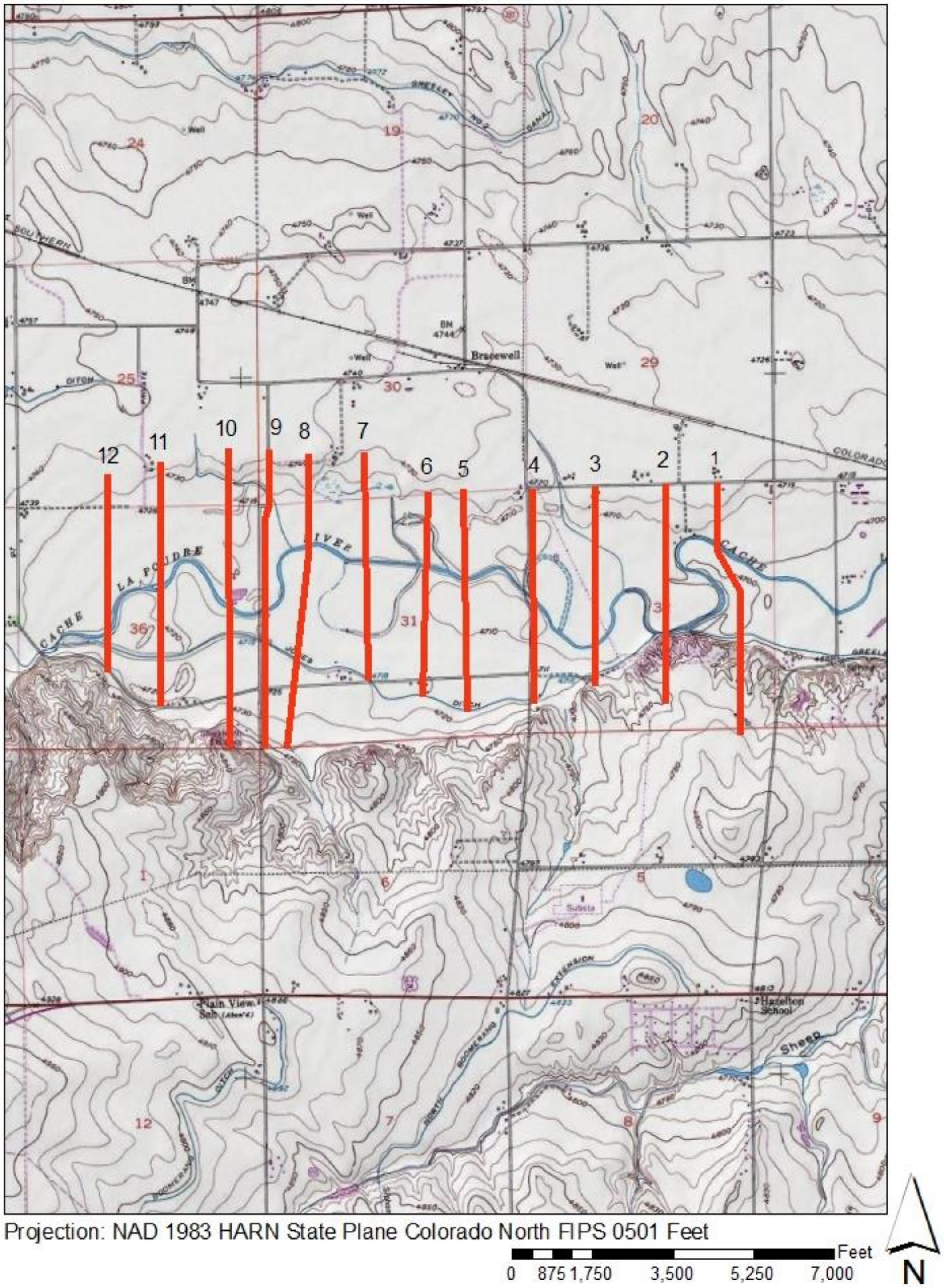
Water surface profiles have been displayed graphically for visual comparison. As with the cross-section data, it was felt that graphical plots would provide the most meaningful comparison. The graphical plots have been exaggerated vertically such that the vertical scale is one hundred times that of the horizontal for the Greeley data sets, and ten times that of the horizontal for the La Veta data sets.

### 3.1.13 Results – Greeley, Colorado

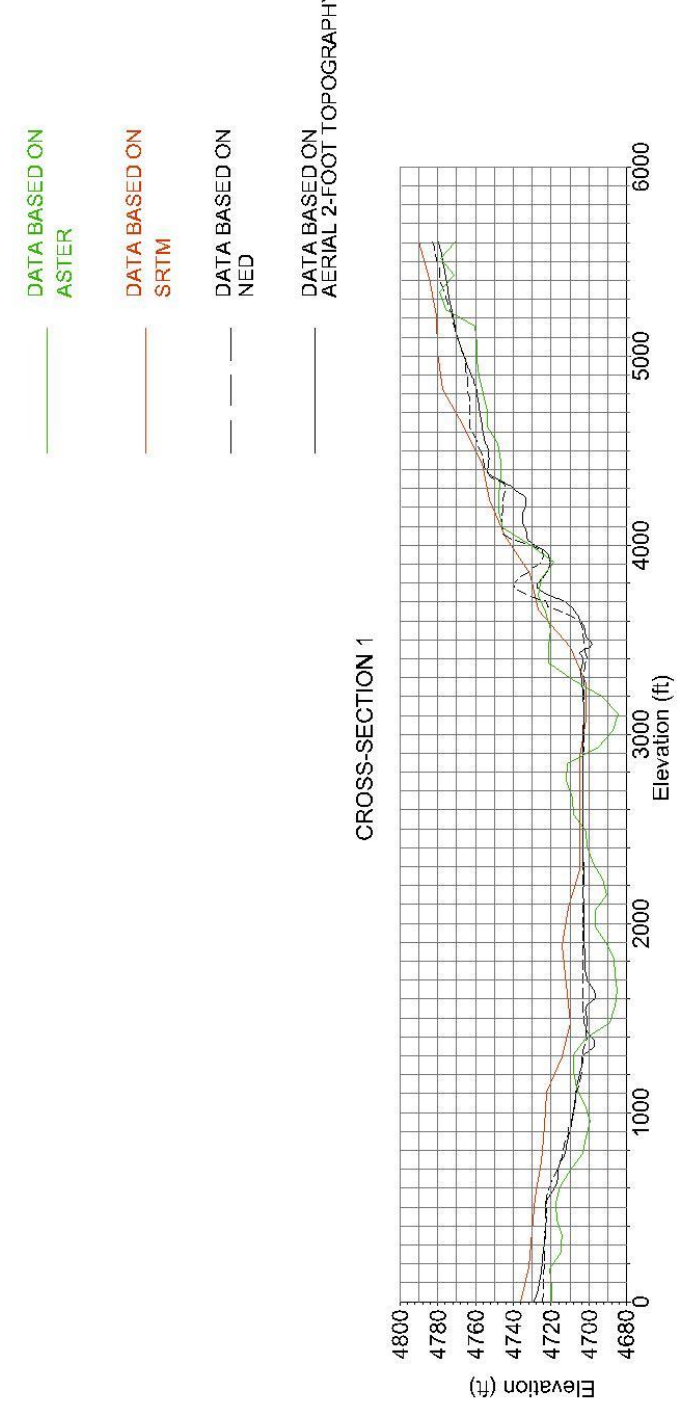
The following cross-section plots for Greeley, Colorado show NED data as a dashed black line, data from a local source (2-foot interval aerial topographic mapping) as a solid black line, ASTER as a solid green line, and SRTM data as a solid red line. NED elevation data is referenced to the NAVD88 vertical datum, which is an orthometric elevation model. Data from the 2-foot interval aerial topographic mapping is referenced to the NGVD29 vertical datum, which is also an orthometric elevation model. SRTM data is referenced to the EGM96 which is a geoid elevation model.

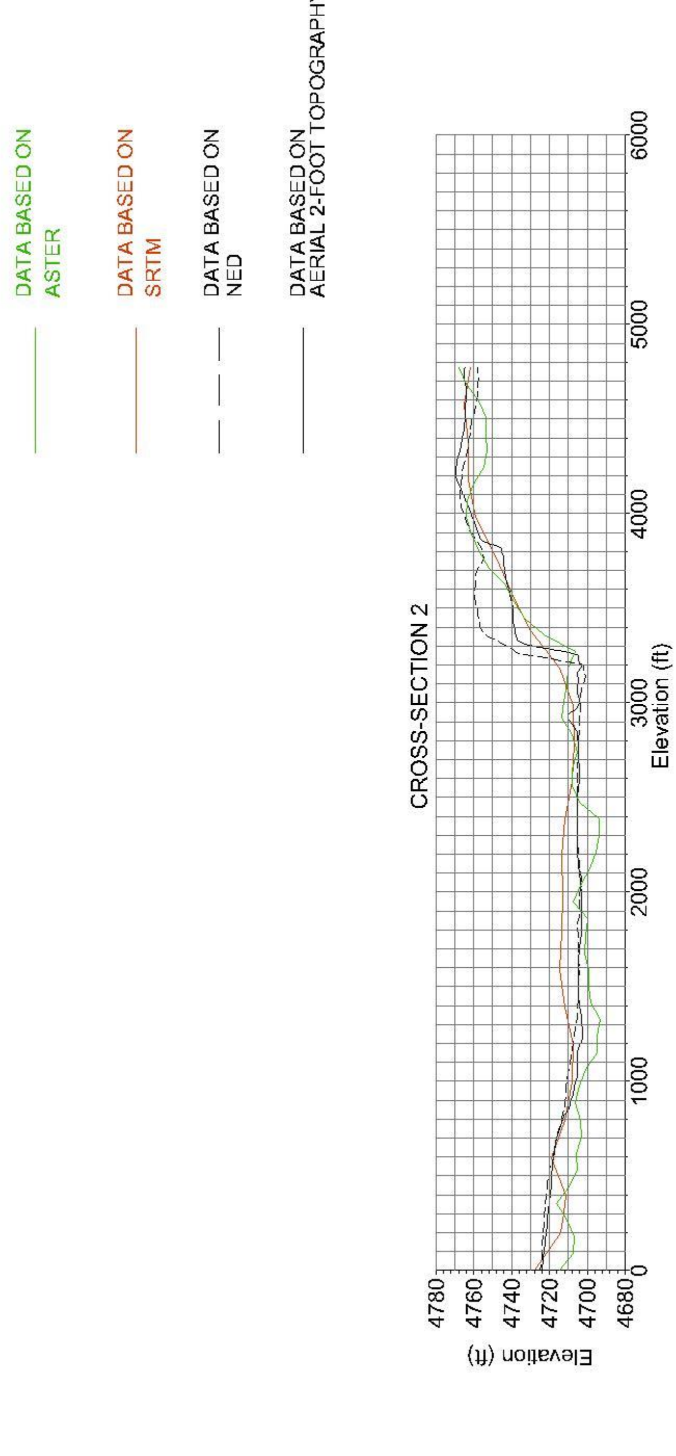
Conversion from the NGVD29 to the NAVD88 was done utilizing the NGS (National Geodedic Survey) online conversion calculator (http://www.ngs.noaa.gov/cgi-bin/VERTCON/vert_con.prl). A vertical conversion factor of +2.93 feet was utilized for the Greeley area to convert from NGVD29 to the NAVD88.

**Vicinity Map - Greeley, CO**

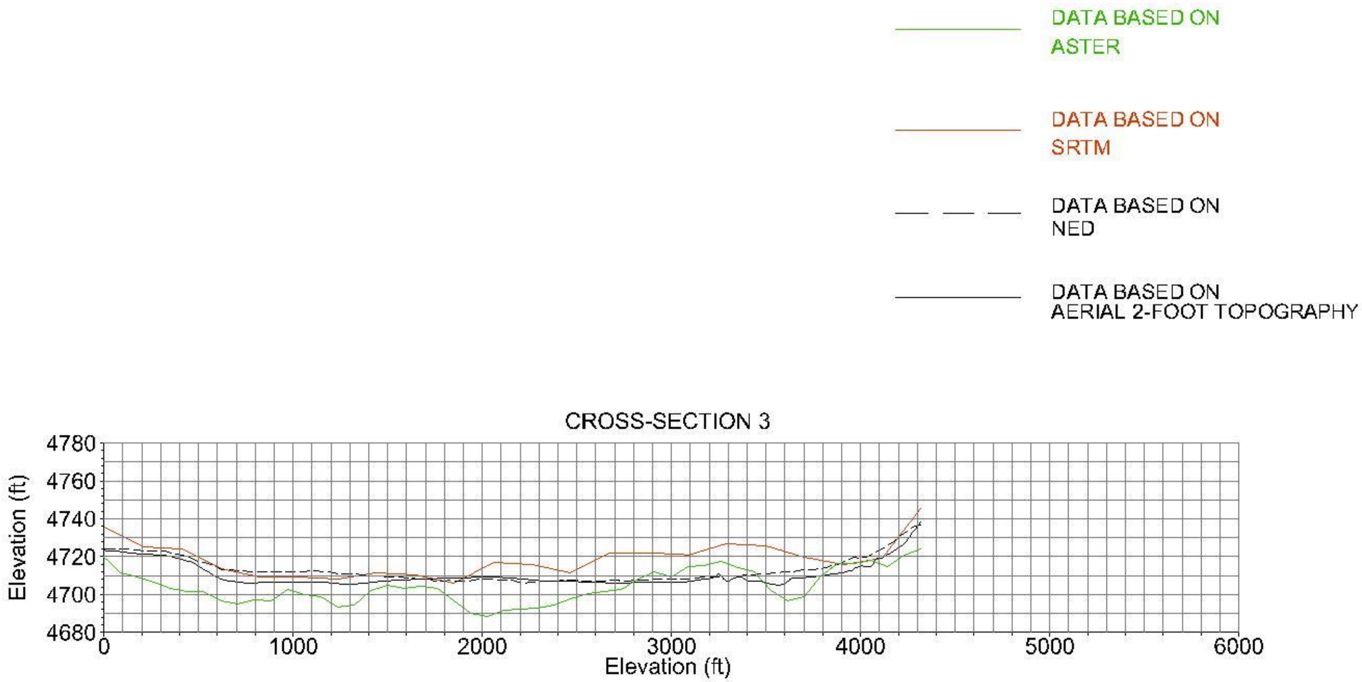


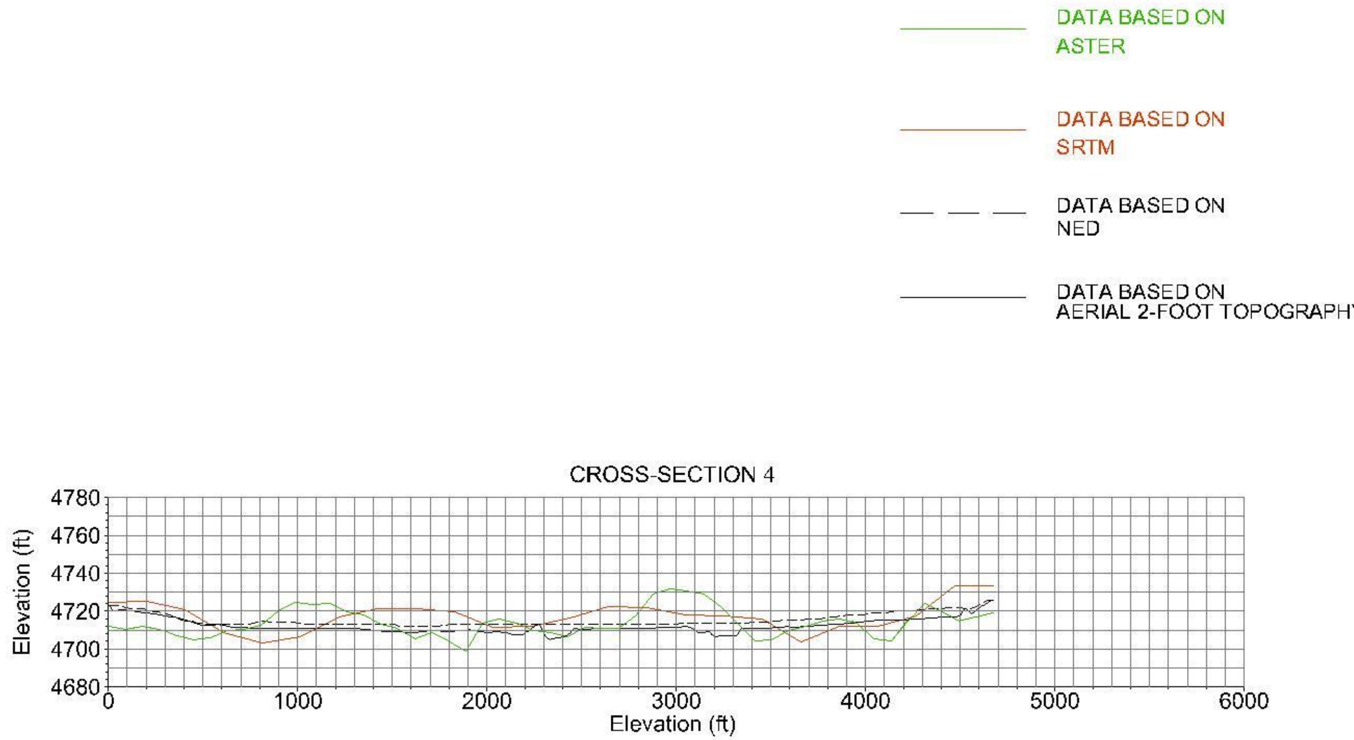

Projection: NAD 1983 HARN State Plane Colorado North FIPS 0501 Feet

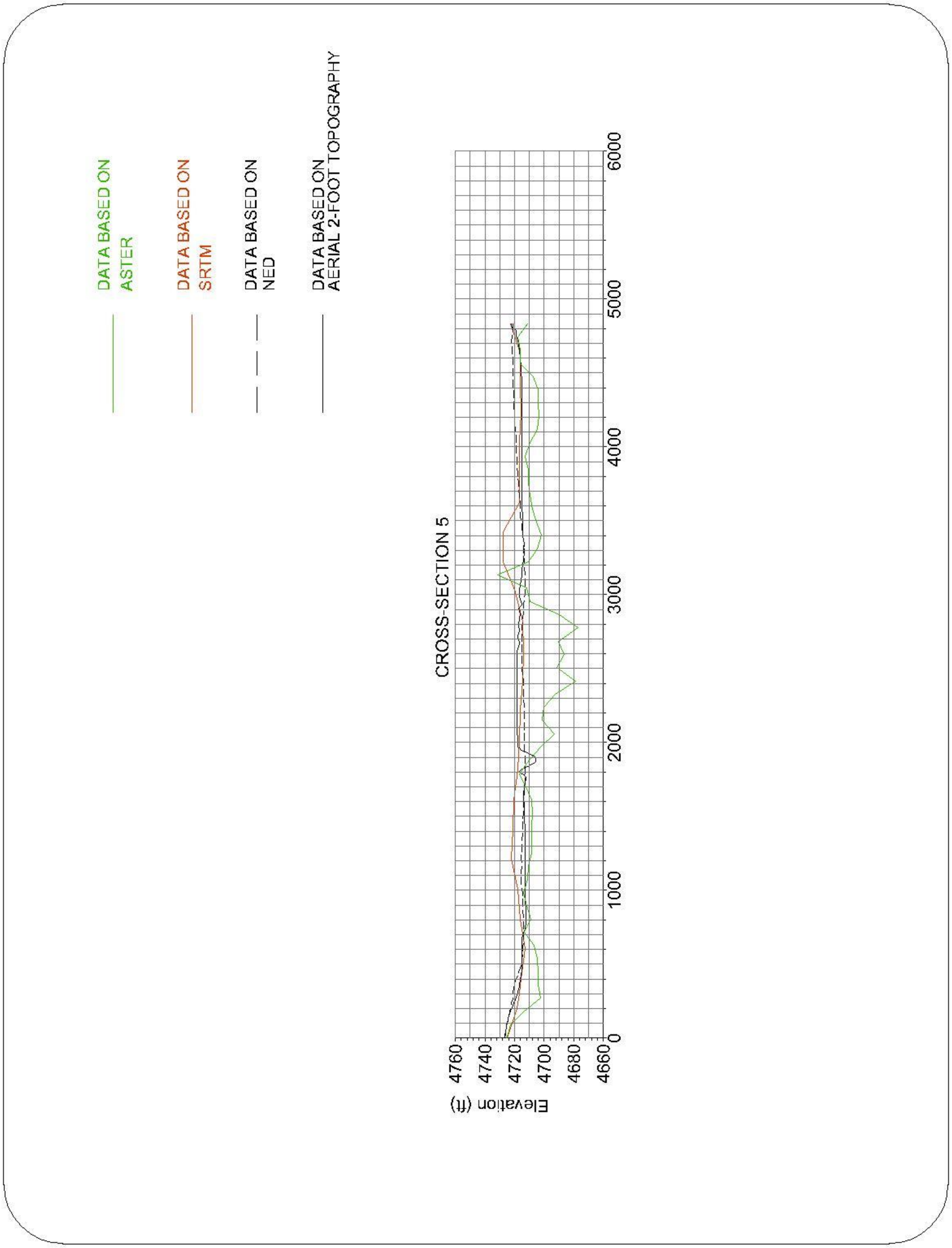

CROSS-SECTION 1
DATA BASED ON ASTER
DATA BASED ON SRTM
DATA BASED ON NED
DATA BASED ON AERIAL 2-FOOT TOPOGRAPHY
Elevation (ft)
4800
4780
4760
4740
4720
4700
4680
0
1000
2000
3000
4000
5000
6000
Elevation (ft)

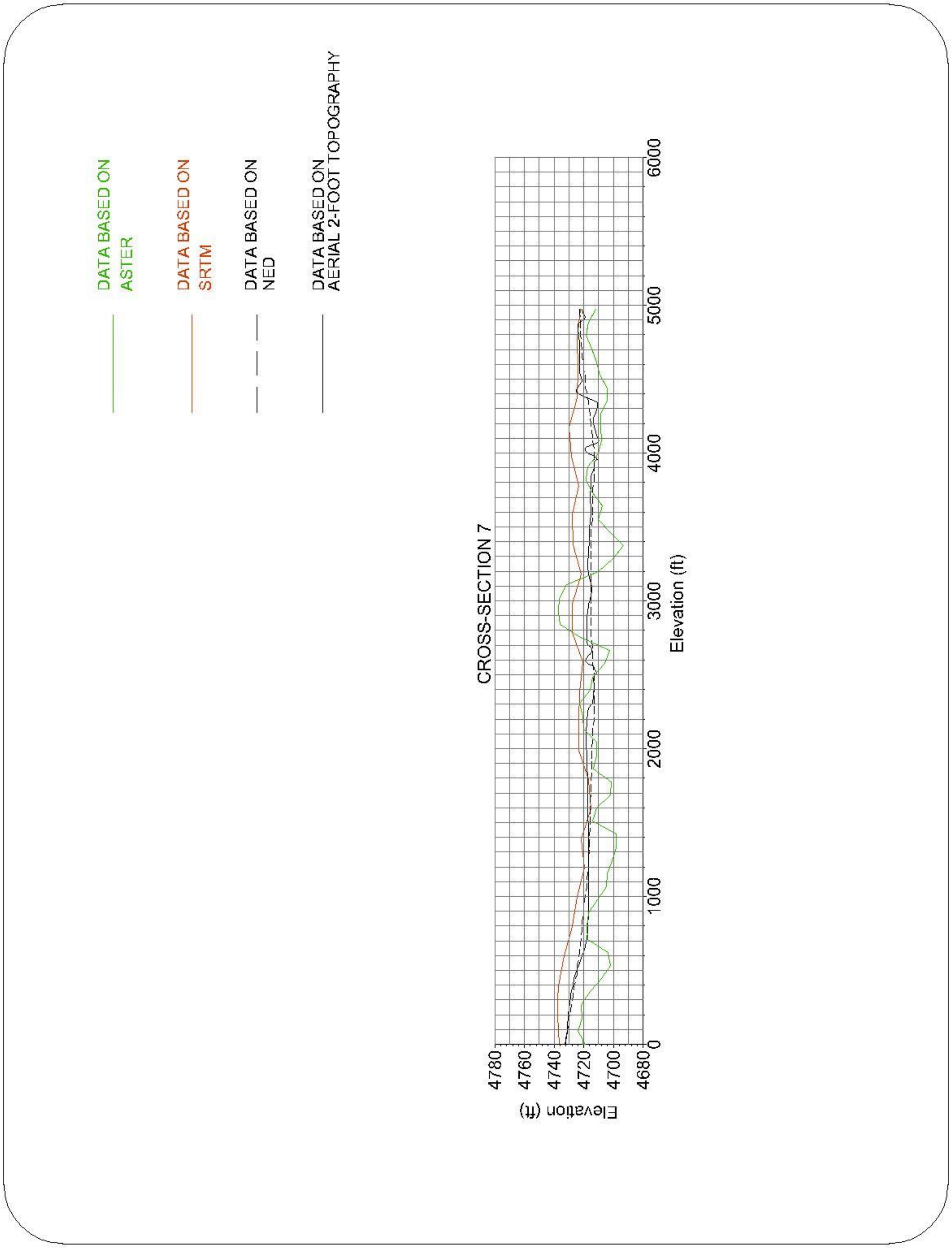


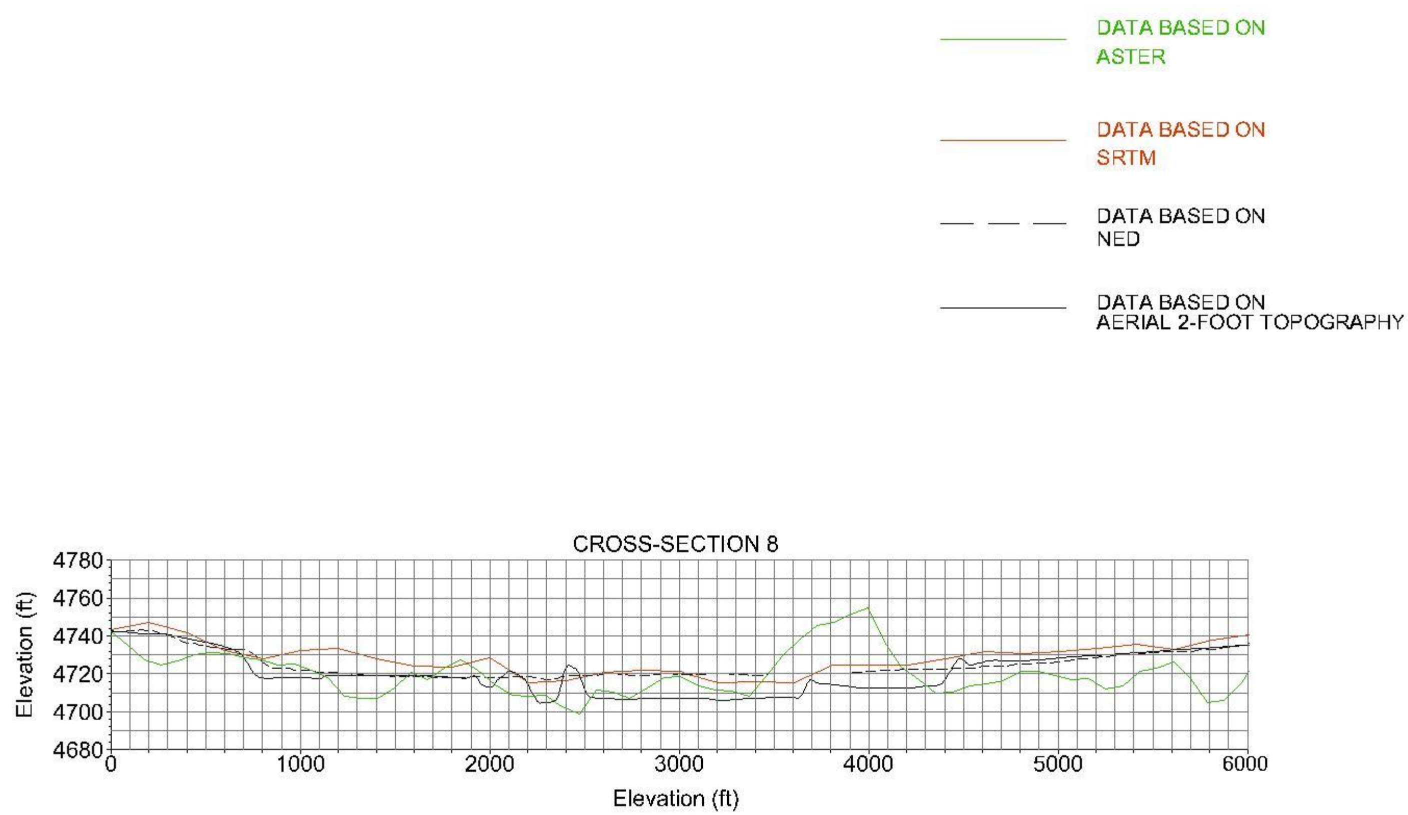
CROSS-SECTION 2
DATA BASED ON ASTER
DATA BASED ON SRTM
DATA BASED ON NED
DATA BASED ON AERIAL 2-FOOT TOPOGRAPHY
Elevation (ft)
4780
4760
4740
4720
4700
4680
0
1000
2000
3000
4000
5000
6000

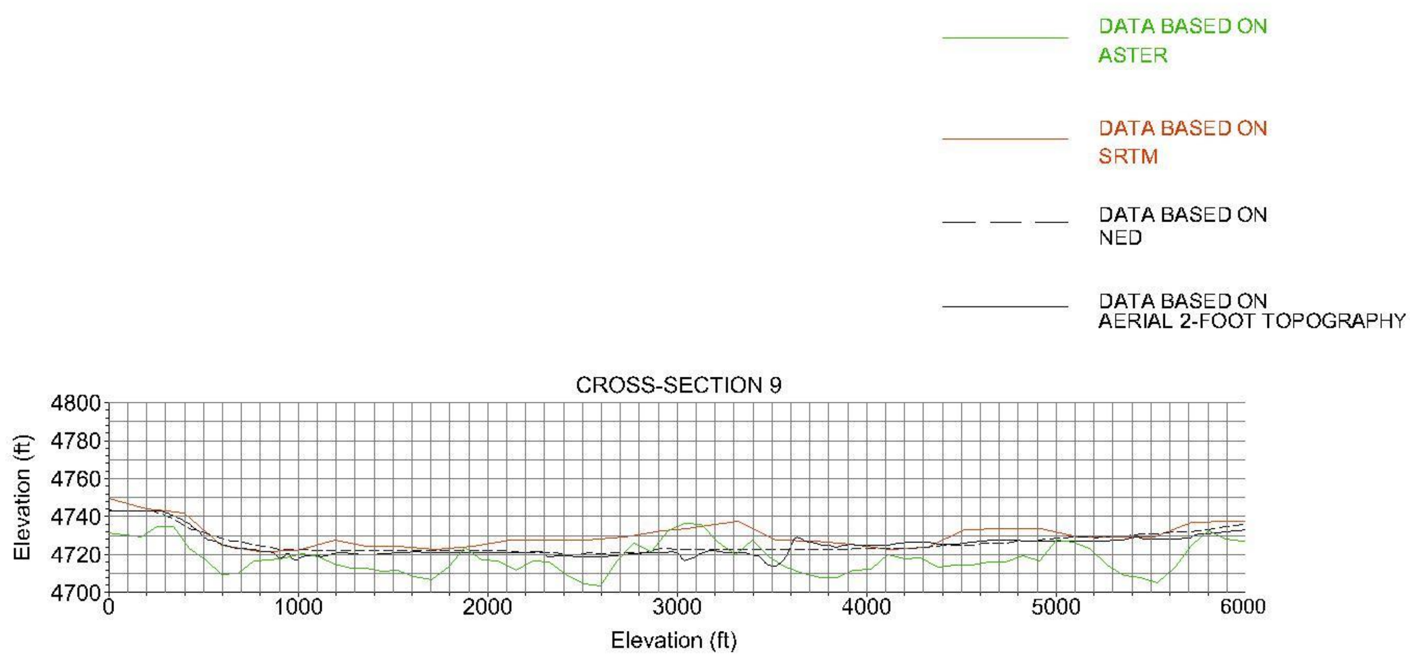

DATA BASED ON
ASTER
DATA BASED ON
SRTM
DATA BASED ON
NED
DATA BASED ON
AERIAL 2-FOOT TOPOGRAPHY
CROSS-SECTION 3
4780
4760
4740
4720
4700
4680
Elevation (ft)
0
1000
2000
3000
4000
5000
6000
Elevation (ft)

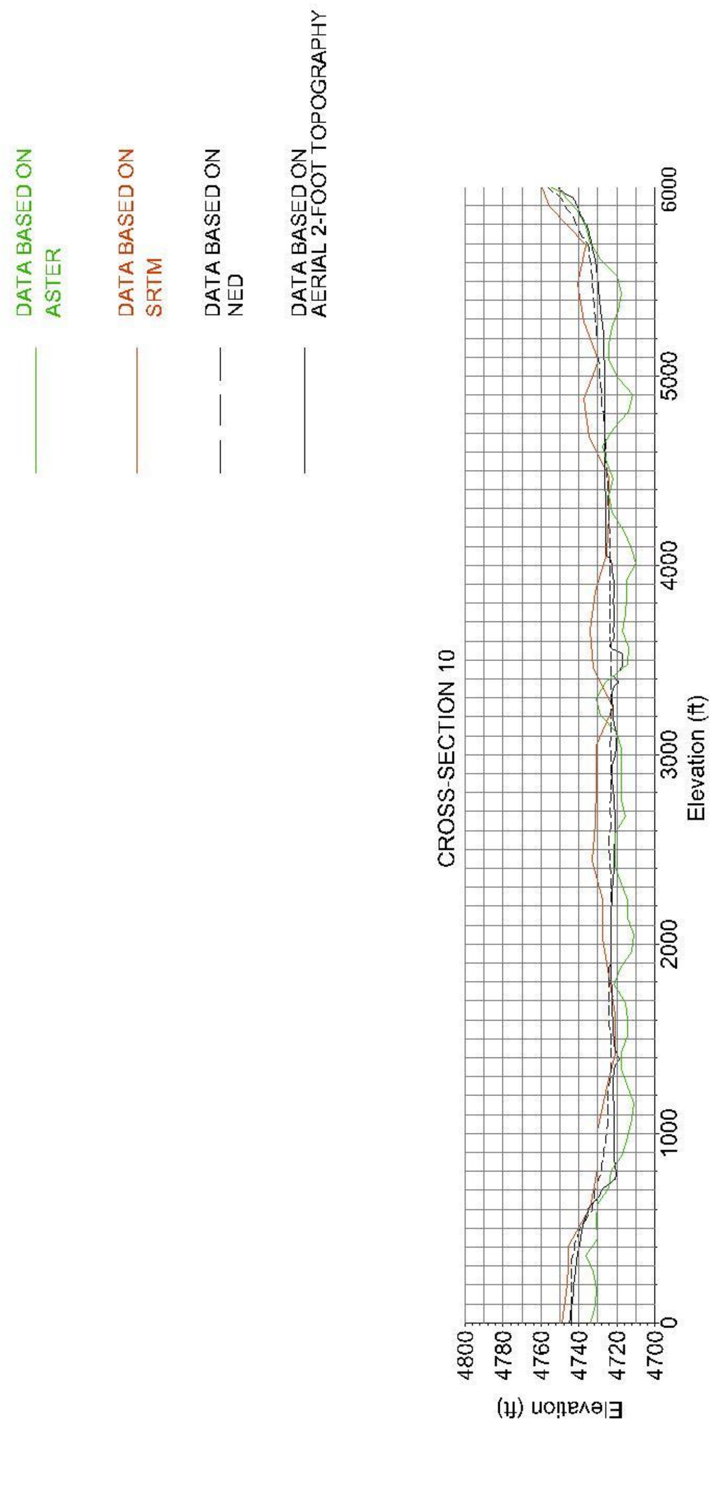

DATA BASED ON
ASTER
DATA BASED ON
SRTM
DATA BASED ON
NED
DATA BASED ON
AERIAL 2-FOOT TOPOGRAPHY
CROSS-SECTION 4
Elevation (ft)
4780
4760
4740
4720
4700
4680
0
1000
2000
3000
4000
5000
6000
Elevation (ft)

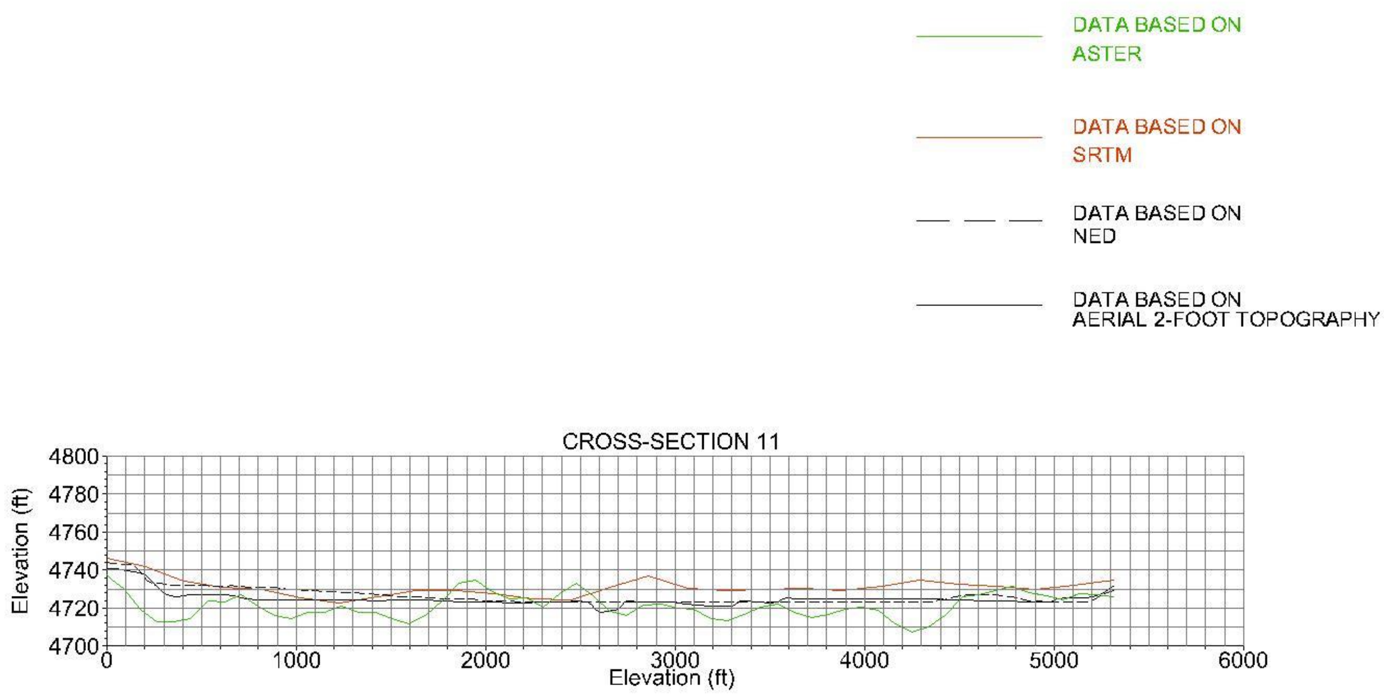

DATA BASED ON
ASTER
DATA BASED ON
SRTM
DATA BASED ON
NED
DATA BASED ON
AERIAL 2-FOOT TOPOGRAPHY
CROSS-SECTION 5
Elevation (ft)
4760
4740
4720
4700
4680
4660
0
1000
2000
3000
4000
5000
6000

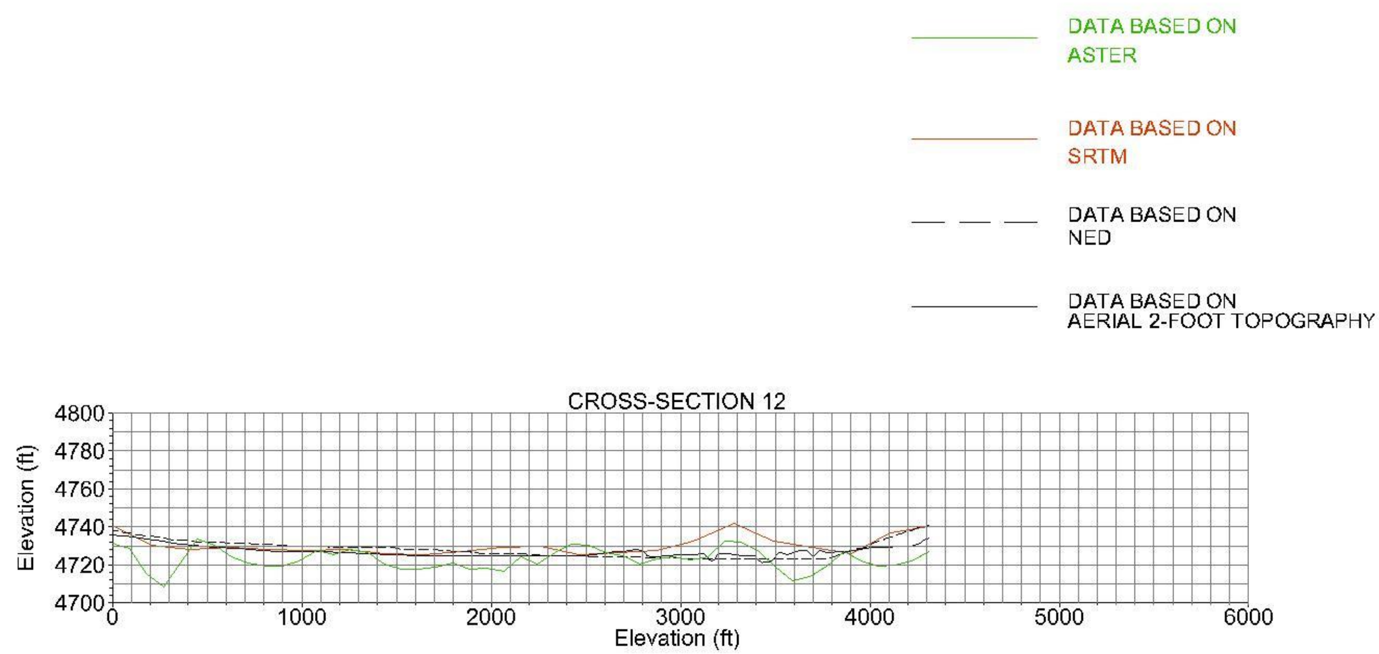

DATA BASED ON
ASTER
DATA BASED ON
SRTM
DATA BASED ON
NED
DATA BASED ON
AERIAL 2-FOOT TOPOGRAPHY
CROSS-SECTION 7
Elevation (ft)
Elevation (ft)
4780
4760
4740
4720
4700
4680
0
1000
2000
3000
4000
5000
6000

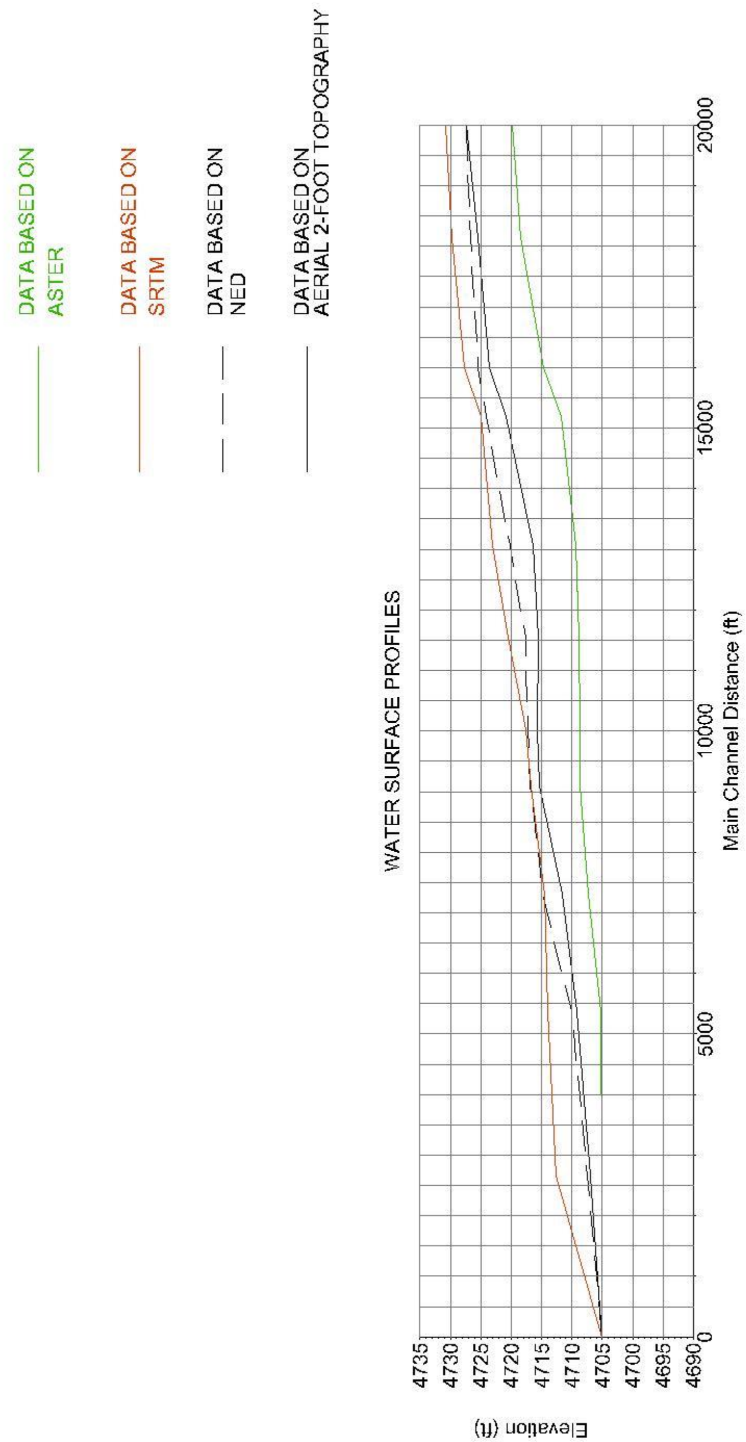

DATA BASED ON
ASTER
DATA BASED ON
SRTM
DATA BASED ON
NED
DATA BASED ON
AERIAL 2-FOOT TOPOGRAPHY
CROSS-SECTION 8
Elevation (ft)
4780
4760
4740
4720
4700
4680
0
1000
2000
3000
4000
5000
6000
Elevation (ft)


DATA BASED ON
ASTER
DATA BASED ON
SRTM
DATA BASED ON
NED
DATA BASED ON
AERIAL 2-FOOT TOPOGRAPHY
CROSS-SECTION 9
4800
4780
4760
4740
4720
4700
Elevation (ft)
0
1000
2000
3000
4000
5000
6000
Elevation (ft)


DATA BASED ON ASTER
DATA BASED ON SRTM
DATA BASED ON NED
DATA BASED ON AERIAL 2-FOOT TOPOGRAPHY
CROSS-SECTION 10
Elevation (ft)
4800
4780
4760
4740
4720
4700
0
1000
2000
3000
4000
5000
6000
Elevation (ft)


DATA BASED ON ASTER
DATA BASED ON SRTM
DATA BASED ON NED
DATA BASED ON AERIAL 2-FOOT TOPOGRAPHY
CROSS-SECTION 11
4800
4780
4760
4740
4720
4700
Elevation (ft)
0
1000
2000
3000
4000
5000
6000
Elevation (ft)

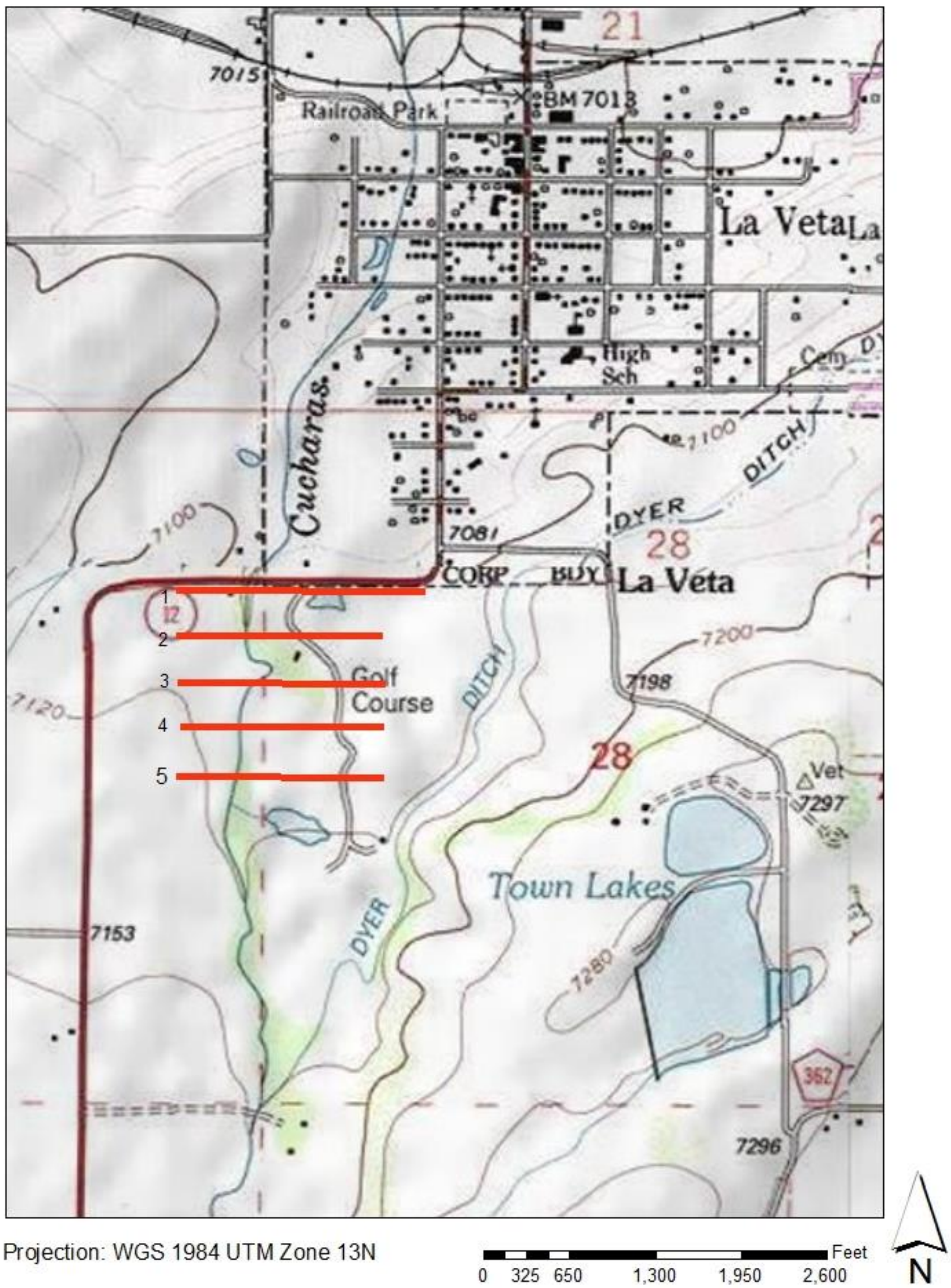

DATA BASED ON
ASTER
DATA BASED ON
SRTM
DATA BASED ON
NED
DATA BASED ON
AERIAL 2-FOOT TOPOGRAPHY
CROSS-SECTION 12
4800
4780
4760
4740
4720
4700
Elevation (ft)
0
1000
2000
3000
4000
5000
6000
Elevation (ft)

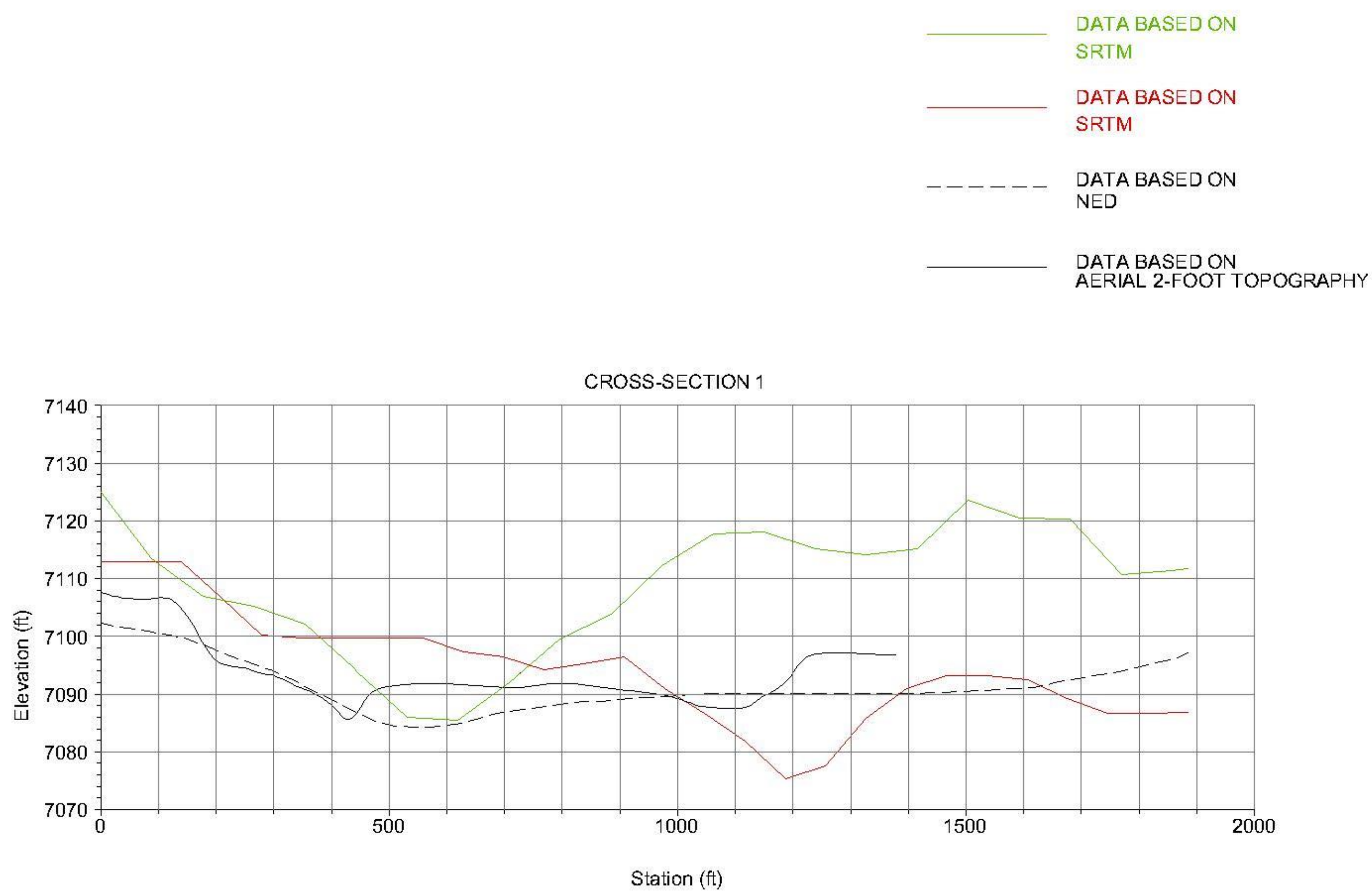

WATER SURFACE PROFILES
DATA BASED ON ASTER
DATA BASED ON SRTM
DATA BASED ON NED
DATA BASED ON AERIAL 2-FOOT TOPOGRAPHY
Elevation (ft)
4735
4730
4725
4720
4715
4710
4705
4700
4695
4690
Main Channel Distance (ft)
0
5000
10000
15000
20000

### 3.1.14 Results – La Veta, Colorado

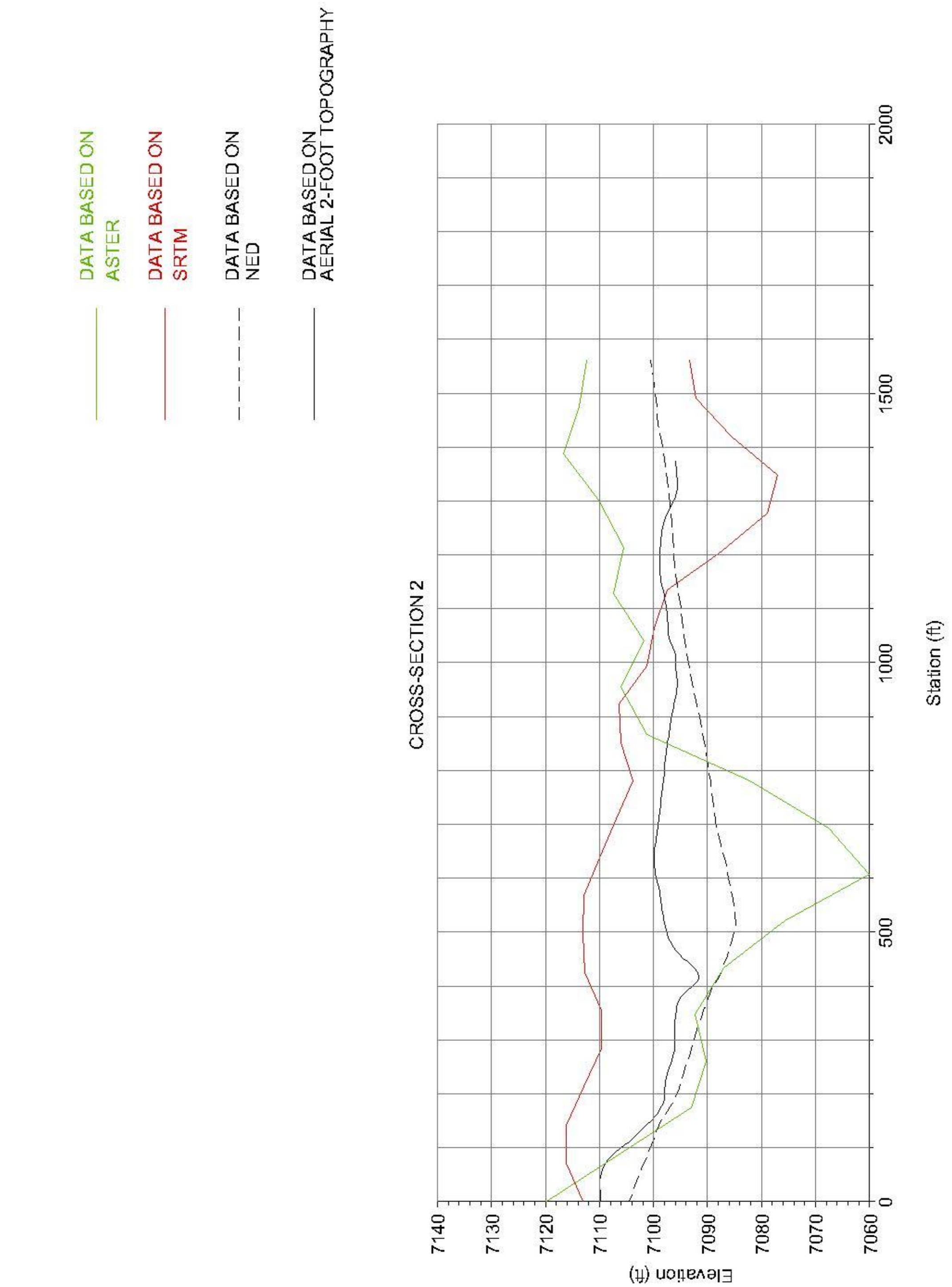
The following cross-section plots for La Veta, Colorado show NED data as a dashed black line, data from a local source (2-foot interval aerial topographic mapping) as a solid black line, ASTER data as a solid green line, and SRTM data as a solid red line. NED elevation data is referenced to the NAVD88 vertical datum, which is an orthometric elevation model. Data from the 2-foot interval aerial topographic mapping is referenced to the NGVD29 vertical datum, which is also an orthometric elevation model. SRTM data is referenced to the EGM96 which is a geoid elevation model

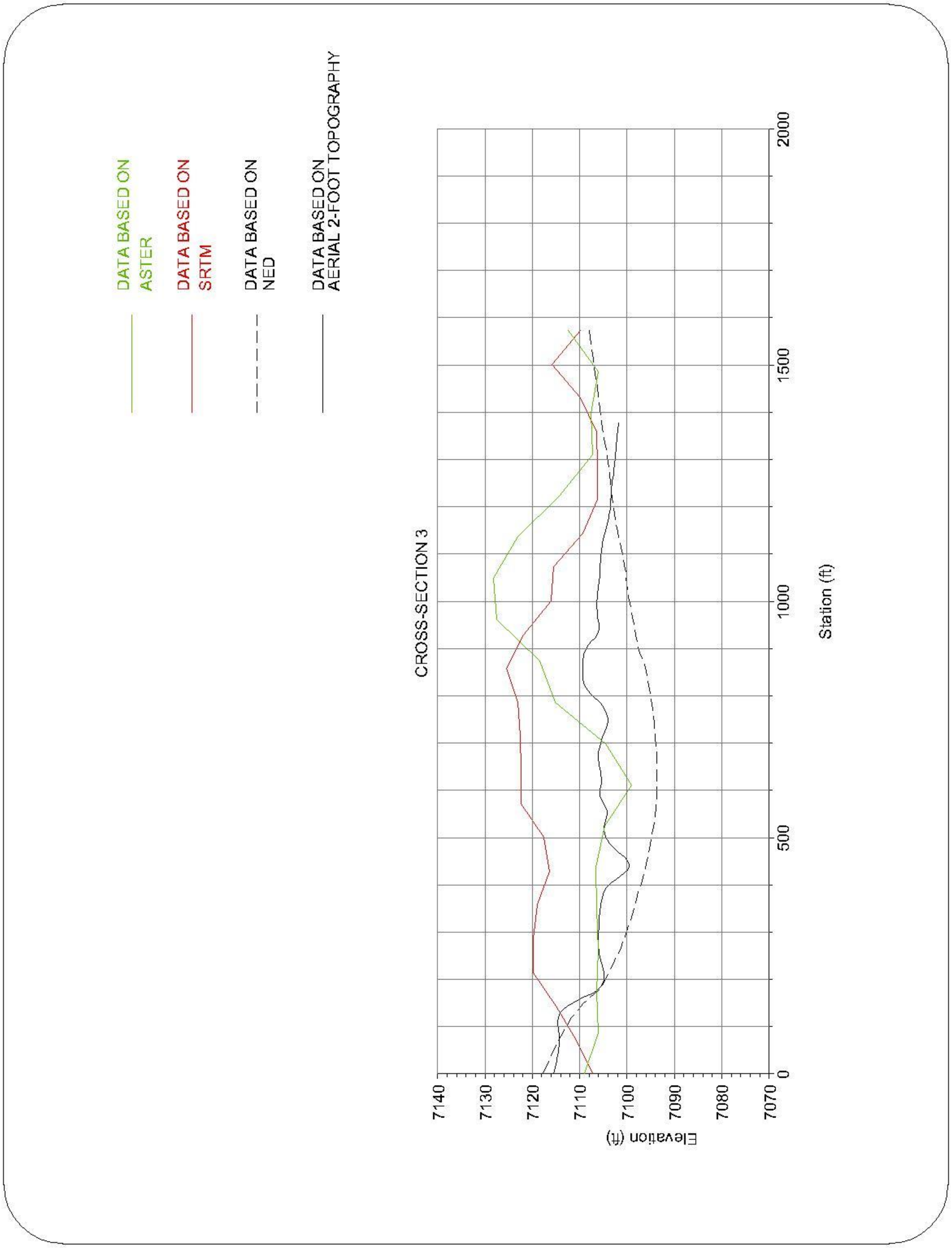
## Vicinity Map - La Veta, CO

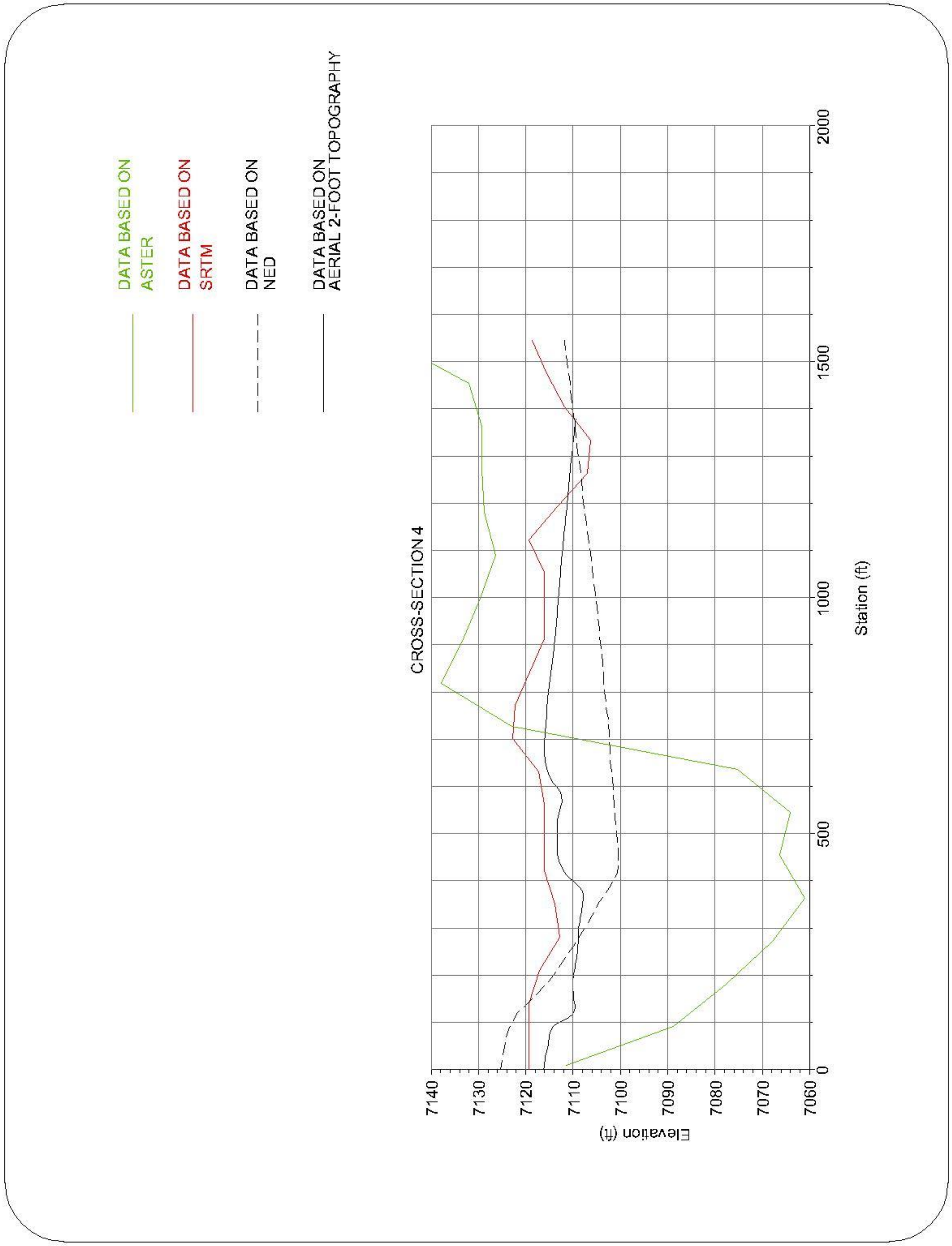


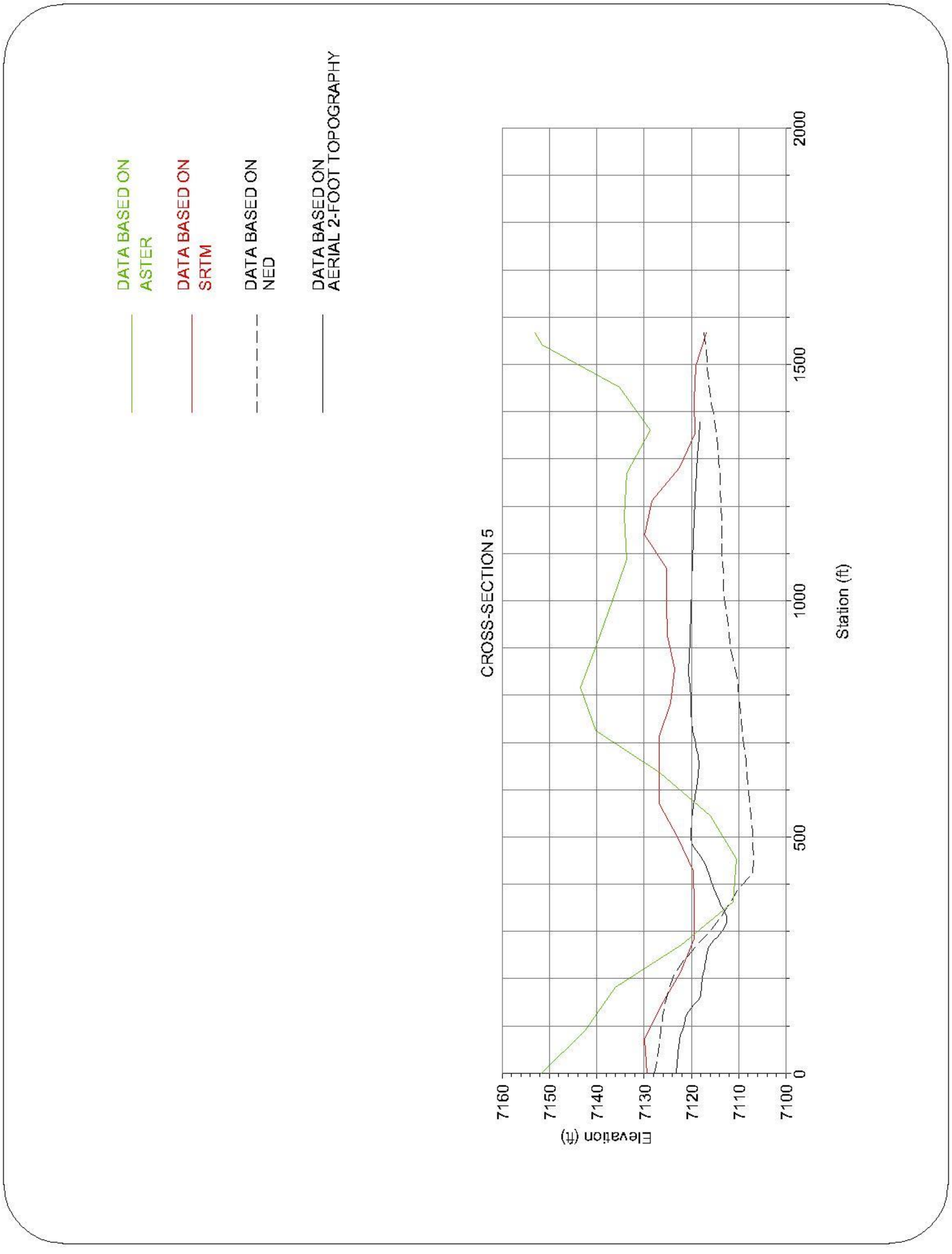


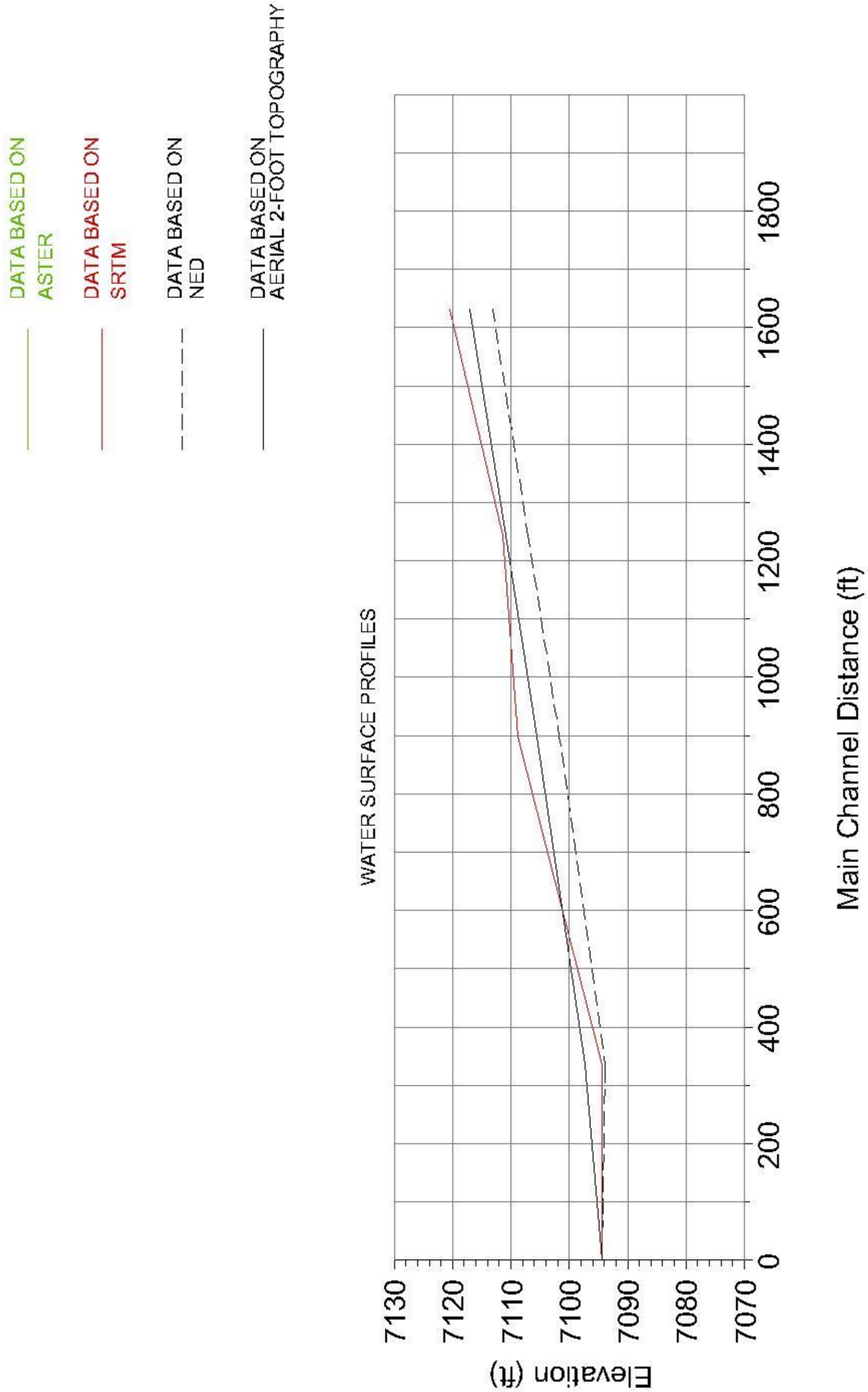
DATA BASED ON
SRTM
DATA BASED ON
SRTM
DATA BASED ON
NED
DATA BASED ON
AERIAL 2-FOOT TOPOGRAPHY
CROSS-SECTION 1
7140
7130
7120
7110
7100
7090
7080
7070
Elevation (ft)
0
500
1000
1500
2000
Station (ft)


CROSS-SECTION 2
DATA BASED ON ASTER
DATA BASED ON SRTM
DATA BASED ON NED
DATA BASED ON AERIAL 2-FOOT TOPOGRAPHY
Elevation (ft)
7140
7130
7120
7110
7100
7090
7080
7070
7060
Station (ft)
0
500
1000
1500
2000


CROSS-SECTION 3
DATA BASED ON ASTER
DATA BASED ON SRTM
DATA BASED ON NED
DATA BASED ON AERIAL 2-FOOT TOPOGRAPHY
Elevation (ft)
7140
7130
7120
7110
7100
7090
7080
7070
Station (ft)
0
500
1000
1500
2000


CROSS-SECTION 4
DATA BASED ON ASTER
DATA BASED ON SRTM
DATA BASED ON NED
DATA BASED ON AERIAL 2-FOOT TOPOGRAPHY
Elevation (ft)
Station (ft)
7140
7130
7120
7110
7100
7090
7080
7070
7060
0
500
1000
1500
2000


CROSS-SECTION 5
DATA BASED ON ASTER
DATA BASED ON SRTM
DATA BASED ON NED
DATA BASED ON AERIAL 2-FOOT TOPOGRAPHY
Elevation (ft)
7160
7150
7140
7130
7120
7110
7100
Station (ft)
0
500
1000
1500
2000


WATER SURFACE PROFILES
DATA BASED ON ASTER
DATA BASED ON SRTM
DATA BASED ON NED
DATA BASED ON AERIAL 2-FOOT TOPOGRAPHY
Elevation (ft)
7130
7120
7110
7100
7090
7080
7070
Main Channel Distance (ft)
0
200
400
600
800
1000
1200
1400
1600
1800

### 3.1.15 Small Scale Data Analysis

Small scale data analysis of the SRTM and ASTER data was conducted by comparison of SRTM and ASTER data with one another. Both data sets are referenced to the 1996 Earth Gravitational Model (EGM96), which is a geoid-based model.

Ten cross-sections have been analyzed throughout the Lower Mekong Basin as shown on the following vicinity map. Cross-sectional information has been displayed graphically in the following pages to provide the reader with a visual sense of how the SRTM data compares to the ASTER data.

As seen in the following results section, comparison of SRTM to ASTER data in a cross-sectional format shows somewhat better consistency between the data sets in areas with more topographic relief (Laos), and less consistency between the data sets in areas which have flat topography (Cambodia and Vietnam).

### 3.1.16 Methodology – Small Scale Data Analysis

Data was managed and manipulated using the Geographic Information System ArcMap by ESRI. The SRTM data was freely downloaded at the Earth Explorer website (www.earthexplorer.usgs.gov). When downloaded, the SRTM data comes as a raster grid that is readily utilized in ArcMap, and is on a geographic coordinate system. ArcMap was utilized to re-project the data into a projected coordinate system. All SRTM data sets were re-projected into the UTM (Universal Transvers Mercator) system.

The ASTER data was freely downloaded at the USGS Global Data Explorer website (http://demex.cr.usgs.gov/DEMEX/). This data is downloaded as a raster grid that is readily utilized in ArcMap. The data from this site can be downloaded on either a geographic or projected coordinate system. All data downloaded for this research was downloaded on the UTM system.

The digital elevation models for the SRTM, and ASTER data sets were incorporated in a single ArcMap document in order for comparative analysis of river cross-sections to be performed.

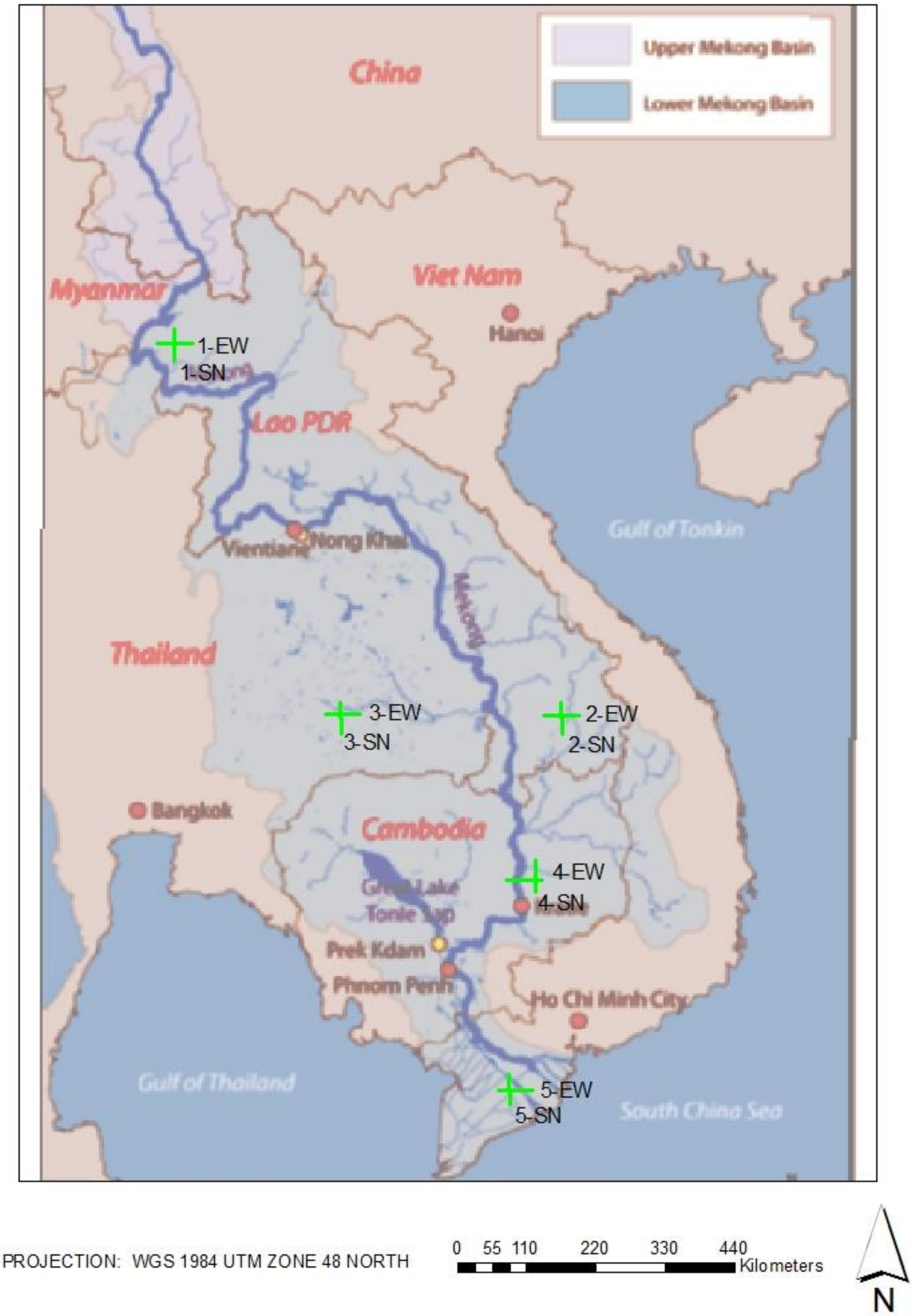
Using HEC-geoRAS, cross-sections were cut through the digital elevation models (DEM). River cross-sections based on the DEMs are shown in the following Results section. Cross-sections based on the SRTM data is shown as a solid red line, cross-sections based on the ASTER data is shown as a solid green line.

Cross-sections have been displayed graphically for visual comparison. For the purposes of this study, it was felt that graphical plots of the cross-sections would provide the most meaningful comparison. The graphical plots have been exaggerated vertically such that the vertical scale is one hundred times that of the horizontal.

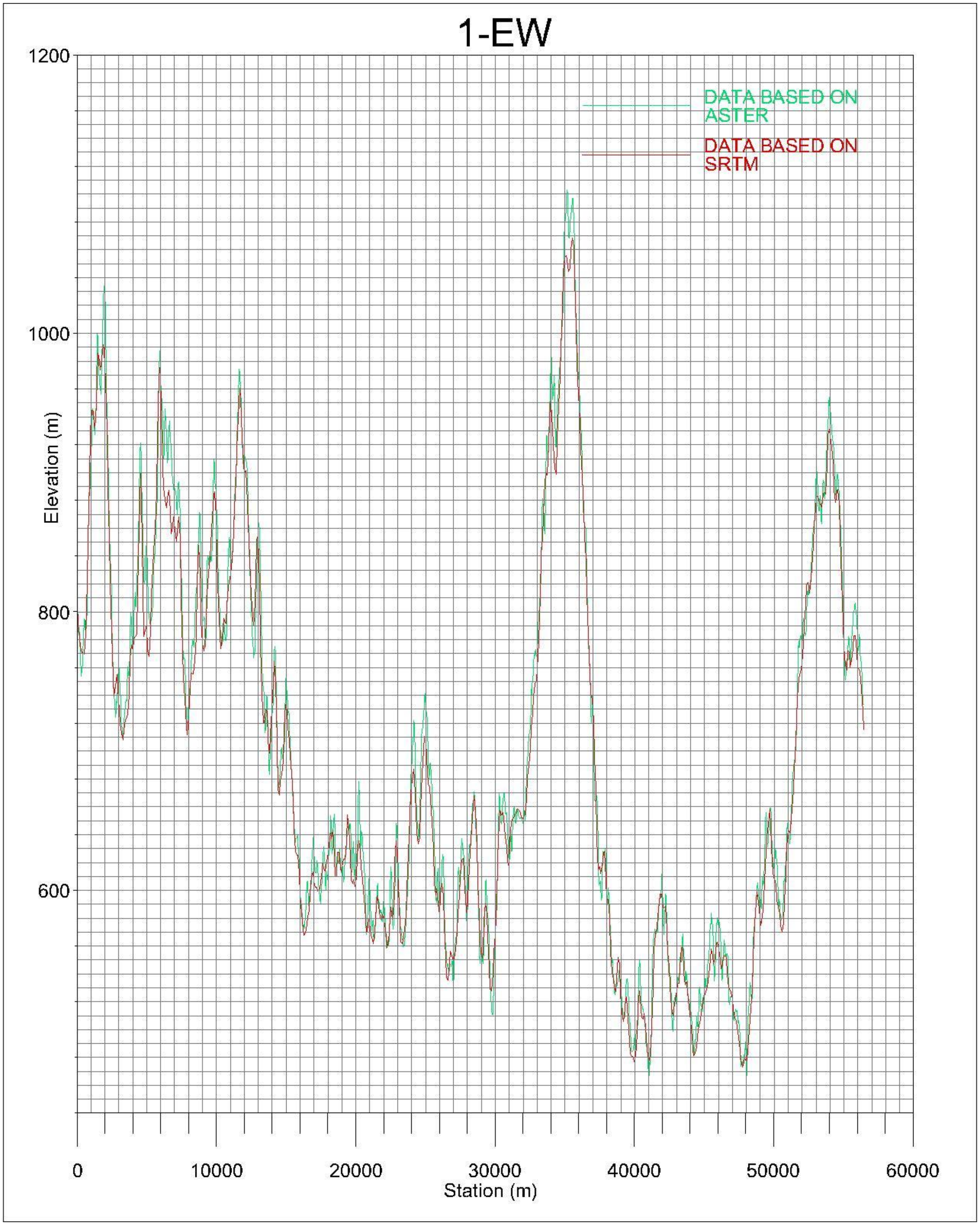
### 3.1.17 Results – Lower Mekong Basin

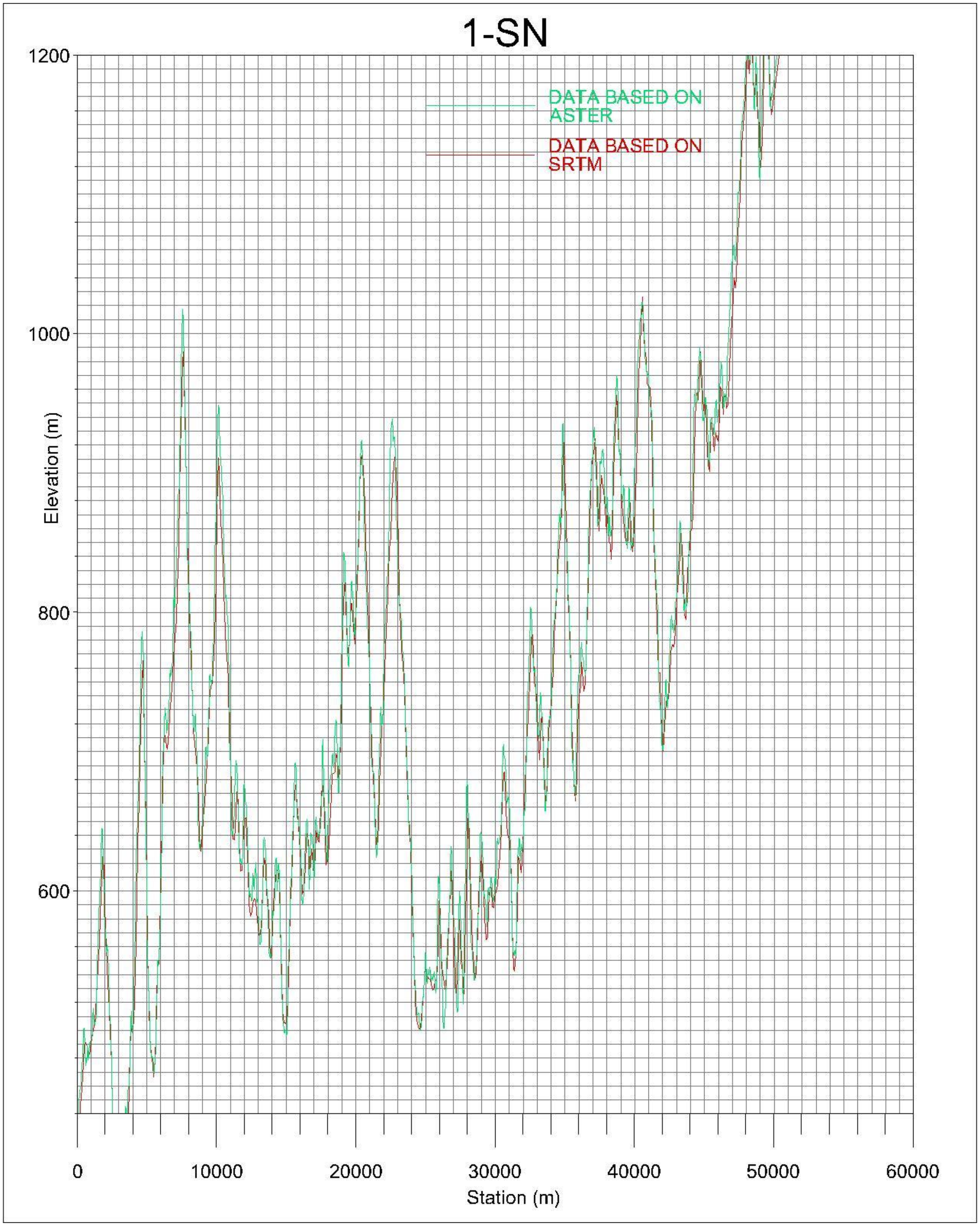
The following cross-section plots for Lower Mekong Basin show SRTM data as a solid red line, and ASTER data a solid green line. As discussed above SRTM and ASTER elevation data is referenced to the EGM96 vertical datum.

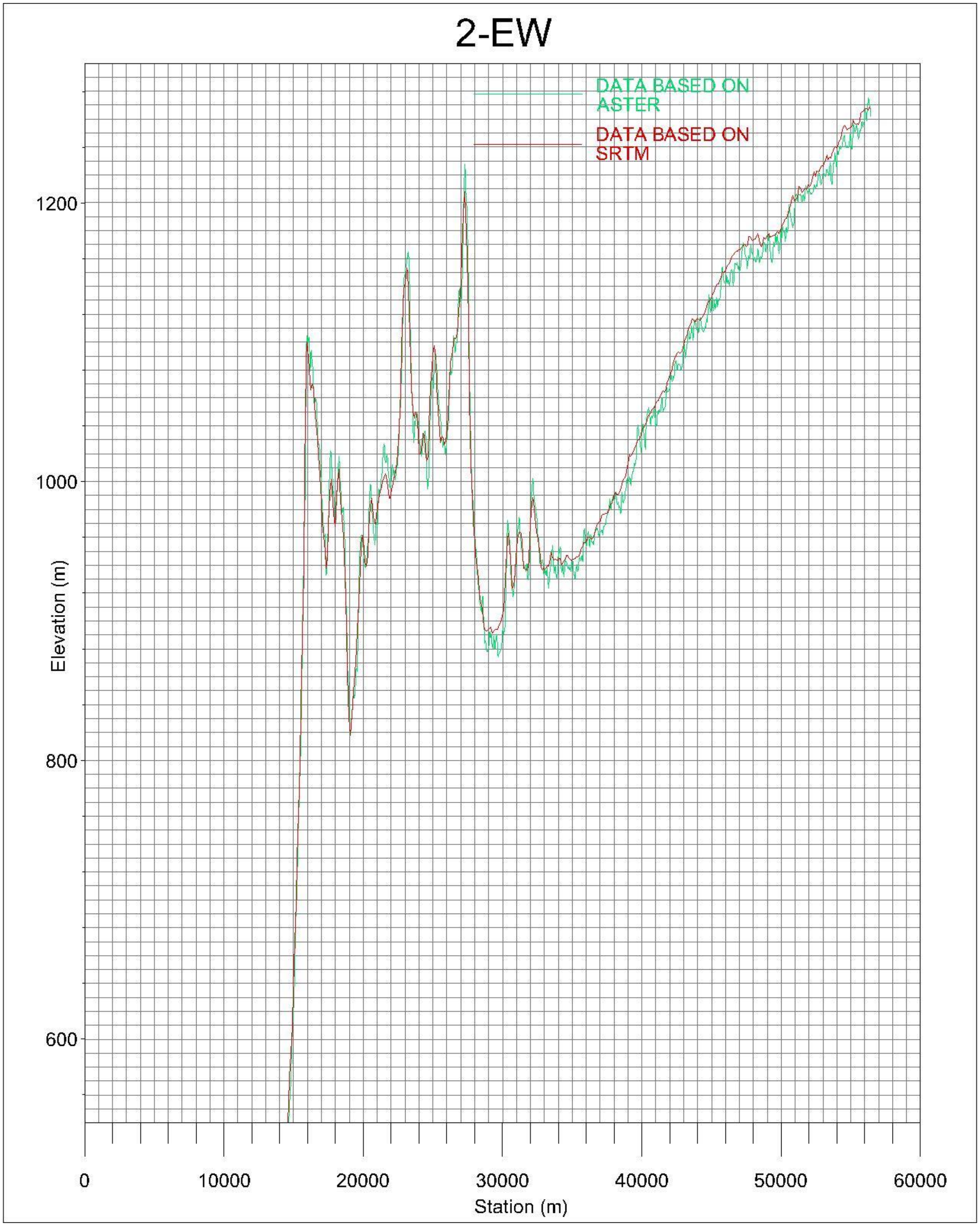
**VICINITY MAP - LOWER MEKONG BASIN**



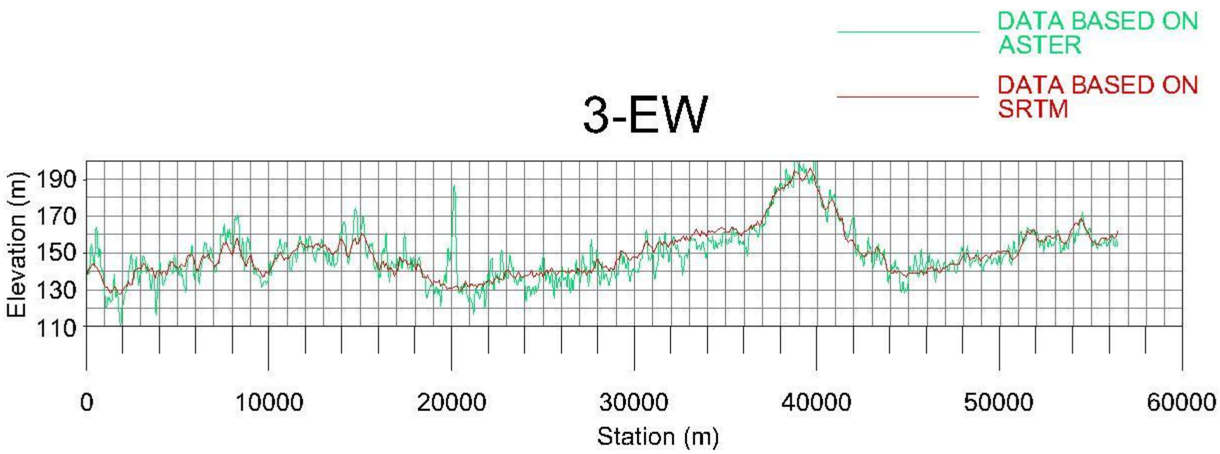

PROJECTION: WGS 1984 UTM ZONE 48 NORTH

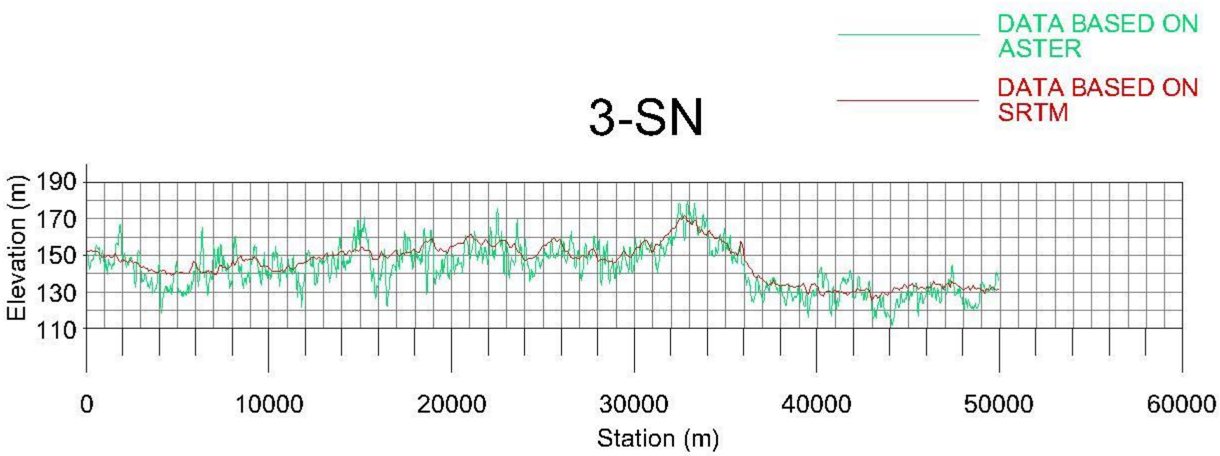

1-EW
DATA BASED ON ASTER
DATA BASED ON SRTM
Elevation (m)
1200
1000
800
600
0
10000
20000
30000
40000
50000
60000
Station (m)

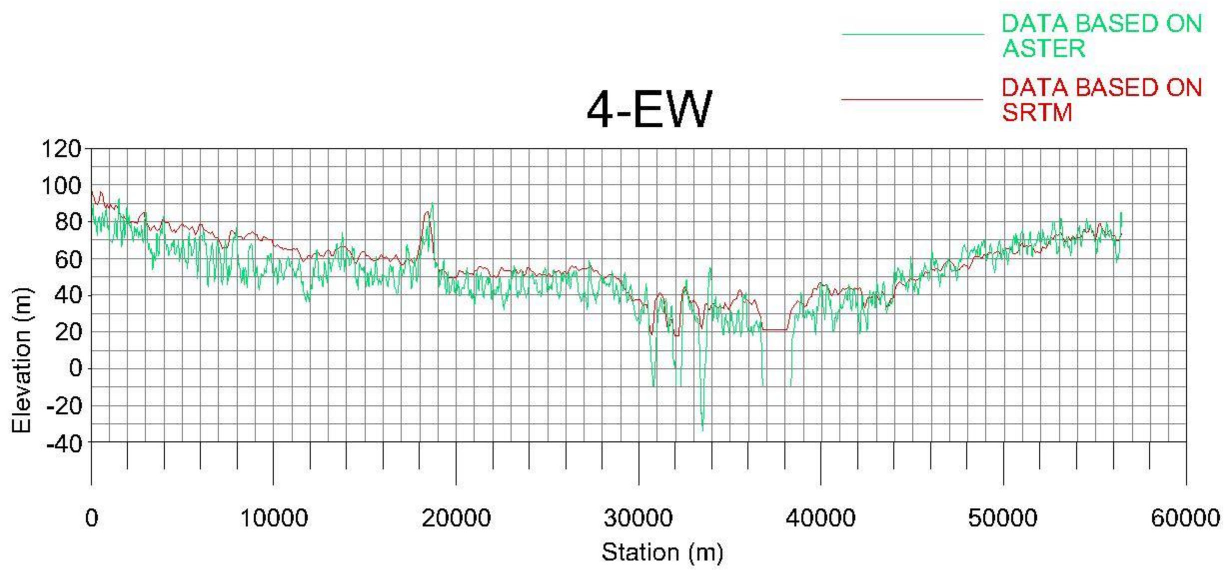

1-SN
DATA BASED ON ASTER
DATA BASED ON SRTM
Elevation (m)
1200
1000
800
600
0
10000
20000
30000
40000
50000
60000
Station (m)


2-EW
DATA BASED ON ASTER
DATA BASED ON SRTM
1200
1000
800
600
Elevation (m)
0
10000
20000
30000
40000
50000
60000
Station (m)

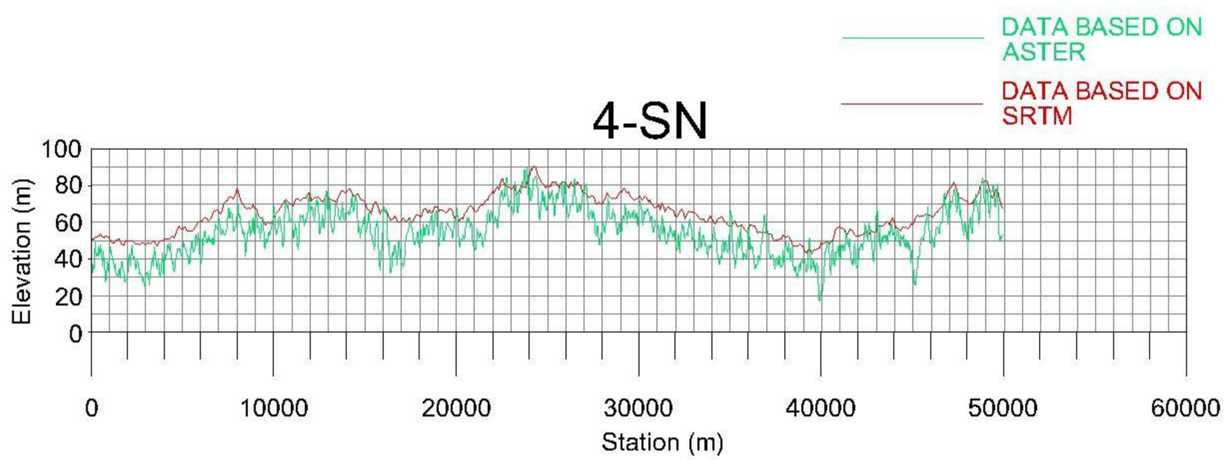

2-SN
DATA BASED ON ASTER
DATA BASED ON SRTM
1200
1000
800
600
Elevation (m)
0
10000
20000
30000
40000
50000
60000
Station (m)


DATA BASED ON ASTER
DATA BASED ON SRTM
3-EW
Elevation (m)
190
170
150
130
110
0
10000
20000
30000
40000
50000
60000
Station (m)

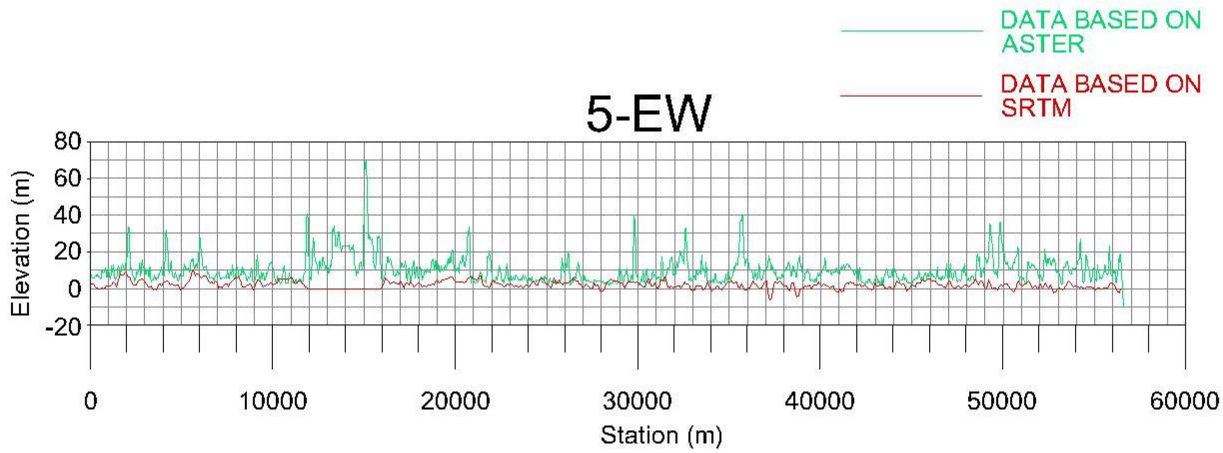

DATA BASED ON ASTER
DATA BASED ON SRTM
3-SN
Elevation (m)
190
170
150
130
110
0
10000
20000
30000
40000
50000
60000
Station (m)

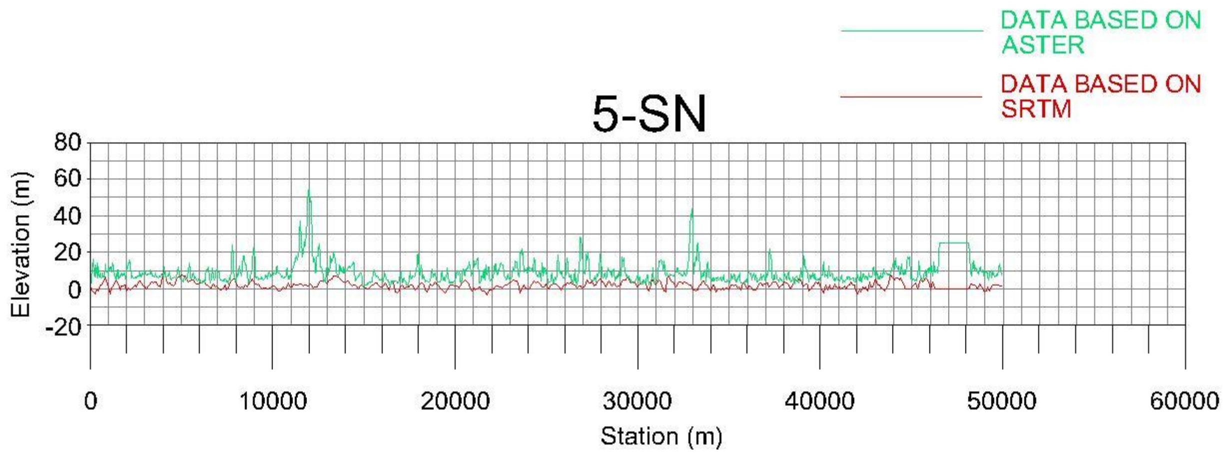


DATA BASED ON ASTER
DATA BASED ON SRTM
4-EW
120
100
80
60
40
20
0
-20
-40
Elevation (m)
0
10000
20000
30000
40000
50000
60000
Station (m)

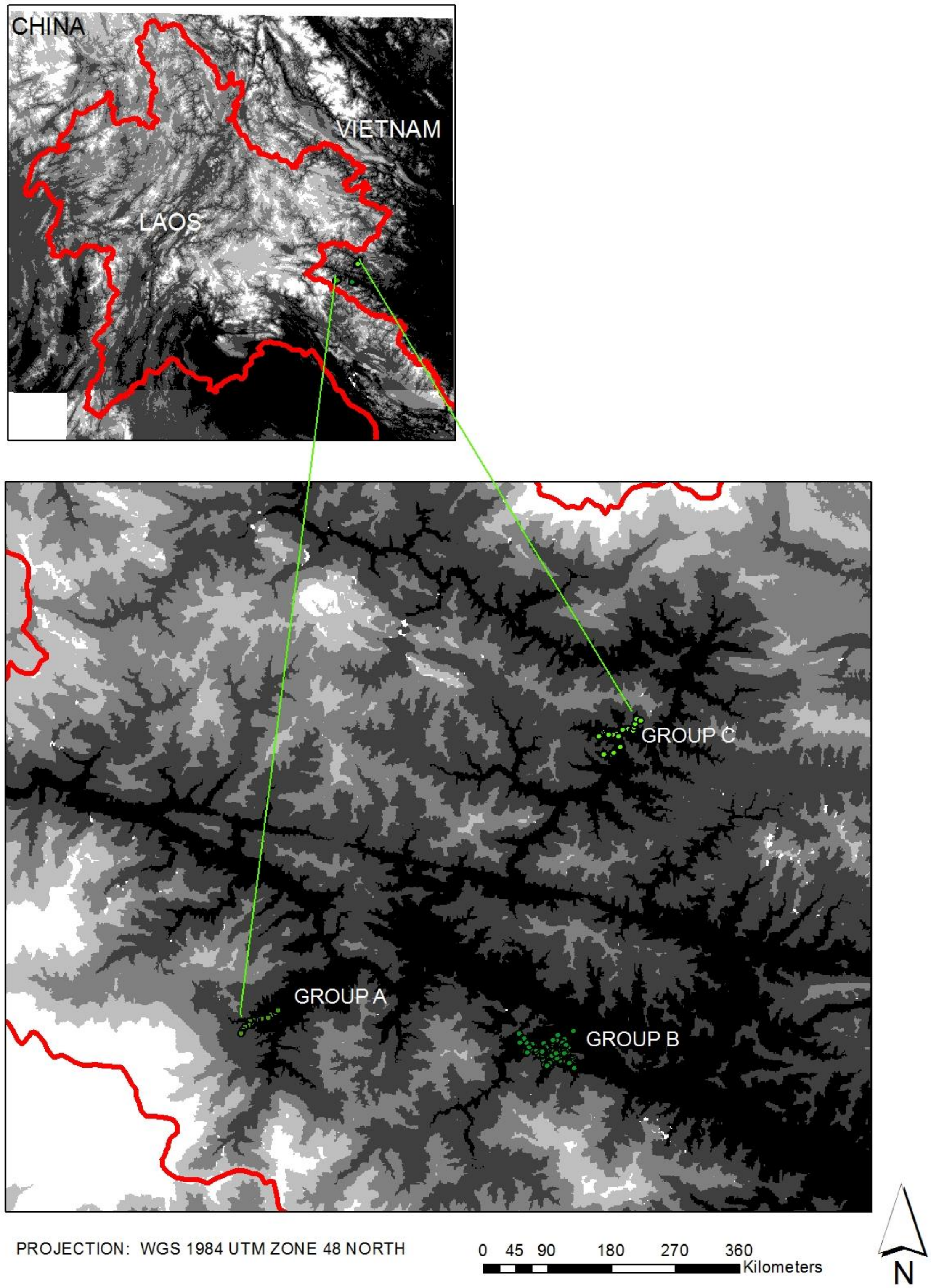
DATA BASED ON ASTER
DATA BASED ON SRTM
4-SN
100
80
60
40
20
0
Elevation (m)
0
10000
20000
30000
40000
50000
60000
Station (m)


DATA BASED ON ASTER
DATA BASED ON SRTM
5-EW
Elevation (m)
Station (m)


DATA BASED ON ASTER
DATA BASED ON SRTM
5-SN
Elevation (m)
Station (m)

### 3.1.18 Point Elevation Comparison

Point data has was compared in order to gain a sense of the validity of the SRTM and ASTER data sets. Professor Stephen Leisz, Colorado State University Geography Department, provided ground elevations which he personally surveyed in Northwestern Vietnam in 2001 - 2005. These ground elevations have been imported in ArcMap with the SRTM and ASTER data sets overlayed on a common projection and coordinate basis (UTM Zone 48 North, WGS 1984). The following maps show the locations of several groups of point elevations provided by Professor Leisz.


CHINA
VIETNAM
LAOS
GROUP C
GROUP A
GROUP B
PROJECTION: WGS 1984 UTM ZONE 48 NORTH
0 45 90 180 270 360
Kilometers
N

Thirty random points have been selected from Professor Leisz's data. The following table summarizes elevations from the Leisz point data, SRTM data, and ASTER data.

GROUP A

| POINT | EASTING (UTM 48N) | NORTHING (UTM 48N) | LEISZ ELEV (m) | ASTER ELEV (m) | DIFFERENCE (FROM LEISZ,m) | SRTM ELEV (m) | DIFFERENCE (FROM LEISZ,m) |
|---|---|---|---|---|---|---|---|
| 1 | 423533 | 2125700 | 333 | 317 | -16 | 329 | -4 |
| 2 | 423710 | 2126001 | 324 | 331 | 7 | 302 | -22 |
| 3 | 424169 | 2126424 | 269 | 284 | 15 | 280 | 11 |
| 4 | 425217 | 2126958 | 216 | 218 | 2 | 213 | -3 |
| 5 | 423878 | 2126263 | 297 | 293 | -4 | 287 | -10 |
| 6 | 426069 | 2127256 | 183 | 195 | 12 | 185 | 2 |
| 7 | 424562 | 2126799 | 244 | 241 | -3 | 245 | 1 |
| 8 | 426580 | 2127603 | 187 | 216 | 29 | 206 | 19 |
| 9 | 426405 | 2127469 | 187 | 205 | 18 | 201 | 14 |
| 10 | 424905 | 2126858 | 219 | 228 | 9 | 222 | 3 |

GROUP B

| POINT | EASTING (UTM 48N) | NORTHING (UTM 48N) | LEISZ ELEV (m) | ASTER ELEV (m) | DIFFERENCE (FROM LEISZ,m) | SRTM ELEV (m) | DIFFERENCE (FROM LEISZ,m) |
|---|---|---|---|---|---|---|---|
| 1 | 446663 | 2125105 | 106 | 91 | -15 | 110 | 4 |
| 2 | 446960 | 2124829 | 155 | 132 | -23 | 155 | 0 |
| 3 | 447842 | 2124452 | 102 | 71 | -31 | 97 | -5 |
| 4 | 448488 | 2124345 | 110 | 98 | -12 | 96 | -14 |
| 5 | 448975 | 2124406 | 114 | 111 | -3 | 110 | -4 |
| 6 | 450073 | 2124300 | 214 | 213 | -1 | 213 | -1 |
| 7 | 449742 | 2125063 | 88 | 79 | -9 | 84 | -4 |
| 8 | 450918 | 2125926 | 79 | 55 | -24 | 68 | -11 |
| 9 | 450540 | 2123341 | 132 | 147 | 15 | 129 | -3 |
| 10 | 449573 | 2124530 | 108 | 87 | -21 | 108 | 0 |

GROUP C

| POINT | EASTING (UTM 48N) | NORTHING (UTM 48N) | LEISZ ELEV (m) | ASTER ELEV (m) | DIFFERENCE (FROM LEISZ,m) | SRTM ELEV (m) | DIFFERENCE (FROM LEISZ,m) |
|---|---|---|---|---|---|---|---|
| 1 | 452988 | 2150180 | 285 | 280 | -5 | 268 | -17 |
| 2 | 453111 | 2150437 | 234 | 202 | -32 | 207 | -27 |
| 3 | 453787 | 2150297 | 141 | 146 | 5 | 146 | 5 |
| 4 | 454161 | 2150328 | 143 | 149 | 6 | 132 | -11 |
| 5 | 454637 | 2150165 | 114 | 129 | 15 | 127 | 13 |
| 6 | 453366 | 2148673 | 208 | 212 | 4 | 220 | 12 |
| 7 | 453476 | 2148761 | 177 | 199 | 22 | 209 | 32 |
| 8 | 456465 | 2151446 | 435 | 404 | -31 | 373 | -62 |
| 9 | 455983 | 2151172 | 200 | 178 | -22 | 188 | -12 |
| 10 | 455852 | 2150608 | 222 | 217 | -5 | 210 | -12 |

## 3.2 GEOSPATIAL LAND COVER DATA

### 3.2.1 Landsat Data Research

The Landsat dataset provides land cover scenes for nearly the entire globe. The data is available typically on a 30 meter grid (30 m x 30 m pixels). Scenes are available on a temporal resolution based on a 16-day revisit. Studies such as vegetation change over time can be conducted with this data set. The Landsat data is very efficiently managed and manipulated in contemporary Geographic Information Systems (GIS), as the data is provided in a grid raster format.

### 3.2.2 Background

The Landsat program is a combined effort between the USGS and NASA. The Landsat program has been in operation since 1972, and is the world's longest continuously acquired collection of spaceborne land remote sensing data. The Landsat remote sensing satellites are passive remote sensing devices. Passive devices rely on outside energy sources and only receive electromagnetic energy, either reflected or emitted; whereas active remote sensing devices both emit and receive energy.

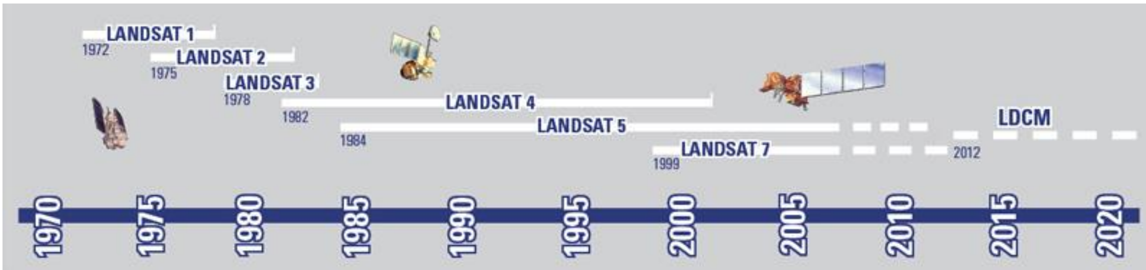



**FIGURE 3.2.1 -** Landsat Timeline. Reference:

http://landsat.usgs.gov/about_mission_history.php

The data utilized in this study is from the Landsat Thematic Mapper remote sensing device. Thematic Mapper was utilized for the Landsat 4, 5 and 7 missions (Landsat 6 did not succeed in making orbit). Images from the Thematic Mapper consist of seven spectral bands. Images for Bands 1 through 5, and Band 7 have a spatial resolution of 30 meters. The image for Band 6 has a spatial resolution of 120 meters (with the exception of Landsat 7, where it had a pixel resolution of 60m); however the image has been resampled to provide a 30 meter resolution consistent with the images for Bands 1 through 5, and Band 7. The Thematic Mapper device orbits the earth on an 16-day cycle; thus providing a temporal resolution of 16-days (USGS, 2011).

| Thematic Mapper (TM) | Landsat 4-5 | Wavelength (micrometers) | Resolution (meters) |
|---|---|---|---|
| | Band 1 | 0.45-0.52 | 30 |
| | Band 2 | 0.52-0.60 | 30 |
| | Band 3 | 0.63-0.69 | 30 |
| | Band 4 | 0.76-0.90 | 30 |
| | Band 5 | 1.55-1.75 | 30 |
| | Band 6 | 10.40-12.50 | 120* (30) |
| | Band 7 | 2.08-2.35 | 30 |

**FIGURE 3.2.2-** Landsat Thematic Mapper Image Band Wavelength and Resolution

Reference: http://landsat.usgs.gov/band_designations_landsat_satellites.php

The data provided by the Landsat Thematic Mapper remote sensing device has many uses, including geologic mapping, agricultural applications, natural resource studies, water resource planning, etc. as summarized in the following figure.

| Spectral Bands | | Use |
|---|---|---|
| 1 | Blue-green | Bathymetric mapping; distinguishes soil from vegetation; deciduous from coniferous vegetation |
| 2 | Green | Emphasizes peak vegetation, which is useful for assessing plant vigor |
| 3 | Red | Emphasizes vegetation slopes |
| 4 | Reflected IR | Emphasizes biomass content and shorelines |
| 5 | Reflected IR | Discriminates moisture content of soil and vegetation; penetrates thin clouds |
| 6 | Thermal IR | Useful for thermal mapping and estimated soil moisture |
| 7 | Reflected IR | Useful for mapping hydrothermally altered rocks associated with mineral deposits |
| 8 | Panchromatic | Landsat 7 carries a panchromatic band (visible through near infrared) with 15-meter resolution for "sharpening" of multispectral images |

**FIGURE 3.2.3** - Landsat Thematic Mapper Band Descriptions and Uses

Reference: USGS, 2011, Landsat: A Global Land-Imaging Project - paper available at http://landsat.usgs.gov/about_project_descriptions.php

### 3.2.3 Obtaining Landsat Data

Landsat data can be obtained from a number of sources. The USGS Global Visualization Viewer website (http://glovis.usgs.gov/) is the preferred choice of the author. An alternate website from which Landsat data can be obtained is the USGS Earth Explorer website (http://earthexplorer.usgs.gov/).

### 3.2.4 USGS Global Visualization Viewer

Once logged in to the USGS Global Visualization Viewer website (http://glovis.usgs.gov/), the user is provided a map-based user interface. The User can identify an area of interest by first indicating the general area of interest on the world location map on the left side of the screen. Once this is done, a series Landsat scene panels is displayed centered around the area of interest.

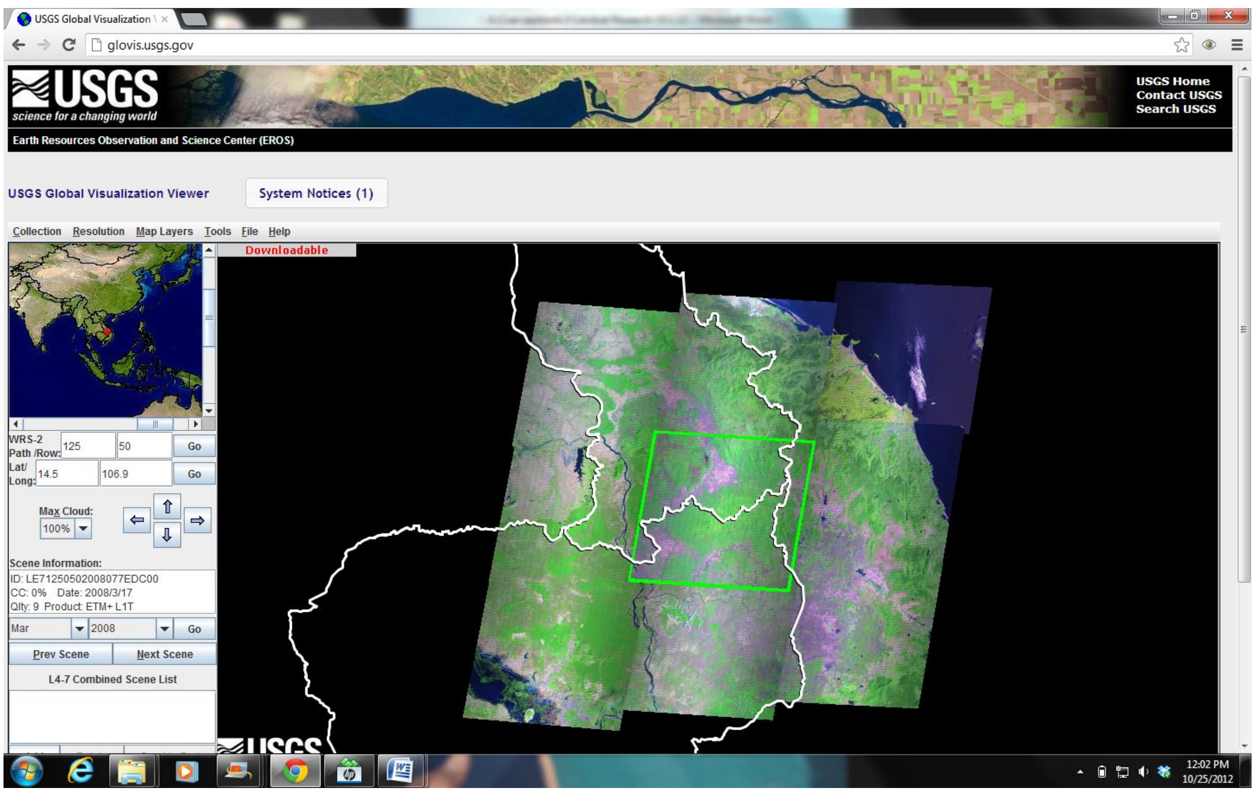



**FIGURE 3.2.4** – USGS Global Visualization Viewer is a map-based user interface to obtain Landsat data. The Landsat panel indicated in bright green is the panel that was selected.

The user then picks the panel of interest, and selects the month and year that the user wishes to view for this area.   The user then selects “Send to Cart” in order to download the Landsat panel.

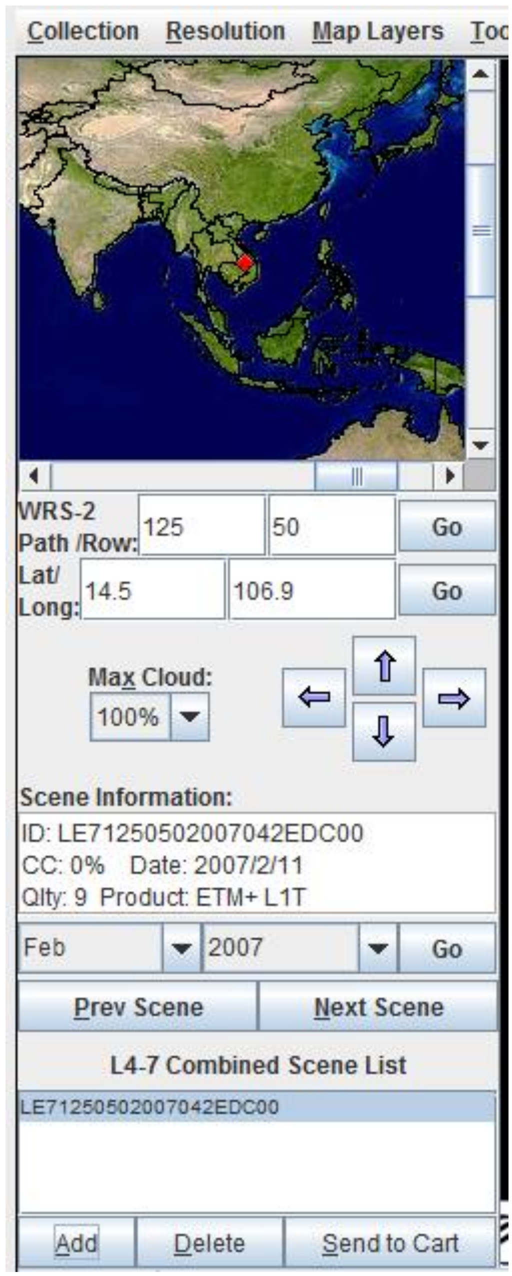



**FIGURE 3.2.5** – USGS Global Visualization Viewer allows the user to select the month and year desired for the Landsat panel.  February of 2007 was selected in this case.

Landsat data was downloaded as roughly 160 x 160 kilometer panels with a file size of roughly 50 MB for each Landsat Band. A total of thirty five Landsat panels were downloaded to provide coverage of the overall Lower Mekong Basin for this research.

When downloaded initially, Landsat panels are in a georeferenced TIFF raster format. Landsat panels can then be converted to a GRID format in order to be manipulated within ArcGIS (by ESRI) for ease of use. In the conversion process, the panels must also be placed within a projected coordinate system. For the Lower Mekong Basin, all Landsat panels were placed on the WGS 1984 UTM Zone 48N coordinate system. When converted to a GRID format, Landsat panels contain cells that are 30 x 30 meters in size.

## 3.3 GEOSPATIAL POPULATION DATA

### 3.3.1 Landsat Data Research

LandScan is a global population data set that is readily imported into a geographic information system as a grid raster. The LandScan raster is provided on a 1 kilometer grid, with each grid cell listing population within that 1 kilometer square.

The majority of Asia is shown below, with Thailand, Laos, Cambodia and Vietnam outlined in cyan. The lightest color gradation of yellow cells represent population of 0 to 100 persons per square kilometer. Color gradations going from shades of orange and red on up to shades of violet and blue represent populations of up to 115,570 persons per square kilometer.

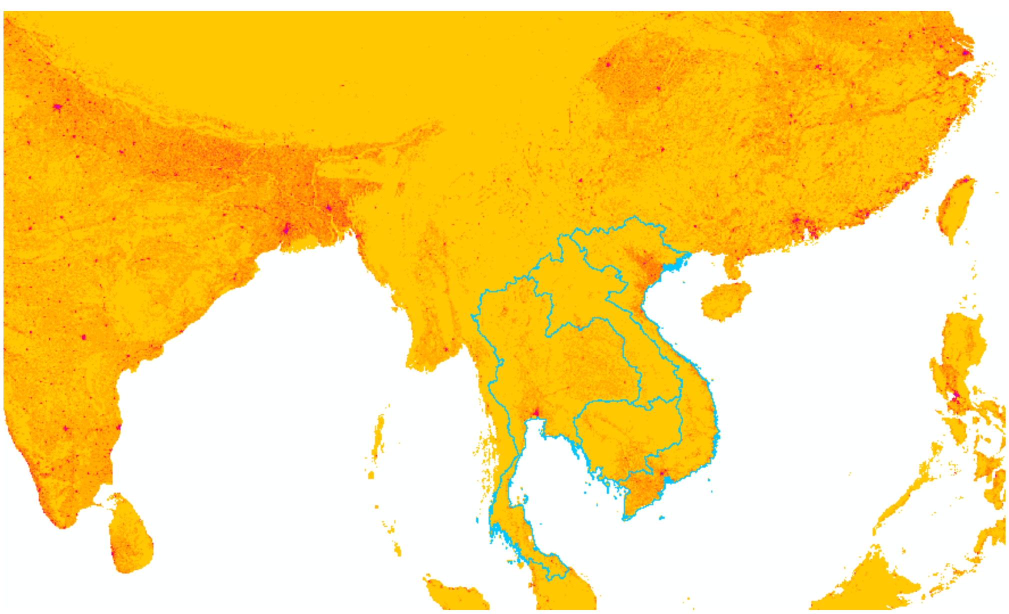


**FIGURE 3.3.1** – LandScan population mapping of the majority of Asia. Thailand, Laos, Cambodia and Vietnam are outlined in cyan.

LandScan data is provided in both ESRI GRID format and ESRI binary raster format. Values of grid cells represent and average (ambient) population distribution.

*"An ambient population integrates diurnal movements and collective travel habits into a single measure (Dobson et al. 2000). Since natural or manmade emergencies may occur at any time of the day, the goal of the LandScan model is to develop a population distribution surface in totality, not just the locations of where people sleep."*
(http://www.ornl.gov/sci/landscan/landscan_documentation.shtml)

LandScan uses an approach with GIS and Remote sensing which gives ambient population mapping for the majority of the globe. The LandScan algorithm utilizes spatial data and imagery analysis technologies in order to disaggregate census counts within an administrative boundary.

*"Since no single population distribution model can account for the differences in spatial data availability, quality, scale, and accuracy as well as the differences in cultural settlement practices, LandScan population distribution models are tailored to match the data conditions and geographical nature of each individual country and region."*
(http://www.ornl.gov/sci/landscan/landscan_documentation.shtml)

### 3.3.2 Landscan Methodolology

The LandScan data set has a spatial resolution of 30 arc-seconds (1 kilometer grid) and is provided on the WGS 84 datum, which is a geographic coordinate system. The Landsat database is updated annually by incorporating new spatial data and imagery analysis into the population distribution algorithms

The general LandScan methodology is described below:

*"The LandScan global population distribution models are a multi-layered, dasymetric, spatial modeling approach that is also referred to as a "smart interpolation" technique. In dasymetric mapping, a source layer is converted to a surface and an ancillary data layer is added to the surface with a weighting scheme applied to cells coinciding with identified or derived density level values in the ancillary data. In the LandScan models, the typical dasymetric modeling is improved by integrating and employing multiple ancillary or indicator data layers. The modeling process uses sub-national level census counts for each country and primary geospatial input or ancillary datasets, including land cover, roads, slope, urban areas, village locations, and high resolution imagery analysis; all of which are key indicators of population distribution. Based upon the spatial data and the socioeconomic and cultural understanding of an area, cells are preferentially weighted for the possible occurrence of population during a day. Within each country, the population distribution model calculates a "likelihood" coefficient for each cell and applies the coefficients to the census counts, which are employed as control totals for appropriate areas. The total population for that area is then allocated to each cell*

*proportionally to the calculated population coefficient. The resultant population count is an ambient or average day/night population count."*

**(**http://www.ornl.gov/sci/landscan/landscan_documentation.shtml)

### 3.3.3 Background

In 1998 the first LandScan dataset was produced as an improved resolution global population distribution dataset for the purpose of estimating populations at risk. The original Landscan algorithms were based on relatively coarse spatial data, and input data for each nation or region were assigned customized weighting factors in a spatial model to characterize diverse spatial settlement patterns.

With recent innovations in remote sensing and spatial data, there has been a marked improvement in spatial data; however there are still challenges in utilizing this data.

*"The last decade has seen significant growth of global spatial data and a tremendous increase in the volume of high resolution satellite imagery. These data and imagery present an opportunity to improve the spatial fidelity of annual data releases. However, the production of new spatial data is often fragmented, and the LandScan algorithms must account for disparate input data resolutions and temporal incongruities"*

(http://www.ornl.gov/sci/landscan/landscan_documentation.shtml)

### 3.3.4 Obtaining Landscan Data

Landscan data can be obtained by placing a data request at the Oak Ridge National Laboratory website: http://www.ornl.gov/sci/landscan/. The Oak Ridge National Laboratory is located in Oak Ridge Tennessee, and is sponsored by the U.S. Department of Energy. The 2008 landscan data utilized in this research was freely obtained through the Oak Ridge National Laboratory website by the author in 2009. As of 2010, however, nominal fees are now applied to the distribution of data. The 2008 data set was obtained as a single data file for the entire globe which was 3.4 GB in size. When downloaded initially, Landscan data is in a georeferenced GRID raster format on a geographic coordinate system. Landscan data must then be re-projected onto a geographic coordinate system in order to be manipulated within ArcGIS (by ESRI). For the Lower Mekong Basin, the Landscan data was re-projected onto the WGS 1984 UTM Zone 48N coordinate system.

## 3.4 SATELLITE IMAGERY

### 3.4.1 Satelitte Imagery Research

High resolution satellite imagery is now available for most of the planet. Several commercial providers currently offer satellite imagery products that have up to 0.5m pixel resolution. At this level of resolution, natural and man-made features can be clearly identified. Google Earth is, in a sense, a repository of this aerial imagery. The imagery Google Earth offers is taken from commercial sources, and is free of charge.

Methodologies for georeferencing and utilizing this imagery are presented in this section, and are intended for academic purposes only. It is noted that commercial usage of Google Earth imagery for profit without obtaining a rights clearance from Google may represent copyright infringement.

From Google Earth (2014):

*"We're flattered to hear that you're further incorporating Google Earth into your online world. You can personally use an image from the application (for example on your website, on a blog or in a word document) as long as you preserve the copyrights and attributions including the Google logo attribution. However, you cannot sell these to others, provide them as part of a service, or use them in a commercial product such as a book or TV show without first getting a rights clearance from Google."*

*https://support.google.com/earth/answer/21422?hl=en*

### 3.4.2 Georeferencing Satellite Imagery

First a user would determine an area of interest within the Google Earth global navigator. Once this area of interest is determined, Google Earth can be used to view available satellite imagery of the area. The latitude/longitude grid should be turned on from the “view” menu in Google Earth. An example of this view is shown in the following figure.


**FIGURE 3.4.1** – Google Earth Image of the village of Patumphon (southern Laos).

A simple screen capture from the computer on which Google Earth is being viewed will allow for a TIFF image file to be created in a program such as Photoshop by Adobe. Once the TIFF image file is created, this image can be imported into a GIS.  ArcMap (by ESRI) was utilized to import the image with the “Georeferencing” tool.

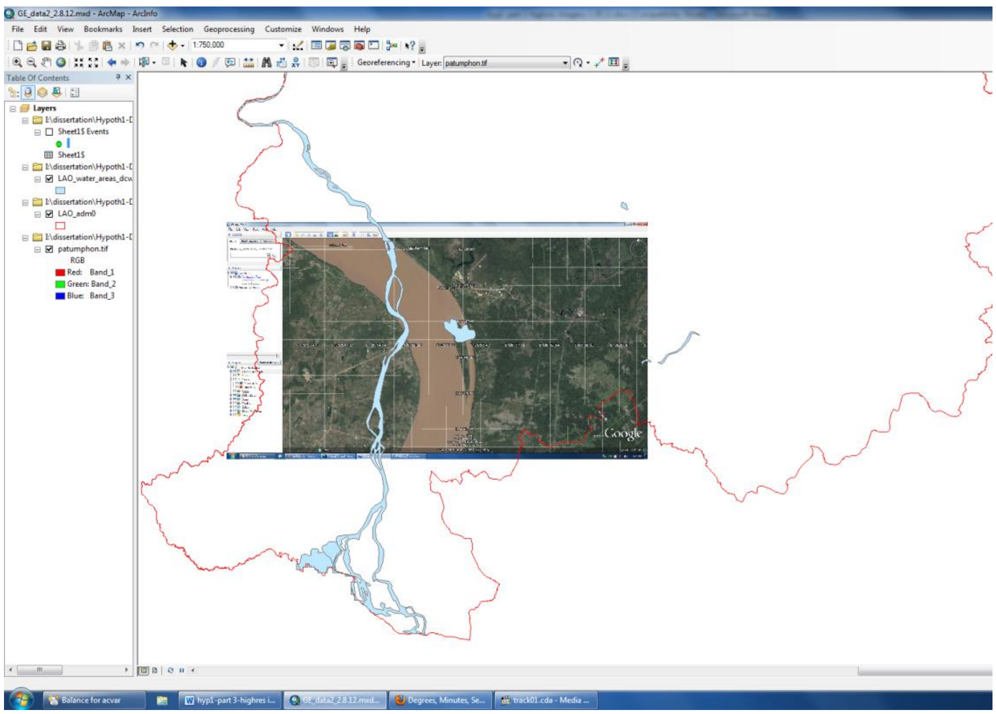



**FIGURE 3.4.2** – Google Earth image of Patumphon, Laos being imported into ArcMap.

Once the image file is brought into ArcMap, three reference points are set, corresponding to three common latitude/longitude points which match the Google Earth latitude/longitude grid.

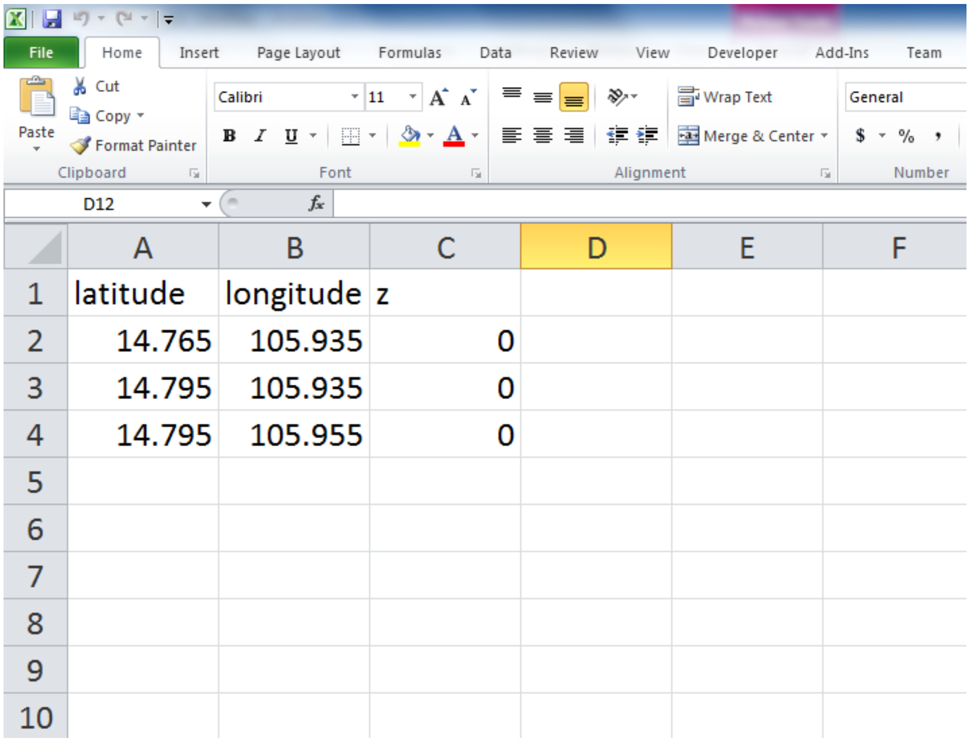



**FIGURE 3.4.3** – Latitude and longitude file set up in Microsoft Excel for the creation of reference points in ArcMap.

Once three common points of reference have been established, the “georeferencing” tool can be utilized to align the Google Earth image within the GIS.

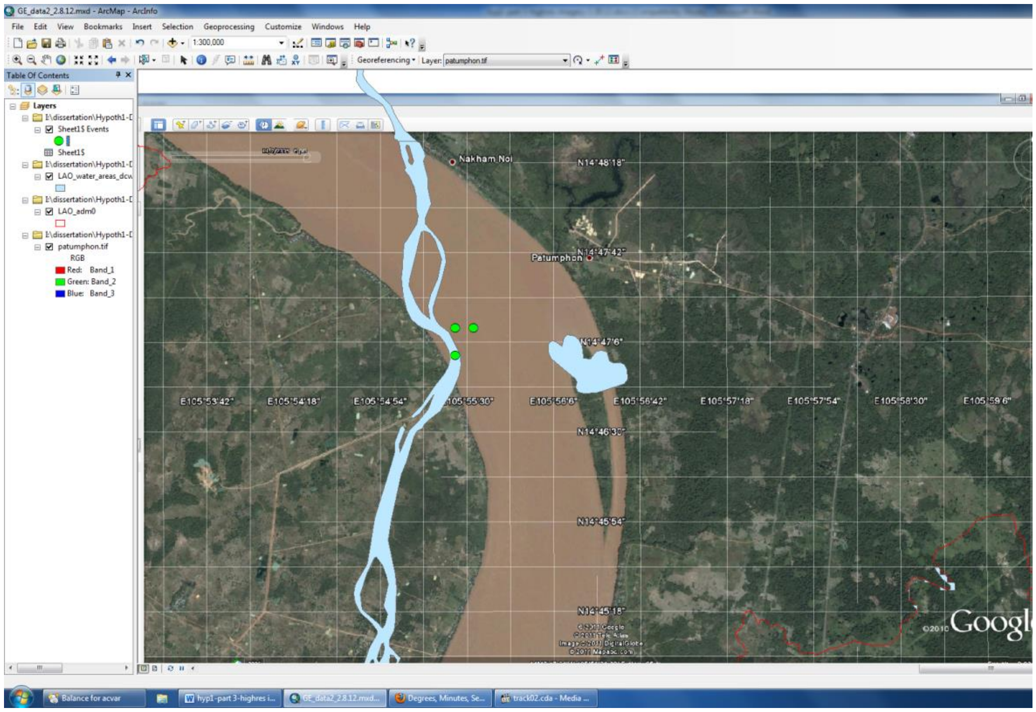



**FIGURE 3.4.4** – Oversized, Imported image in ArcMap. Image will be aligned and scaled according to three points of reference (three green dots in inverted "L" pattern) utilizing the georeferencing tool in ArcMap.

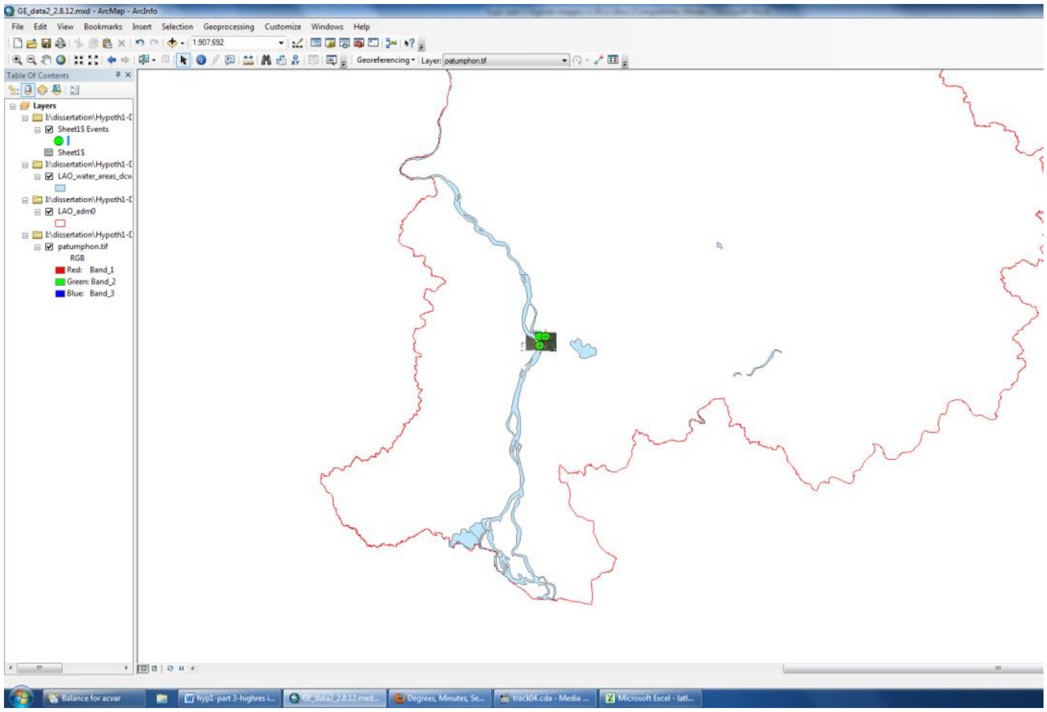



**FIGURE 3.4.5** – Imported image now aligned within ArcMap according to the three points of reference established.

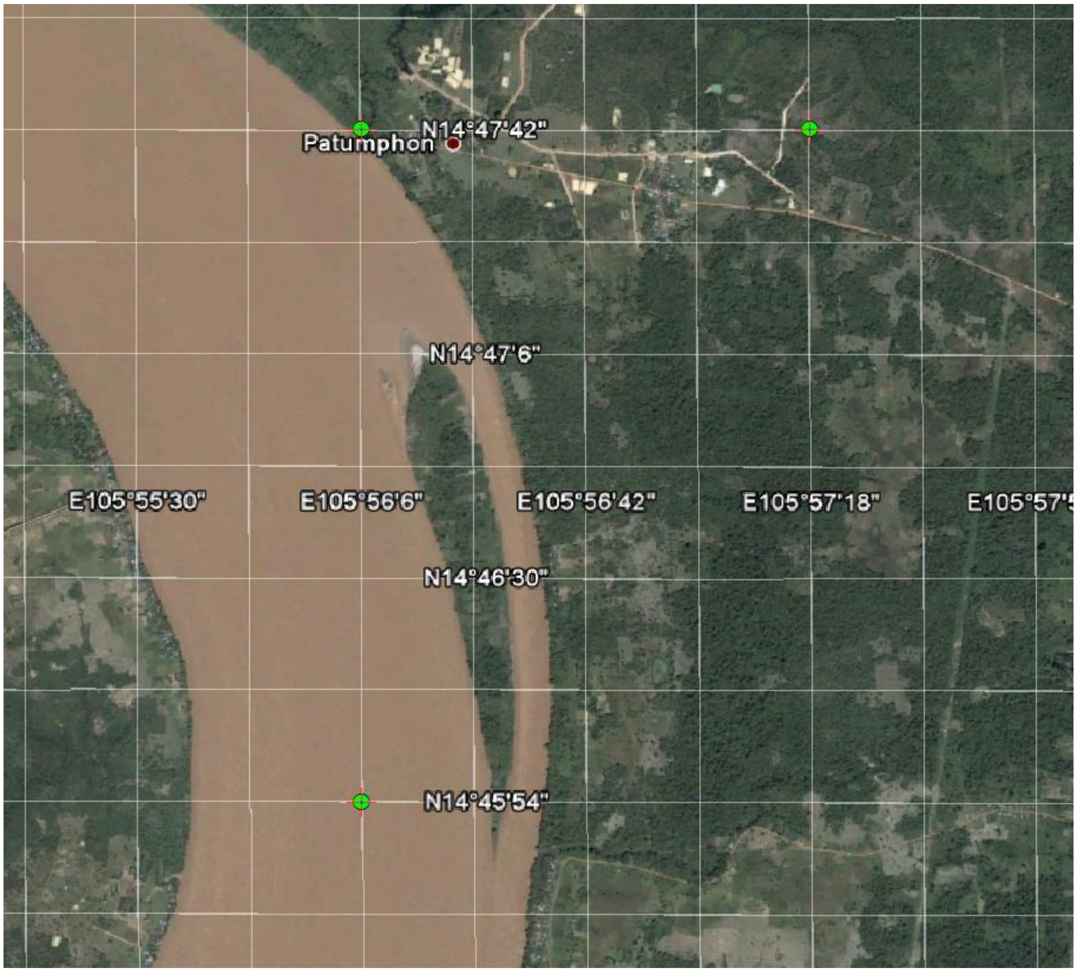



**FIGURE 3.4.6** – ArcMap view of image now aligned within the GIS according to the three points of reference established.

The final step is to export the image as a grid raster on the coordinate basis and projection desired. In the example above, the image was exported onto UTM Zone 48 North (WGS 1984). Now that the image is a georeferenced grid raster, it can be added as a layer to any ArcMap map document, and the image will come in properly aligned and scaled on a UTM projection.

## 3.5 DATA RESEARCH CONCLUSIONS

### 3.5.1 Conclusions

Chapter 3 has explored the availability of geospatial data for the purpose of reservoir planning and decision support in developing nations. The author has spent significant time in searching through the data that is now available through the world wide web. There is, in the words of the United Nations World Water Assessment Programme, a “flood” of data now available. Many potential sources of data were investigated, and four data sources were found to stand out as having good potential to be of use. These four geospatial data sources, as discussed in this chapter, are: the SRTM terrain data set, the Landsat land cover data set, the Landscan population data set, and satellite imagery obtained through Google Earth. Significant emphasis has been placed on the Shuttle Radar Topography Mission (SRTM) data set because this is the primary basis for the many of the tools and models created in this research, which are discussed in Chapter 5.

The four data sources were obtained for free, and are global in nature. The four data sources were used to upload geospatial data specific to the Lower Mekong River Basin for the case studies undertaken with this research. However, since these are global data sets, the methodologies created in this research could be applied to any developing nation or data limited area of the globe.

The findings of Chapter 3 support the first hypothesis. Four reliable sources of data have been thoroughly explored in this chapter, and show that the geospatial data is now available to fill the data gaps that have existed in the past for regional scale reservoir planning and decision support in developing nations.

The data research in Chapter 3 is foundational for the concepts and methodologies outlined in Chapters 4 and 5. Chapter 4 shows how the data discovered in Chapter 3 can be used to create “Data Products”. As will be described, these “Data Products” are packaged data sets focused on reservoir planning and decision support which can be readily used in a contemporary Geographic Information System. Chapter 5 describes “Tools” and “Models” created to assist decision makers. These “Tools” and “Models” allow means to extract specific information from the geospatial data discovered in Chapter 3 for the purpose of reservoir planning and decision support.

# 4.0 APPLICATION RESEARCH - DATA PRODUCT CREATION

## 4.0.1 Introduction

The concept presented in this section of the research is to utilize the more advanced capabilities of ArcGIS by Esri to create "data products" which could then be utilized in both ArcGIS as well as freely available open source GIS software. Once data products have been created, the end user could be free obtain an open source GIS program of their own choice and utilize the data products within that GIS software package.

Open source GIS software products are available through various websites. A few examples are:

- Quantum GIS (http://www.qgis.org/)
- GRASS GIS (http://grass.osgeo.org/)
- DIVA-GIS (http://www.diva-gis.org/)

The question that arises is identification of an entity to fill the role of creating and maintaining these data products? Funding for the creation and maintenance of these data products might come from an entity such as the United Nations. Alternatively, a university or group of universities could take on the role of creation and maintenance of data products for a specific group of developing nations. There are many possibilities, however the focus of this research is the creation of data products and their use. Once the methodology of data product creation has been established, possible future research could be conducted in the arena of funding mechanisms for creation and maintenance of data products to aid in water resources planning and decision support in developing nations.

Several products have been created in this research as georeferenced raster files, and have been created utilizing global data sets obtained freely via the world wide web. The case studies that have been conducted in this research (discussed in Chapter 6) focus on the Lower Mekong Basin; however, the data products methodologies presented in this research are valid for any area of the globe.

The data products that have been created in this research for the overall Lower Mekong Basin can be utilized in ArcGIS as well as open source GIS, and are summarized as follows:

- High resolution (90 meter grid) digital elevation model (DEM)
- High resolution (90 meter grid) flow accumulation raster data product
- High resolution (90 meter grid) stream flowline elevation raster data product
- Perennial stream identification raster data product
- Farmland identification raster data product
- Population raster data product
- Low resolution (350 meter pixels) satellite imagery of overall basin
- High resolution (2 meter pixels) satellite imagery of selected cities

The open source computer software “Quantum GIS” was downloaded at no cost from the website http://www.qgis.org/. The data products created in this research with ArcGIS were then opened in Quantum GIS in order to test their usability in an open source GIS software package.

## 4.1 GEOSPATIAL TERRAIN DATA PRODUCTS

### 4.1.1 Finished Data Product – High Resolution DEM of Lower Mekong Basin

This portion of the research explores geospatial terrain data products. The SRTM (Shuttle Radar Topography Mission) data set, discussed previously in Chapter 3, was the basis of the creation of all geospatial terrain data products.

A high resolution (90 meter grid) digital elevation model (DEM) data product is presented for the overall Lower Mekong Basin in this section and is shown in the following figure. The data product has been created in a georeferenced TIFF raster format, and can be utilized in open source GIS software as well as ArcGIS software, by Esri.

This data product was assembled in ArcGIS using base data obtained from the Shuttle Radar Topography Mission (SRTM) Data Set. The data set comes in panels, and ArcGIS was utilized to combine, fill gaps, and trim the data to include only areas within the Lower Mekong River Basin. This data product is the foundation for the latter two data products: "high resolution flow accumulation grid for Lower Mekong Basin", and "high resolution stream flowline elevation grid for Lower Mekong Basin"

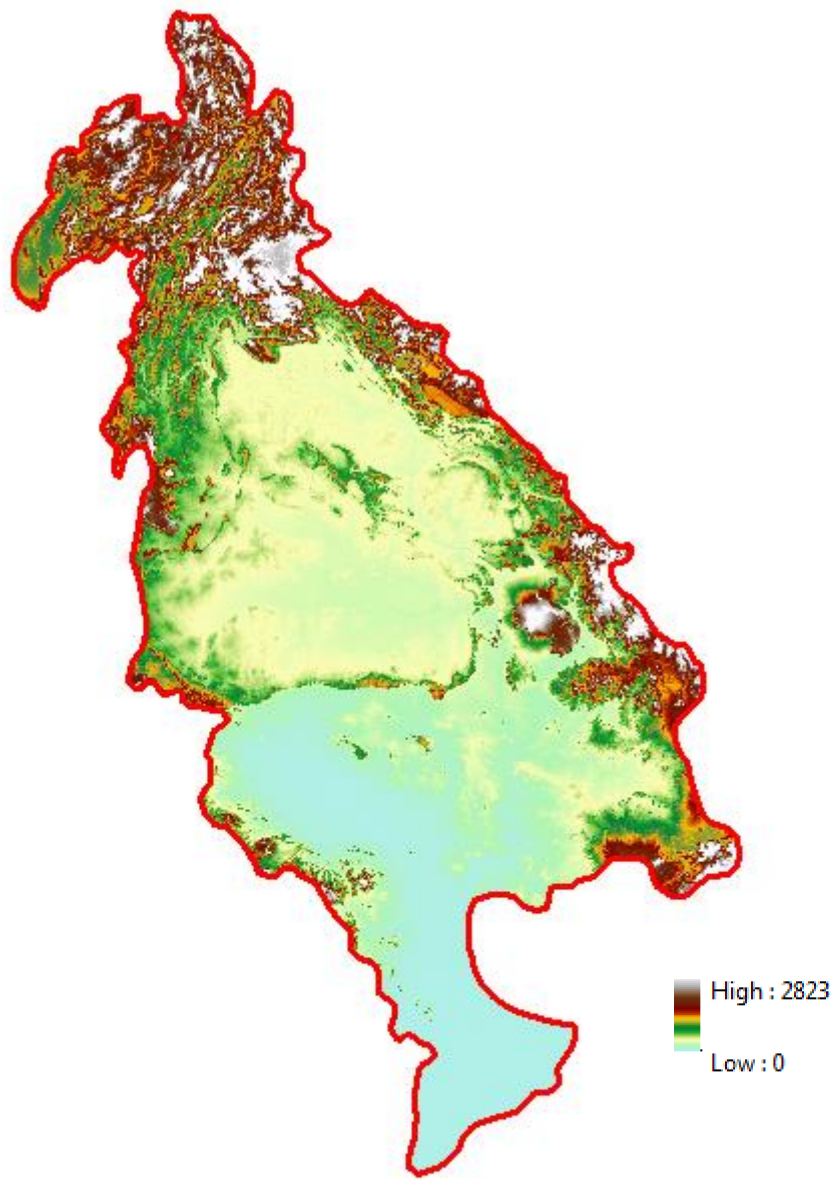



**FIGURE 4.1.1** – ArcMap view of High resolution (90 meter) DEM data product for the Lower Mekong Basin (displayed as red outline). Color pattern indicates topographic elevations

### 4.1.2 Finished Data Product – Flow Accumulation Grid for Lower Mekong Basin

A high resolution (90 meter grid) flow accumulation grid data product is has been created for the overall Lower Mekong Basin and is shown in the following figures.

This data product was created in ArcGIS, utilizing the more advanced tools offered in this geographic information system. The end data product has been created in a georeferenced TIFF raster format, and can be utilized in open source GIS software as well as ArcGIS software, by Esri. This data product can be utilized to determine basin area draining to a stream or river at any point along the stream as illustrated in the following figures. This data product is utilized in the tools and models further discussed in Chapter 5 of this research.


**FIGURE 4.1.2** – ArcMap view of flow accumulation data product for the Lower Mekong Basin (displayed as red outline).

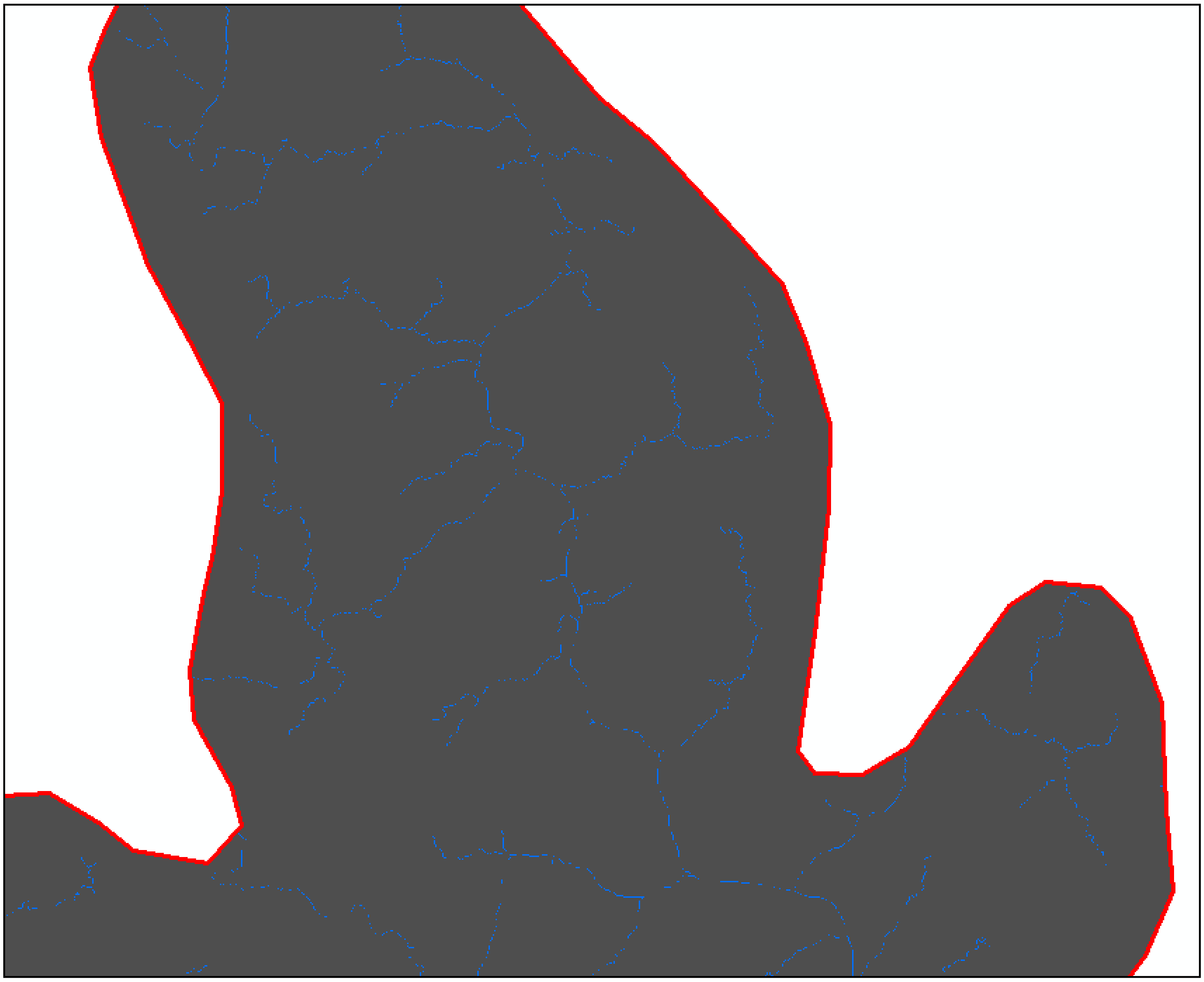


**FIGURE 4.1.3** – ArcMap view of Figure 5.1.19 zoomed in at Location 1 in, as noted above. Stream flowlines are shown in blue. Stream flowlines can be queried to determine flow area/basin area accumulating at any point in the stream.

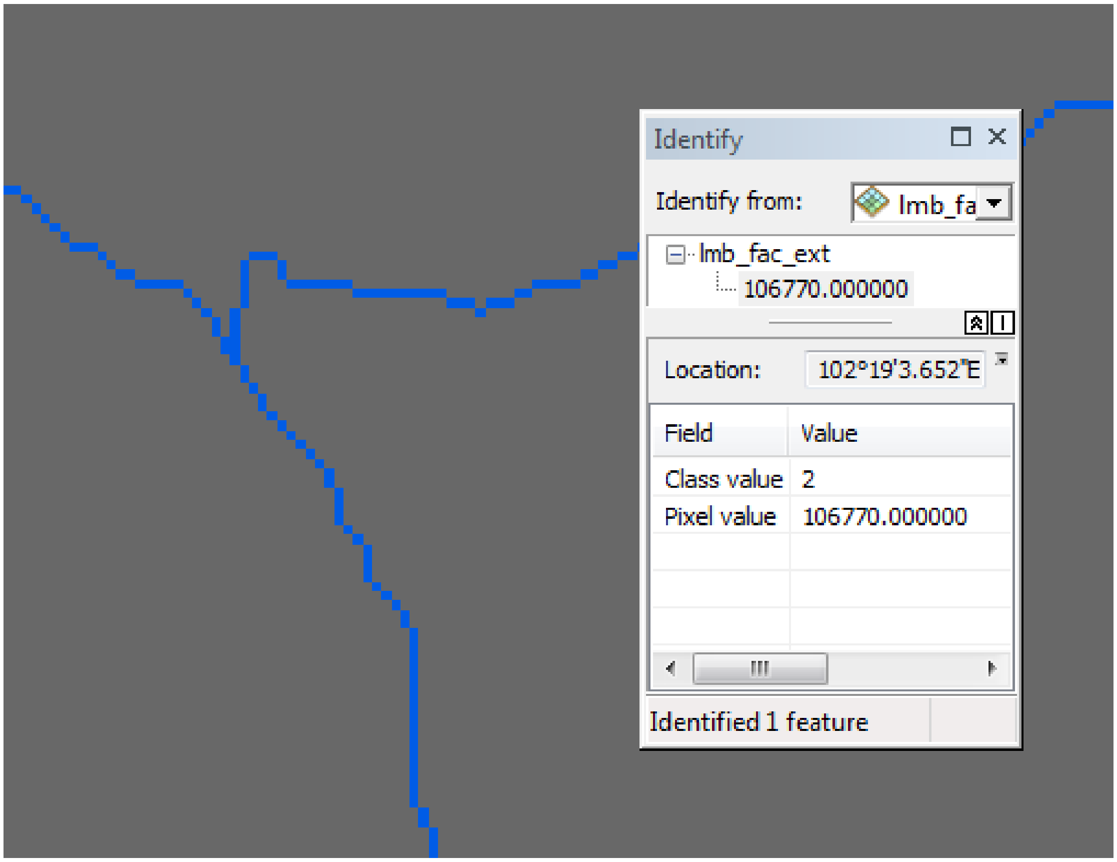



**FIGURE 4.4.4** – Arcmap view zoomed in to stream flowline. Flowline confluence point is queried and found to have 106770 grid cells draining to this point. With 91.3 square meter cells, this translates to 891 square kilometers

### 4.1.3 Finished Data Product – Stream Flowline Elevation Grid for Lower Mekong Basin

A high resolution (90 meter grid) stream flowline data product is has been created for the overall Lower Mekong Basin and is shown in the following figure. This data product was created in ArcGIS, utilizing the more advanced tools offered in this geographic information system. The end data product has been created in a georeferenced TIFF raster format, and can be utilized in open source GIS software as well as ArcGIS software, by Esri. This data product can be utilized to flowline elevation in a stream or river at any point along the stream as illustrated in the following figures. This data product is utilized in the tools and models further discussed in Chapter 5 of this research.


**FIGURE 4.1.5** – Arcmap view of flow accumulation data product for the Lower Mekong Basin (displayed as red outline).

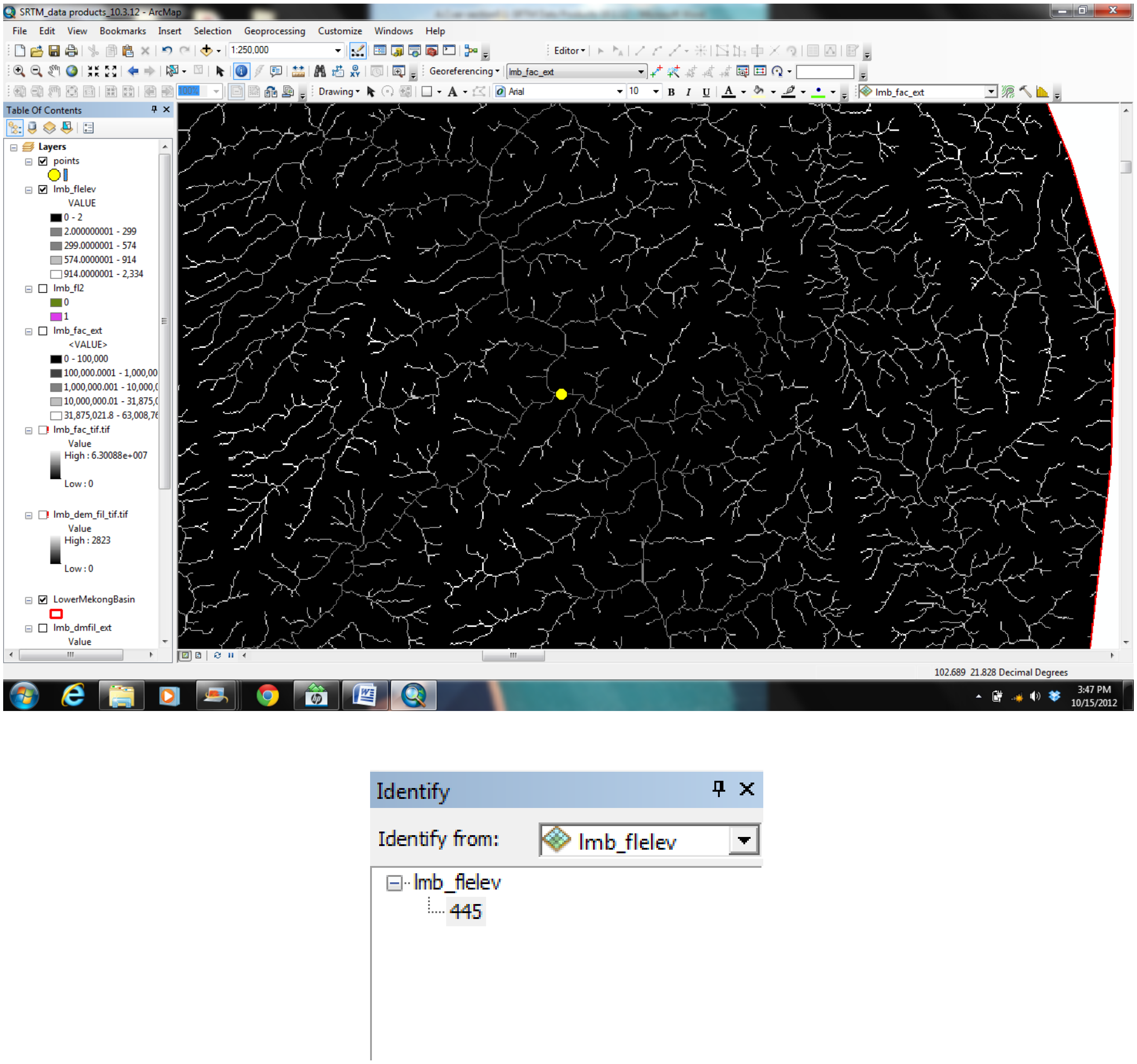



**FIGURE 4.1.6** – Arcmap view zoomed in at Location 1 as identified on Figure to stream flowline.

Point in yellow is queried and found to have an elevation of 445 meters above sea level.

## 4.2 GEOSPATIAL LAND COVER DATA PRODUCTS

### 4.2.1 Geospatial Land Cover Data Product Creation

This section of the research explores land cover data products. The Landsat data set, discussed in Chapter 3, was the basis of the creation of land cover products. Methodology for the creation of data products based on the Landsat data set is discussed in the following sections.

Spectral Indices can be used to create sharper contrast between land cover types, vegetation types, etc. Spectral indices also can eliminate the “illumination effect”, and allow for efficient identification of land cover types. A multiple index methodology (Leisz, Rasmussen, 2011) has been utilized in this research and involves first creating spectral index maps in a geographic information system. Threshold values are imposed on these maps, creating binary mapping of large areas. Two land cover data products have been derived from Landsat data obtained for the Lower Mekong Basin, and a methodology for the creation of these data products is described in this section. A perennial stream identification grid, and a farmland identification grid have been created in this research for the majority of the Lower Mekong Basin.

### 4.2.2 Reflectance and Landsat Wavelength Bands

The Landsat dataset provides land cover scenes for nearly the entire globe. The data is available typically on a 30 meter grid (30 m x 30 m pixels). Landsat data was downloaded as roughly 160 x 160 kilometer panels with a file size of roughly 50 MB for each Landsat Band. When downloaded initially Landsat panels are in a georeferenced TIFF raster format. Landsat panels can then be converted to a GRID format within ArcMap (by ESRI) for ease of use. In the conversion process, the panels must also be placed within a projected coordinate system. For the Lower Mekong Basin, all Landsat panels were placed on the WGS 1984 UTM Zone 48N coordinate system. When converted to a GRID format, Landsat panels contain cells that are 30 x 30 meters in size.

Landsat data is formatted with each of the spectral bands being provided as a grayscale image. Thus, a landsat data set will include multiple images with associated georeferencing information. Reflectance is typically shown for each spectral band image as a level of grey and assigned a numeric value from 0 to 255. A value of 0 indicates no reflectance off of a particular land cover type in that spectral band, whereas value of 255 indicates the highest reflectance. Different land cover types reflect more in some spectral bands than others, as shown in the following figure.

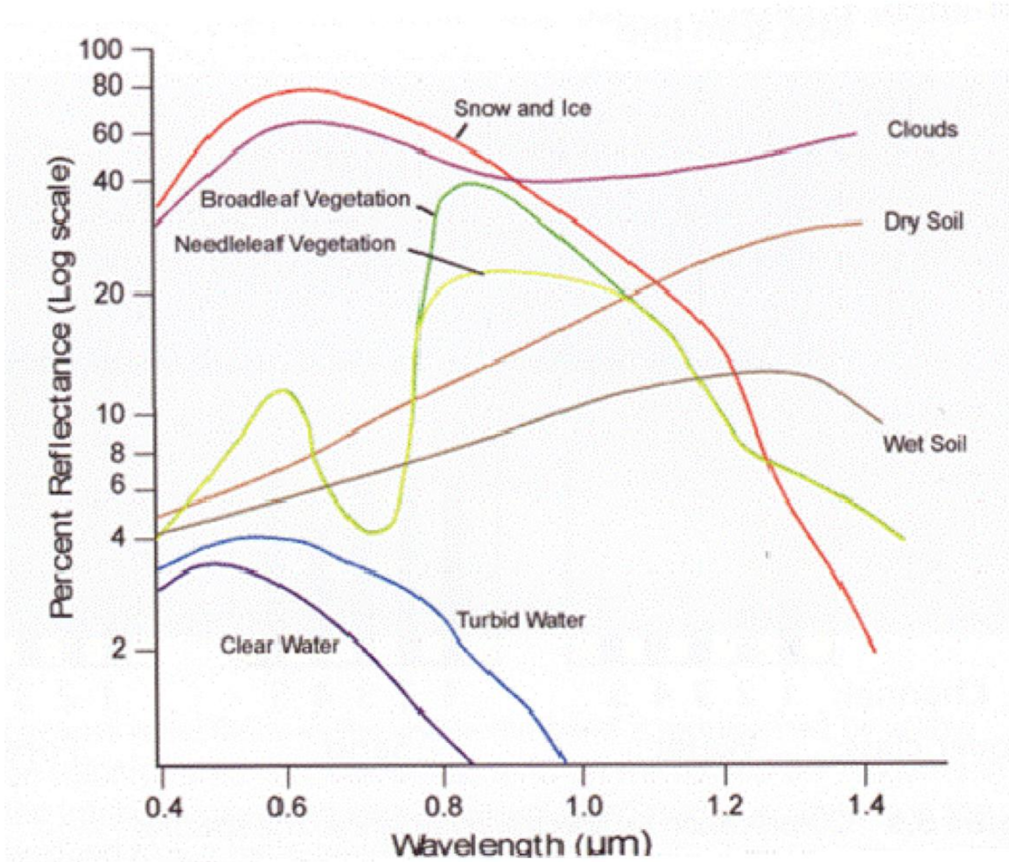
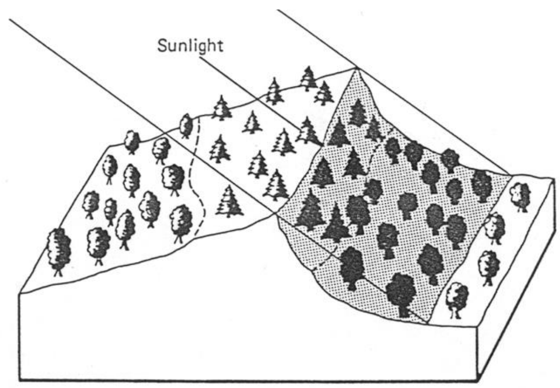



**FIGURE 4.2.1** – Spectral Signatures of different types of land cover. Reference: Aronoff (2005), "Remote Sensing for GIS Managers", ESRI Press.

Knowing the spectral characteristics of different land cover types, spectral band data can be used very effectively in identifying land cover types. In addition to identifying land cover types, spectral information can also be used to assess vegetation moisture content, geologic formations, soil moisture, and other information regarding the land surface.

### 4.2.3 Spectral Indices

Spectral Indices can be used to create sharper contrast between land cover types, vegetation types, etc. Spectral indices also can eliminate the "illumination effect", as shown in the following figure.




| Land Cover/Illumination | Digital Number | | |
| --- | --- | --- | --- |
| | Band A | Band B | Ratio (Band A/Band B) |
| Deciduous | | | |
| Sunlit | 48 | 50 | 0.96 |
| Shadow | 18 | 19 | 0.95 |
| Coniferous | | | |
| Sunlit | 31 | 45 | 0.69 |
| Shadow | 11 | 16 | 0.69 |

**FIGURE 4.2.2** – Reduction of scene illumination effects through spectral ratioing (calculation of spectral index) Reference: Lilesand, Kiefer (2008), "Remote Sensing and Image Interpretation, Sixth Edition", Wiley Publishing.

A very common spectral index is the Normalized Vegetation Index (NDVI). This index is used primarily for vegetation identification, and to determine the lushness of vegetated land surfaces.

NDVI is calculated as:

NDVI = (Near Infrared - Red) / (Near Infrared + Red)

Thematic Mapper classifies Near Infrared (0.76 – 0.90 nm) as Band 4 and Red (0.63 – 0.69 nm) as Band 3.

*"The principle behind NDVI is that Channel 1 is in the red-light region of the electromagnetic spectrum where chlorophyll causes considerable absorption of incoming sunlight, whereas Channel 2 is in the near-infrared region of the spectrum where a plant's spongy mesophyll leaf structure creates considerable reflectance (Tucker 1979, Jackson et al.1983, Tucker et al. 1991). As a result, vigorously growing healthy vegetation has low red-light reflectance and high near-infrared reflectance, and hence, high NDVI values. This relatively simply algorithm produces output values in the range of -1.0 to 1.0. Increasing positive NDVI values, shown in increasing shades of green on the images, indicate increasing amounts of green vegetation. NDVI values near zero and decreasing negative values indicate non-vegetated features such as barren surfaces (rock and soil) and water, snow, ice, and clouds."*( http://ivm.cr.usgs.gov/whatndvi.php)

The normalized difference moisture index is an index which is useful for identifying the moisture content of vegetation.

NDMI can be calculated as follows:

NDMI = (Near Infrared – Mid Infrared) / (Near Infrared + Mid Infrared)

Thematic Mapper classifies Near Infrared (0.76 – 0.90 nm) as Band 4 and Mid Infrared (1.55 – 1.75 nm) as Band 5.

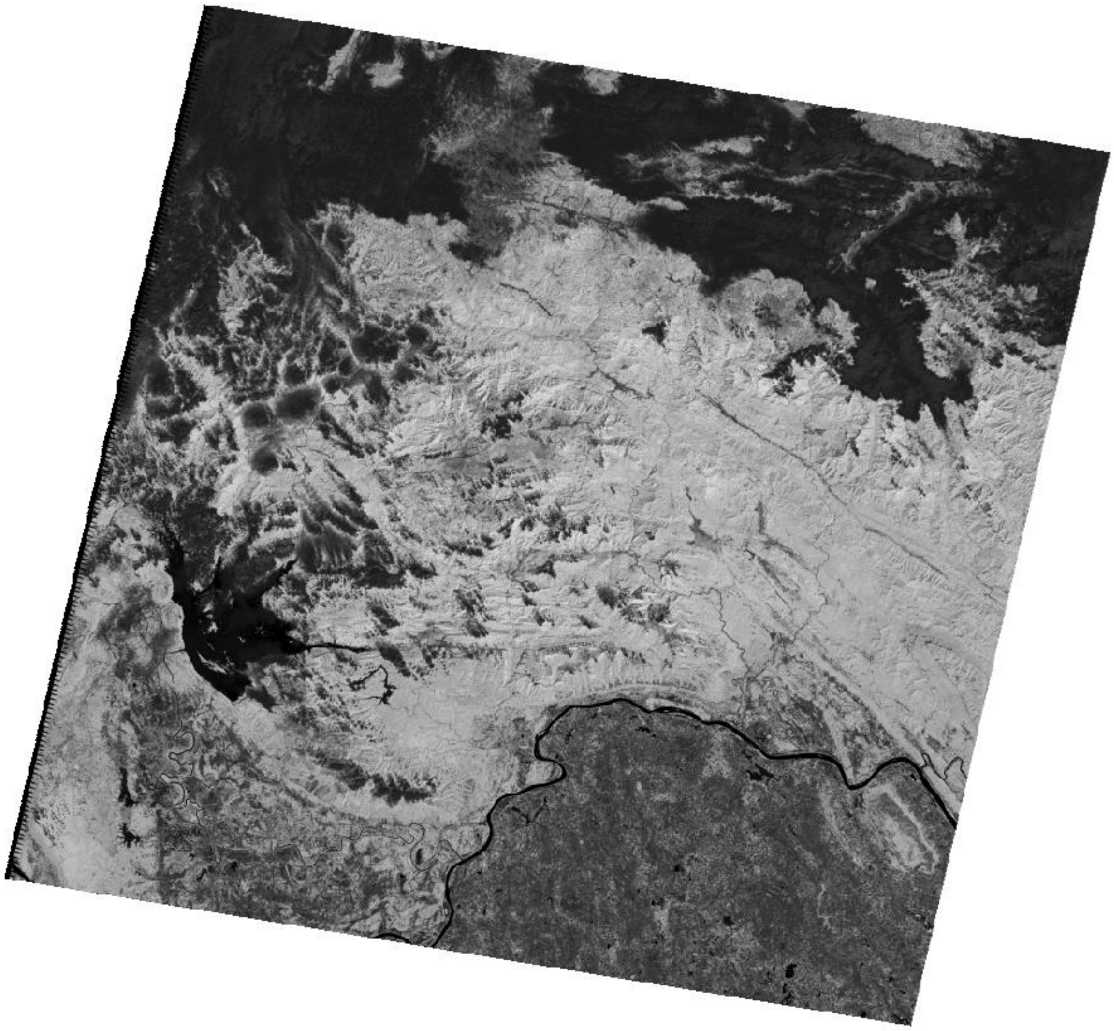


**FIGURE 4.2.3 –** NDVI Map. Black and White image is composed of pixels which indicate a higher (lighter shade) index value or lower (darker shade) index value.

+

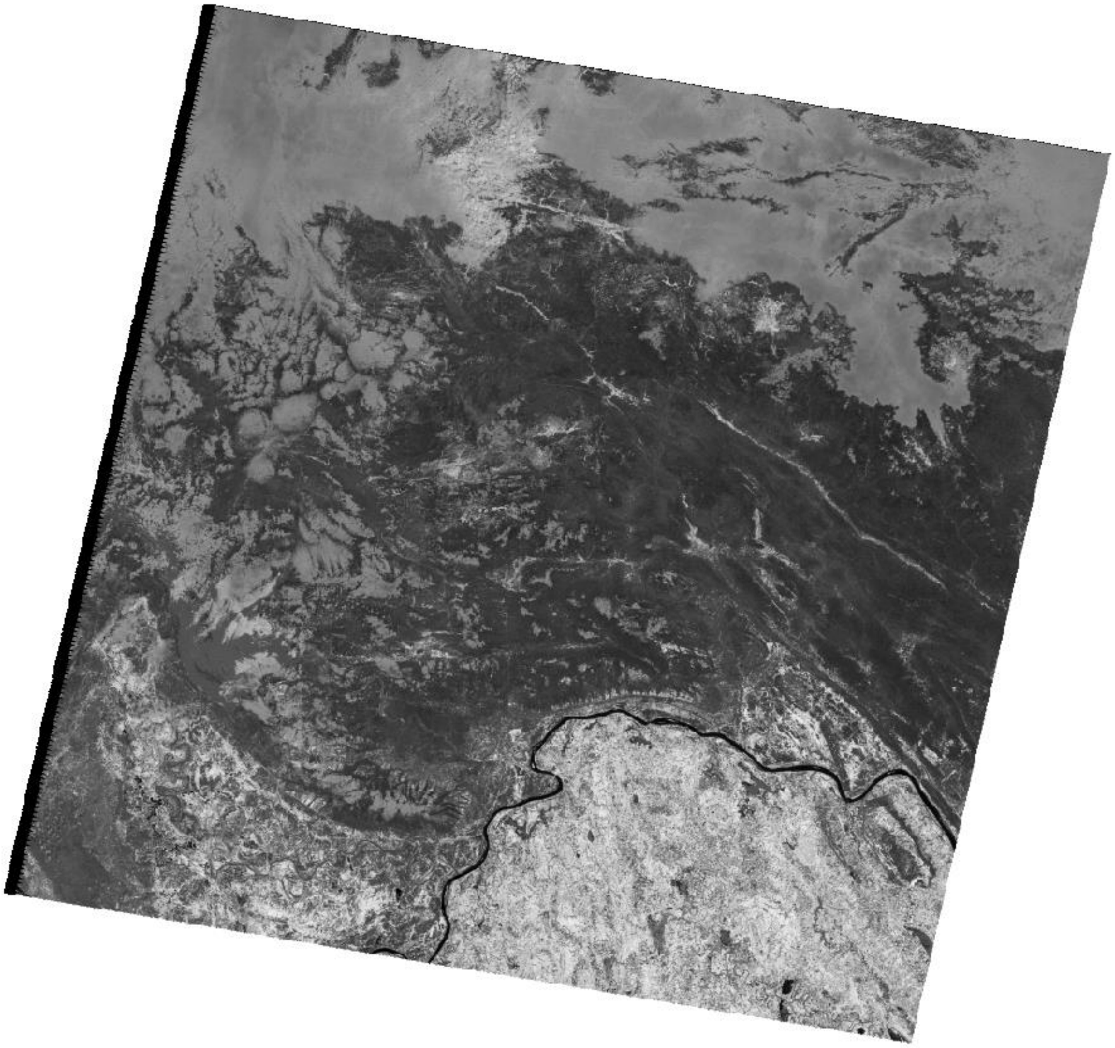


**FIGURE 4.2.4 –** NDMI Map. Black and White image is composed of pixels which indicate a higher (lighter shade) index value or lower (darker shade) index value.

### 4.2.4 Multiple Index Methodology

A multiple index methodology (Leisz, Rasmussen, 2011) has been utilized in this research and involves first creating spectral index maps in a geographic information system. Threshold values are imposed on these maps, creating binary mapping of wet areas. The maps are then overlayed to produce a final "wet area" map with values of 0, 1, 2, and 3. A value of 0 indicates no water was present on any of the spectral indices, a value of 3 indicates water was present on all three of the spectral indices.

As with most remote sensing applications, a spectral index can only indicate the presence of a certain land cover type. The user is not one hundred percent certain that the land cover type has been correctly identified. However, by combining several different indices, the user can have more of a degree of certainty that a certain land cover type is correctly identified.

### 4.2.5 Finished Data Product – Stream Identification Grid for Lower Mekong Basin

A composite "dry season" mapping of the entire Lower Mekong Basin has been created utilizing a multiple index methodology. This mapping is useful on a regional scale for the determination of streams still flowing in the dry season. This composite mapping of all Landsat panels for the Lower Mekong Basin utilizes Landsat panels obtained generally in January and February of 2003. Some panels are not available for every month, and therefore a limited number of the panels were taken from December 2002, and March of 2003.

Composite dry season mapping is shown on a “zoomed out” scale in the following figure. The user can zoom to any part of the Lower Mekong Basin and find relatively high resolution (30 meter pixels) imagery showing perennial streams as shown in the subsequent figure.

The data product has been created in a georeferenced TIFF raster format, and can be utilized in open source GIS software as well as ArcGIS software, by Esri.

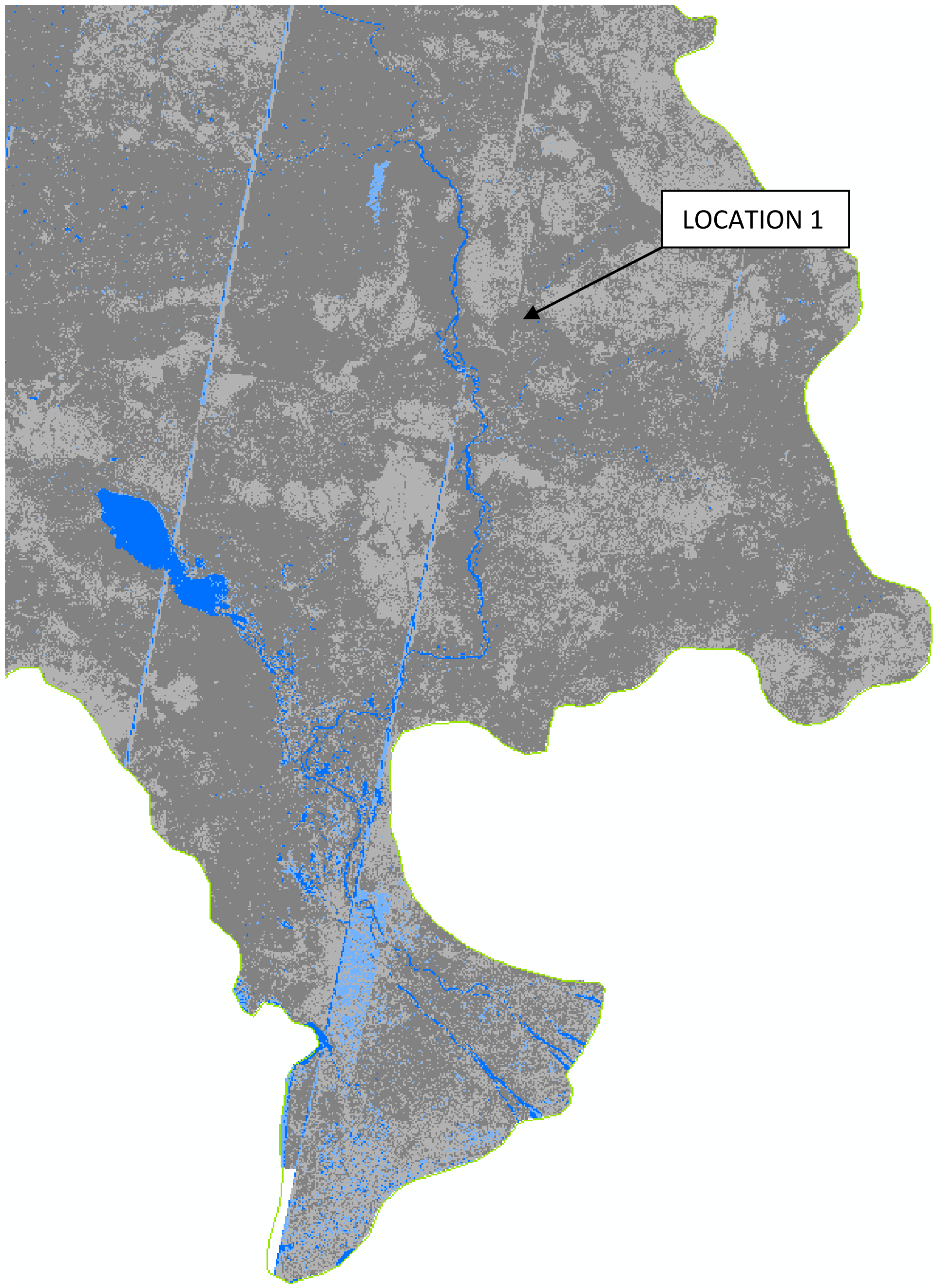



**FIGURE 4.2.6** – ArcMap view of composite multiple index map / perennial stream identification map of the Lower Mekong Basin (outlined in green). "Seams" between landsat scenes appear as light blue lines running diagonally across the composite map data product.

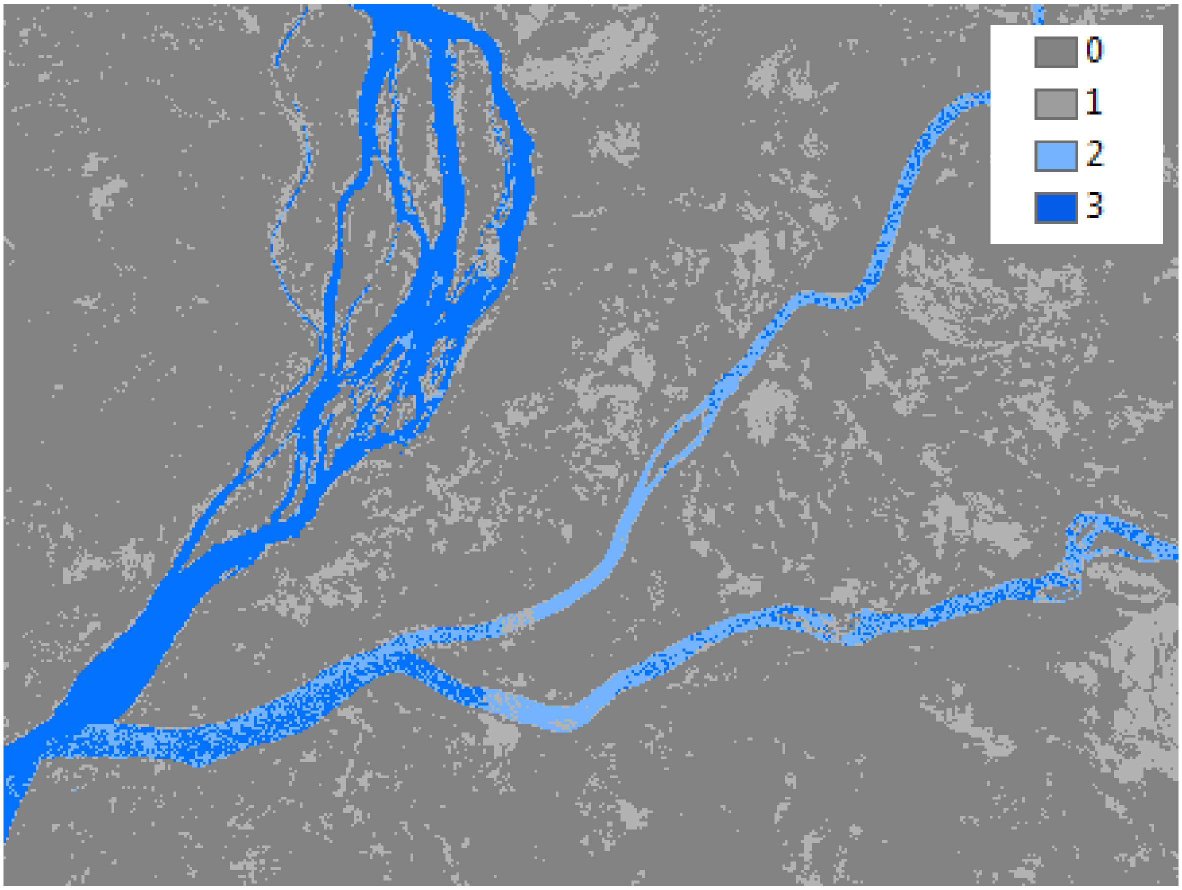



**FIGURE 4.2.7** –Arcmap view zoomed in at Location 1. The user is less sure of the presence of water with a value of 0 or 1 registering on the mapping, the user is somewhat more sure of the presence of water with a value of 2, and fairly sure of the presence of water with a value of 3 registering on the mapping.

#### 4.2.6 Finished Data Product – Farmland Identification Grid for Lower Mekong Basin

A composite mapping data product of farmland for the entire Lower Mekong Basin has been created utilizing a multiple index methodology. This mapping is useful on a regional scale for the determination of farmland which is used in tools described later in this research. This composite mapping of all Landsat panels for the Lower Mekong Basin utilizes Landsat panels obtained generally in January and February of 2003. Some panels are not available for every month, and therefore a limited number of the panels were taken from December 2002, and March of 2003.

Composite farmland mapping is shown on a "zoomed out" scale in the following figure. The user can zoom to any part of the Lower Mekong Basin and find relatively high resolution (30 meter pixels) imagery showing perennial streams as shown in the subsequent figure.

The data product has been created in a georeferenced TIFF raster format, and can be utilized in open source GIS software as well as ArcGIS software, by Esri.

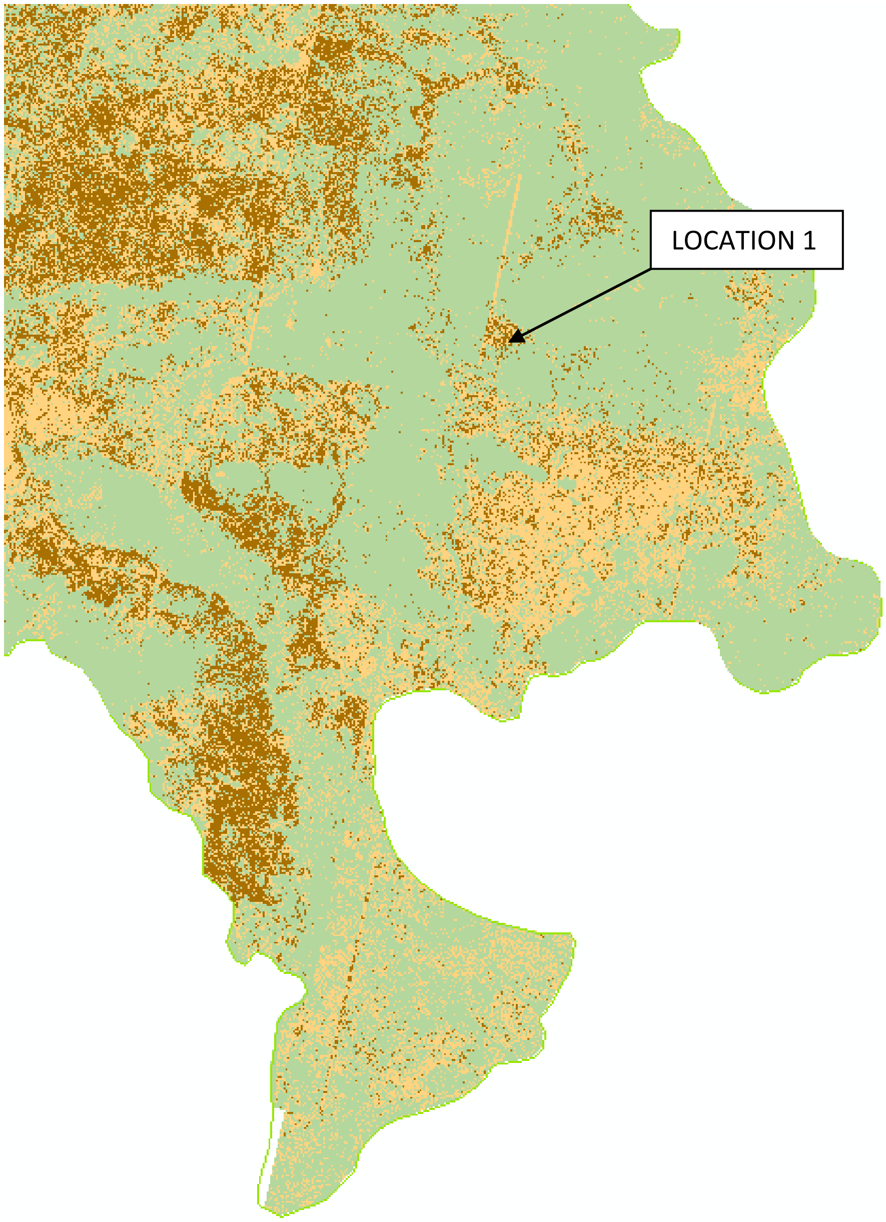



**FIGURE 4.2.8** – ArcMap view of composite multiple index map / farmland identification map of the Lower Mekong Basin. “Seams” between landsat scenes appear as tan lines running diagonally across the composite map data product.

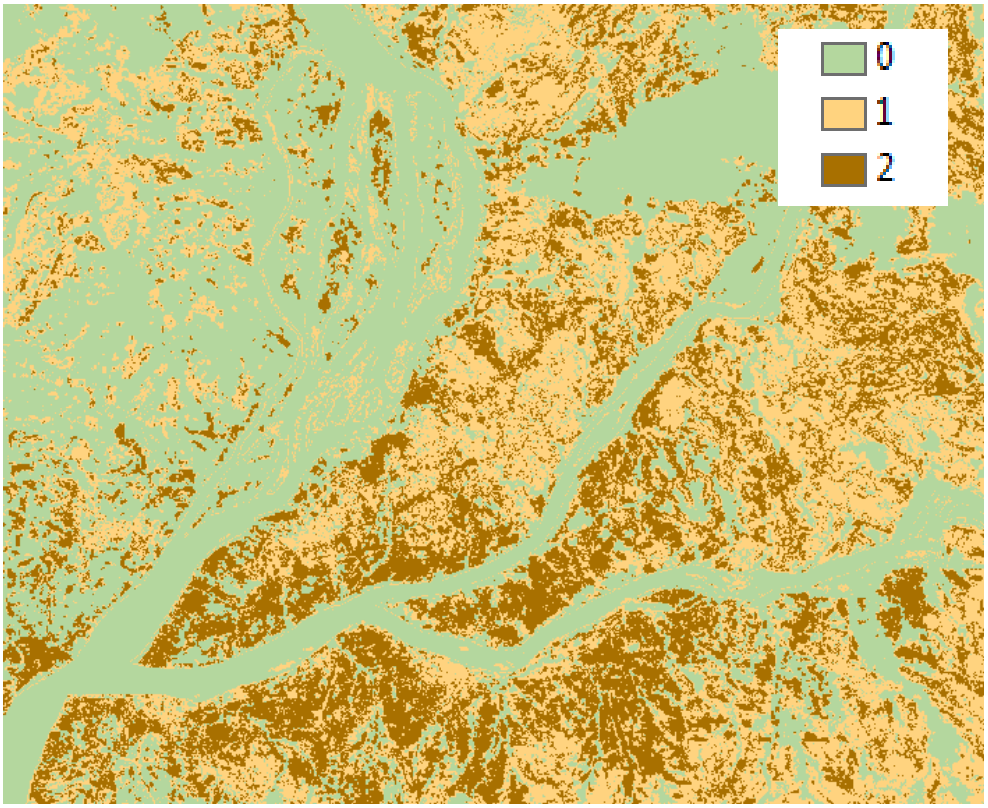



**FIGURE 4.2.9** –Arcmap view zoomed in at Location 1. The user is less sure of the presence of farmland with a value of 0 or 1 registering on the mapping. The user is fairly sure of the presence of farmland with a value of 2 registering on the mapping.

## 4.3 GEOSPATIAL POPULATION DATA PRODUCTS

### 4.3.1 Geospatial Population Data Product Creation

This chapter of the research explores geospatial population data products. The Landscan data set discussed previously in this research was the basis of the creation of geospatial population data products. Methodology for the creation of data products based on the Landscan data set is discussed in detail in the following chapters.

The Landscan dataset provides population data for nearly the entire globe and is based on data from 2008. The data is available on a 1 kilometer meter grid (1000 m x 1000 m pixels), with each grid cell listing population within that 1 kilometer square. Values of grid cells represent and average (ambient) population distribution.

Landscan data was downloaded as a single data file for the entire globe and was 3.4 GB in size. When downloaded initially, Landscan data is in a georeferenced GRID raster format on a geographic coordinate system. Landscan data must then be re-projected onto a geographic coordinate system in order to be manipulated within ArcMap (by ESRI). For the Lower Mekong Basin, the Landscan data was re-projected onto the WGS 1984 UTM Zone 48N coordinate system.

### 4.3.2 Finished Data Product – Basin Population Map for Lower Mekong Basin

As shown in the following figure, the Landscan grid raster has been extracted utilizing the Spatial Analyst Tool: "Extract by Mask" in ArcMap, SRTM panels for the entire Lower Mekong Basin, encompassing Thailand, Laos, Cambodia, and Vietnam. The GRID raster was then exported as a georeferenced TIFF raster file, with a file size of 11.5 MB for the Lower Mekong Basin. Since the data product has been created in a georeferenced TIFF format, it can be utilized in open source GIS software as well as ArcGIS software, by Esri.

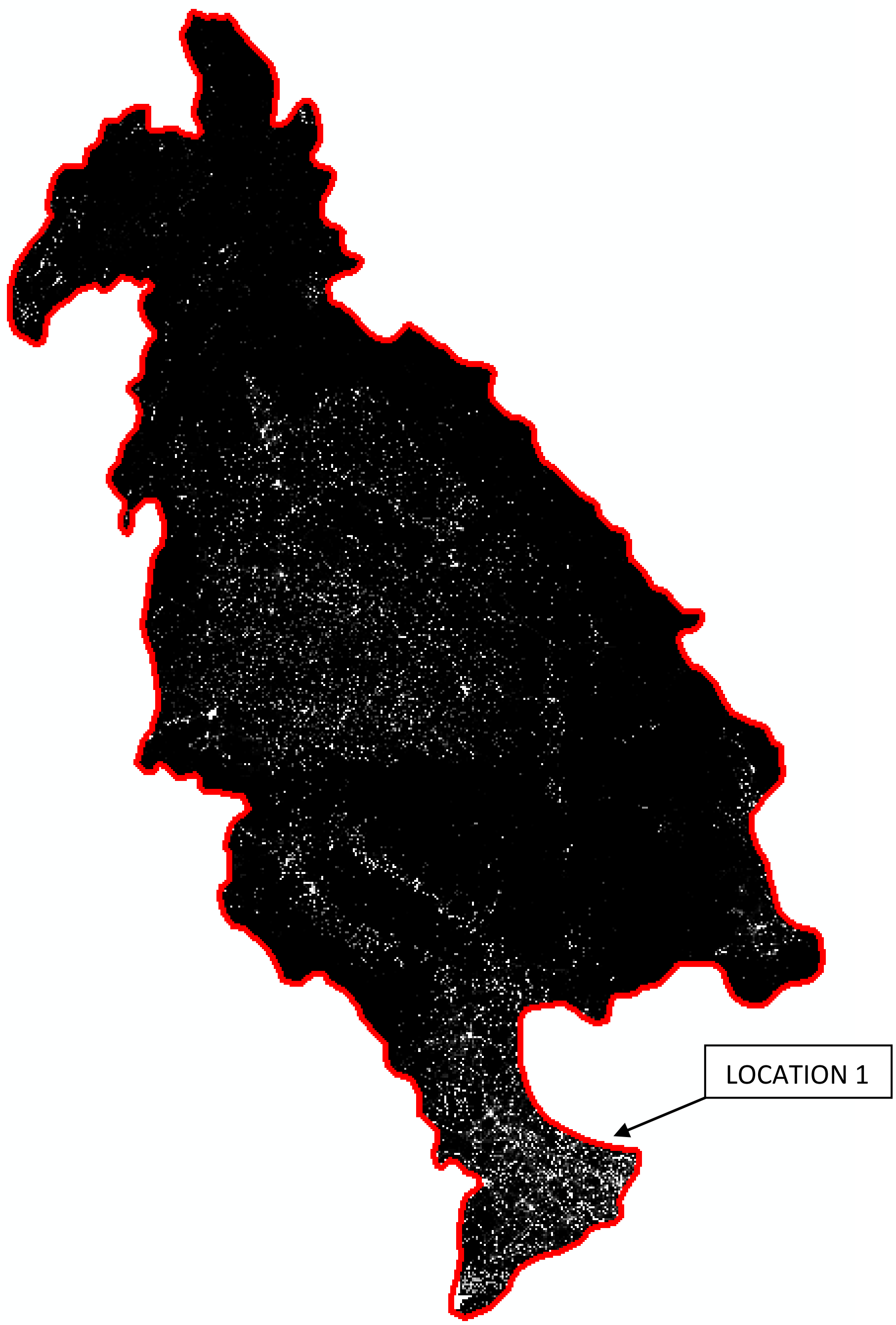



**FIGURE 4.3.1** –ArcMap view of basin population map of Lower Mekong Basin (outlined in red).


**FIGURE 4.3.2** – ArcMap view of Figure 5.3.1 zoomed in at Location 1. In this figure, black indicates no significant population (0 to 128 persons per square kilometer). Darker shades of grey indicate low population (128 to 3587 persons per square kilometer), lighter shades of grey indicate higher population (3587 to 48045 persons per square kilometer).

## 4.4 GEOREFERENCED SATELLITE IMAGERY

### 4.4.1 Georeferenced Satellite Imagery Data Product Creation

This portion of the research explores satellite imagery and methods to capture and georeference satellite imagery for use in a geographic information system. Google Earth imagery, discussed previously in Chapter 3, was the basis of the creation the georeferenced satellite imagery discussed in this section.

Moderate to high resolution satellite imagery is now available for most of the planet. Several commercial providers currently offer satellite imagery products that have up to 0.5m pixel resolution. At this level of resolution, natural and man-made features can be clearly identified.

Google Earth is a free source of this aerial imagery. The imagery Google Earth offers is taken from commercial sources, and is free of charge. Google Earth accredits the commercial source at the bottom of each image. This research shows that images which can be taken from Google Earth are a valid source of data for a water resource decision support system for developing nations. If imagery supplied by Google Earth is too limited or becomes unavailable, any particular image or set of images could be obtained from the commercial source of the imagery for a fee.

Methodologies for georeferencing and utilizing this imagery are presented in this section, and are intended for academic purposes only. It is noted that commercial usage of Google Earth imagery for profit without obtaining a rights clearance from Google may represent copyright infringement.

From Google Earth (2014):

*"We're flattered to hear that you're further incorporating Google Earth into your online world. You can personally use an image from the application (for example on your website, on a blog or in a word document) as long as you preserve the copyrights and attributions including the Google logo attribution. However, you cannot sell these to others, provide them as part of a service, or use them in a commercial product such as a book or TV show without first getting a rights clearance from Google."*

*https://support.google.com/earth/answer/21422?hl=en*

### 4.4.2 Finished Data Product – Satellite Imagery With Topographic Background

Georeferenced high resolution imagery, as discussed in Chapter 4.4, has been combined with the SRTM Digital Elevation Model created in this research for the Lower Mekong Basin. High resolution imagery for the village of Patumphon (southern Laos), the city of Vientiane (northern Laos), and the city of Phnom Penh (southern Cambodia) have been imported and georeferenced within an ArcMap document.

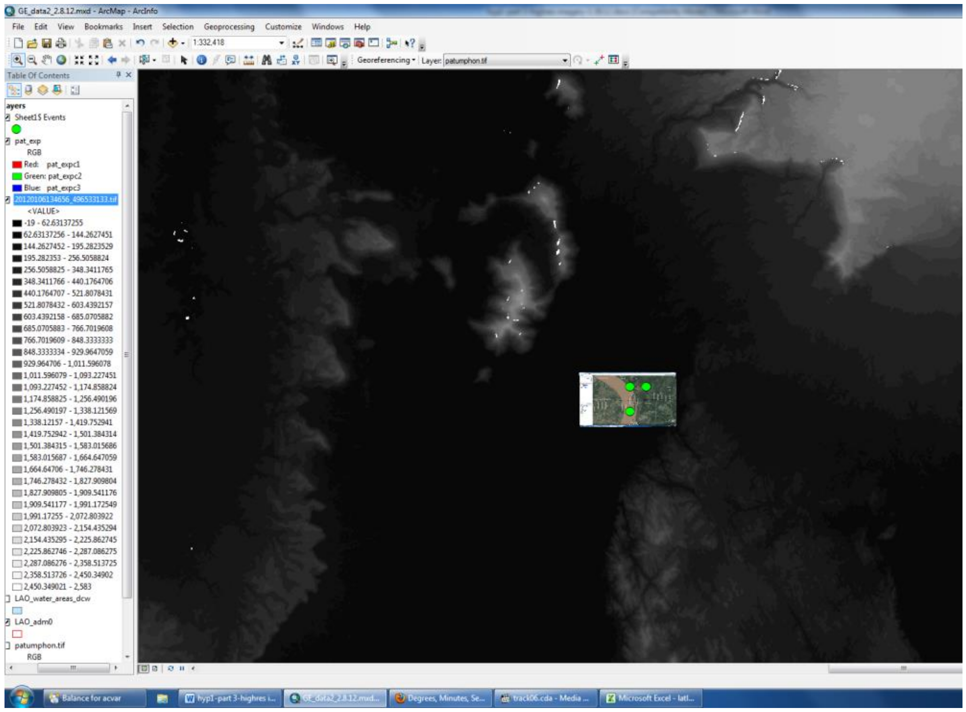
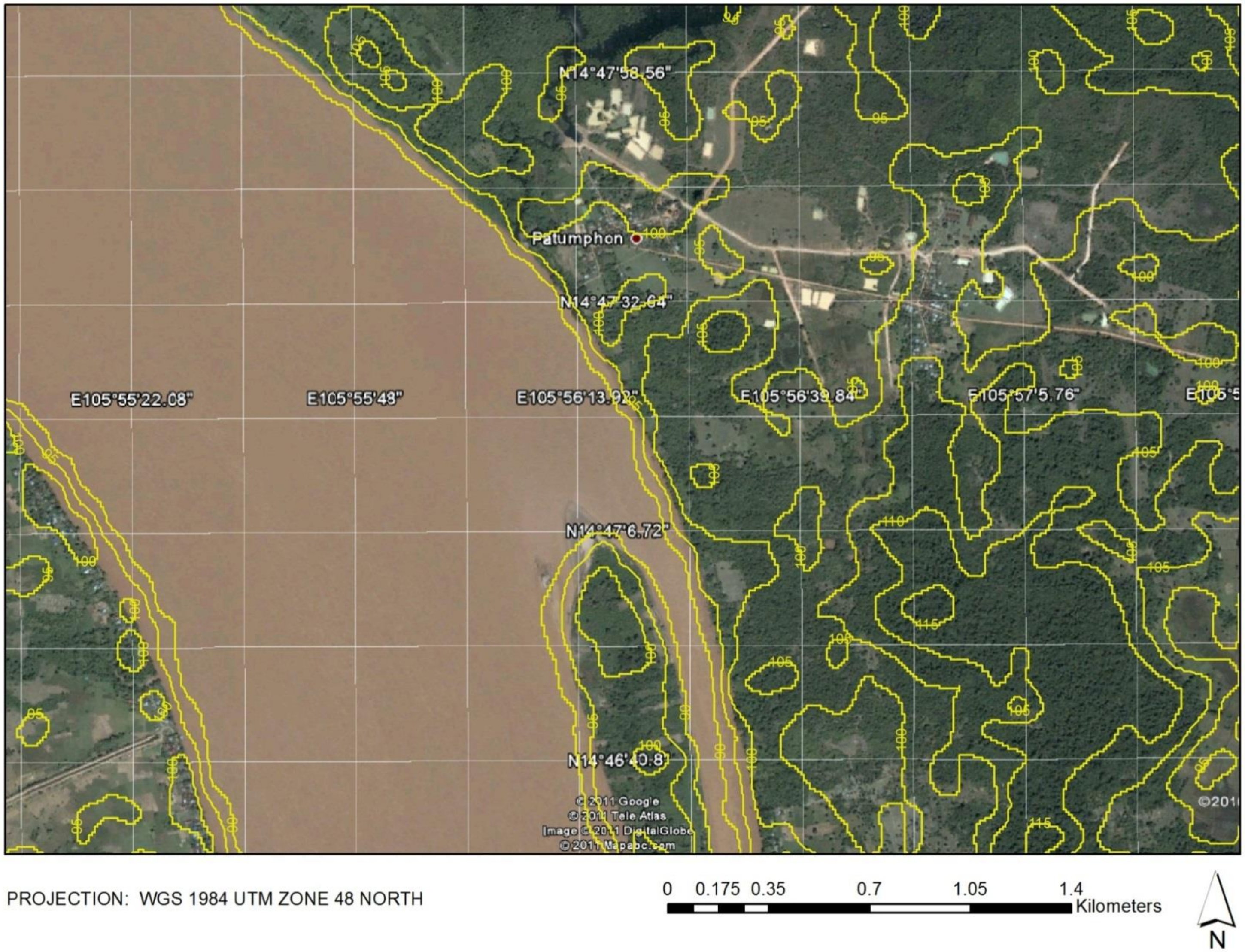


**FIGURE 4.4.1** –Village of Patumphon (southern Laos) with SRTM DEM in background. The three points of reference utilized to align and scale the image in GIS are shown as three green dots in an inverted “L” pattern.

The DEM can be used in ArcMap to create elevation contours, which can provide the user with a sense of topographic relief against the background of the satellite image. The image below is the village of Patumphon with contours generated at an interval of 5 meters utilizing the Shuttle Radar Topography Mission (SRTM) digital elevation model. The data product has been created in a georeferenced TIFF format, and can be utilized in open source GIS software as well as ArcGIS software, by Esri. This overlay of a satellite image with the SRTM data can be done for most areas of the world, as both SRTM data and satellite imagery are available for much of the globe.

## PATUMPHON




PROJECTION: WGS 1984 UTM ZONE 48 NORTH

Following are Google Earth images of Vientiane (northern Laos), and Phnom Penh (southern Cambodia) imported into GIS. Following these images are 5 meter interval contour maps created in GIS utilizing the Shuttle Radar Topography Mission (SRTM) digital elevation model.

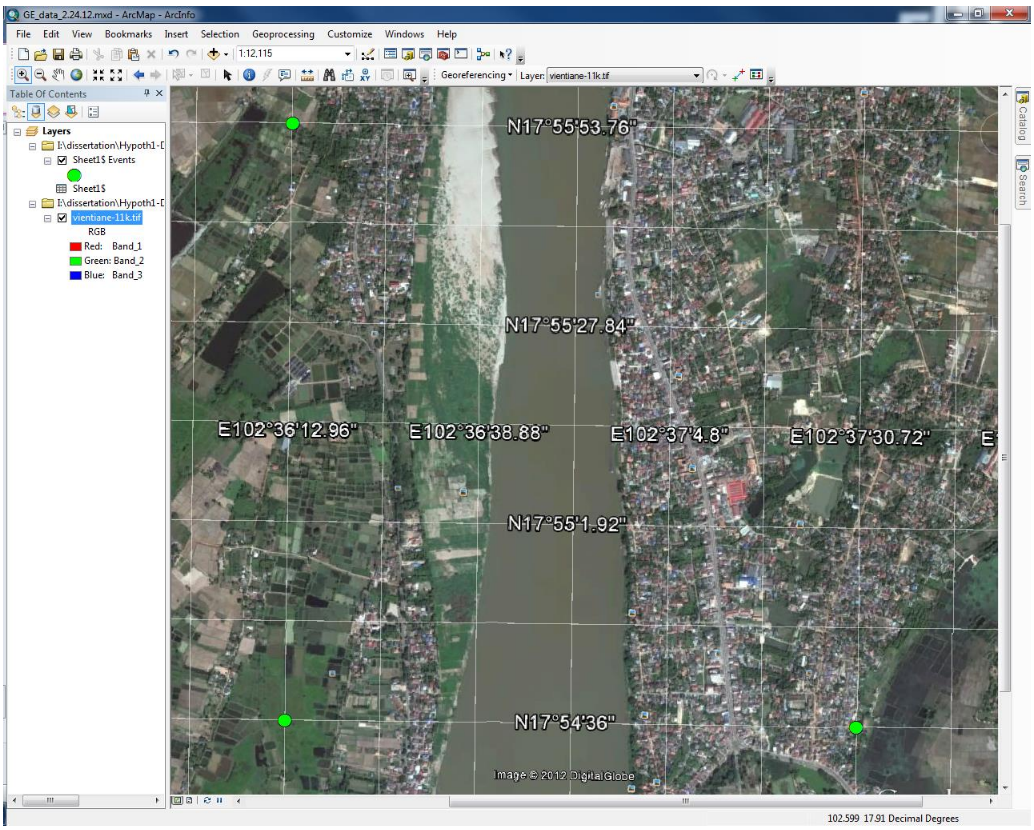



**FIGURE 4.4.2** –City of Vientiane (northern Laos) imported into GIS. The three points of reference utilized to align and scale the image in GIS are shown as three green dots in an "L" pattern.

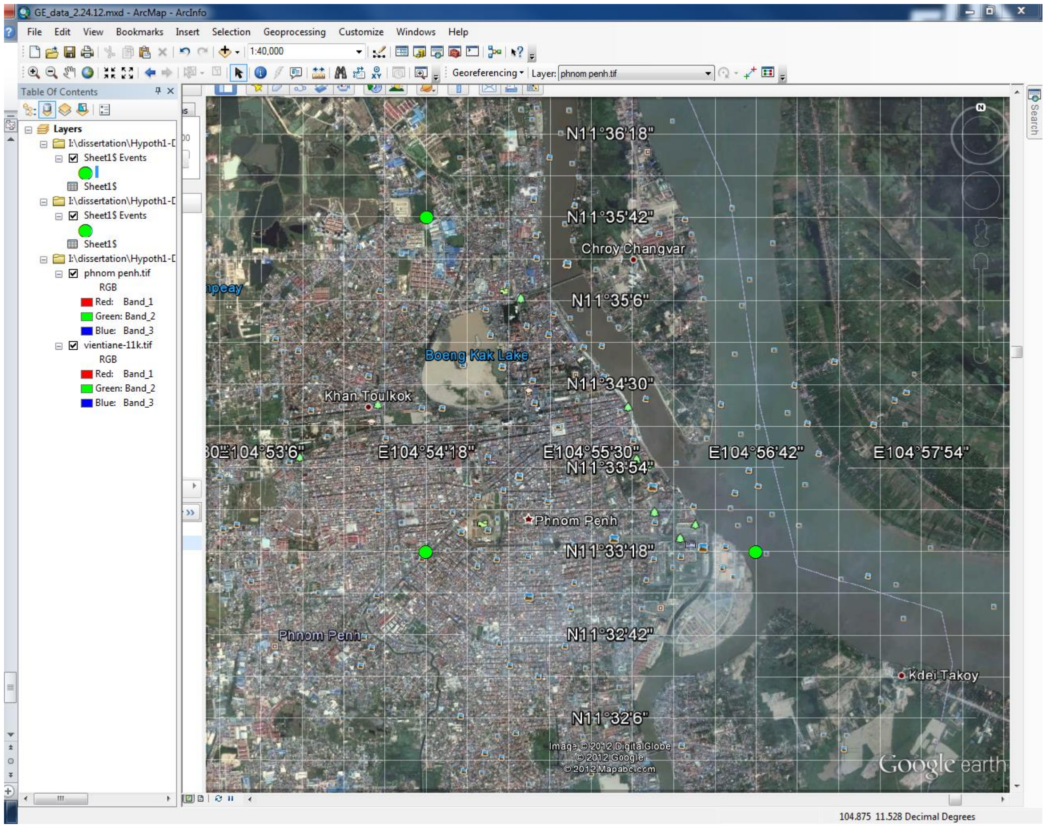
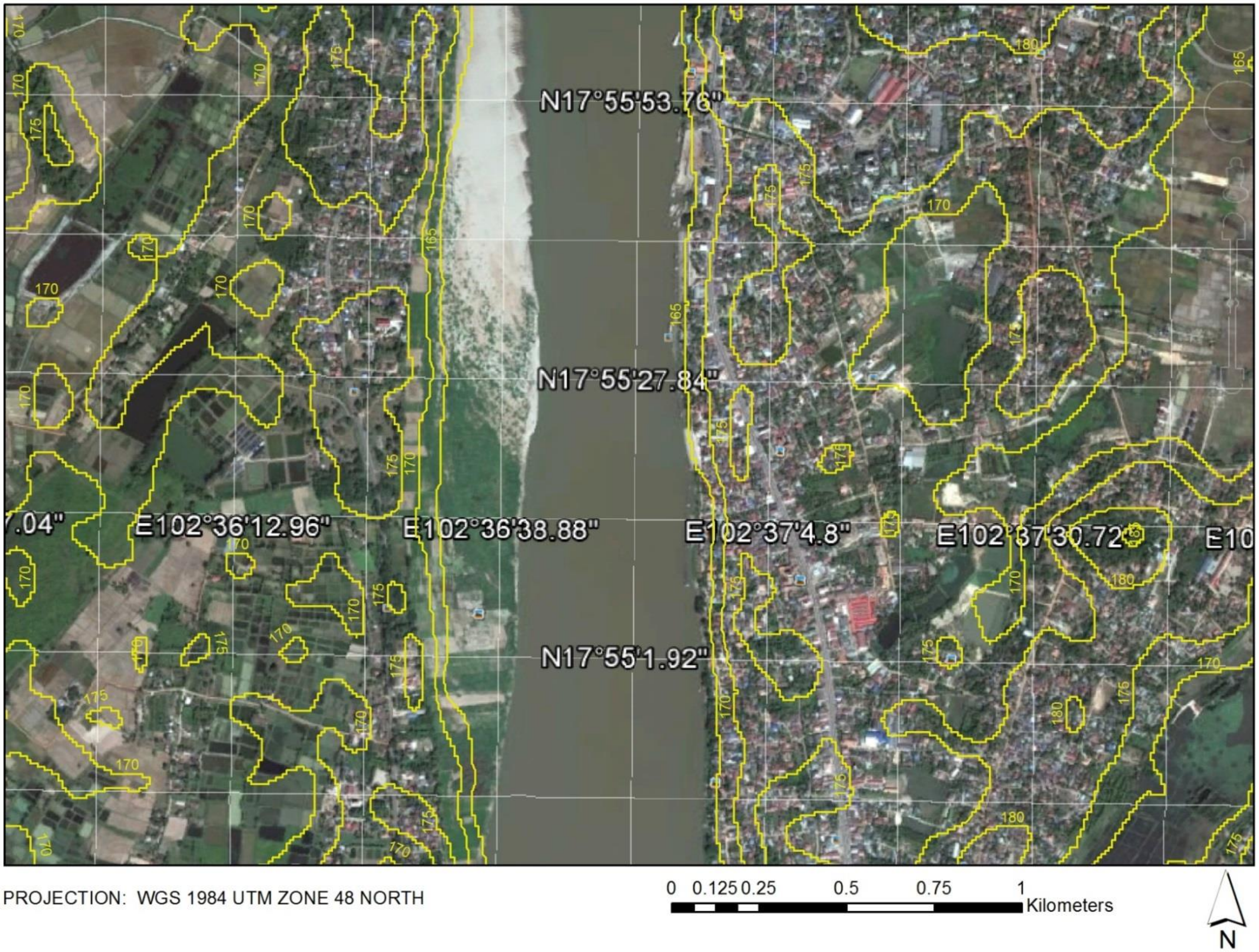


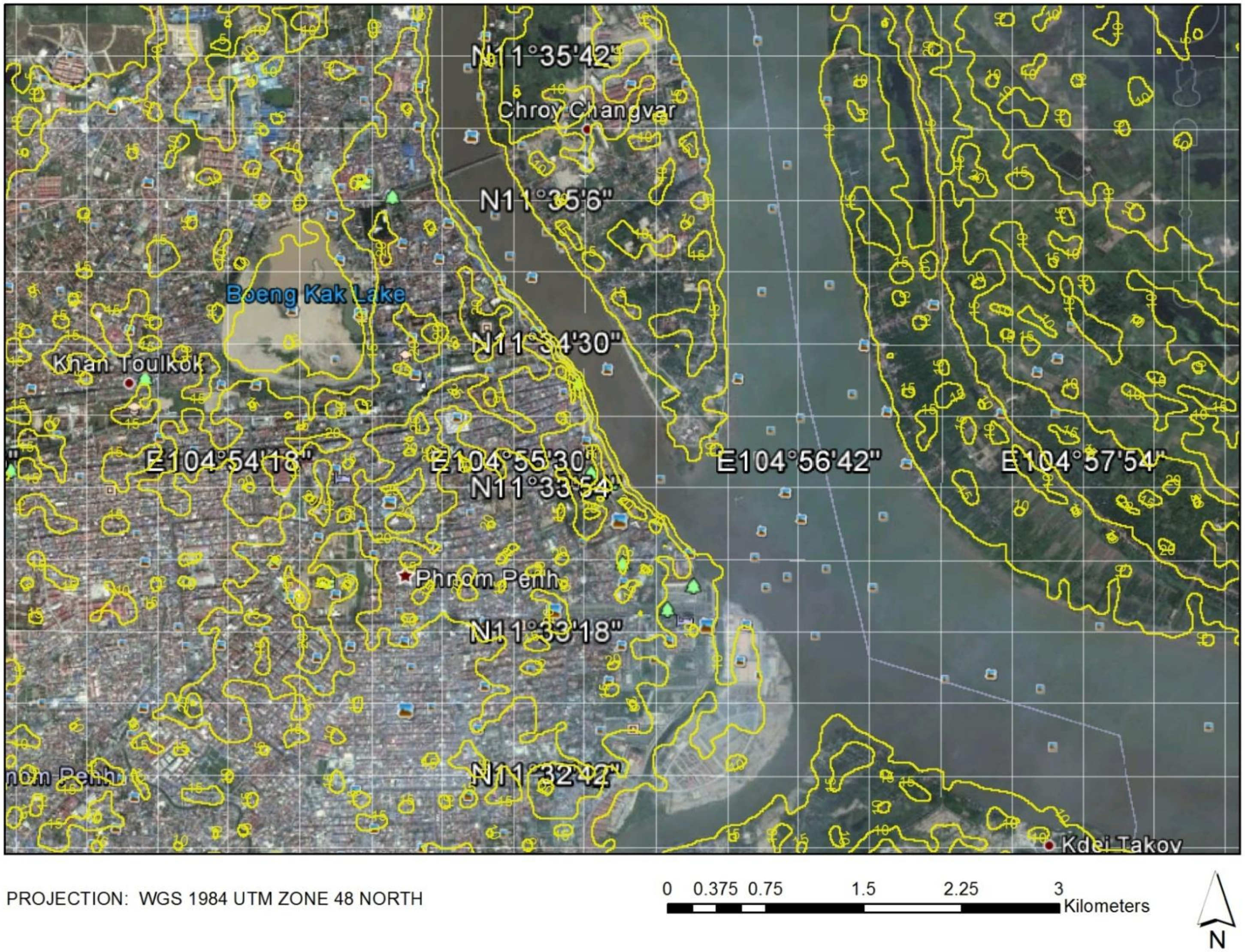

**FIGURE 4.4.3** –City of Phnom Penh (southern Cambodia) imported into GIS. The three points of reference utilized to align and scale the image in GIS are shown as three green dots in an "L" pattern.

## VIENTIANE




PROJECTION: WGS 1984 UTM ZONE 48 NORTH

## PHNOM PENH




PROJECTION: WGS 1984 UTM ZONE 48 NORTH

### 4.4.3 Moderate Resolution Satellite Imagery Data Products

Moderate resolution satellite imagery has been put together for the Lower Mekong Basin utilizing the methodology outlined earlier in this chapter of the research. Google Earth Images at an altitude of roughly 200 miles were taken via screen captures, and saved as TIFF format images in the program Adobe Photoshop. TIFF format images were aligned and georeferenced within the ArcMap environment. Georeferenced images were then exported using the ArcMap "Export Data" function. Finally, a composite image was created for the overall Lower Mekong Basin.

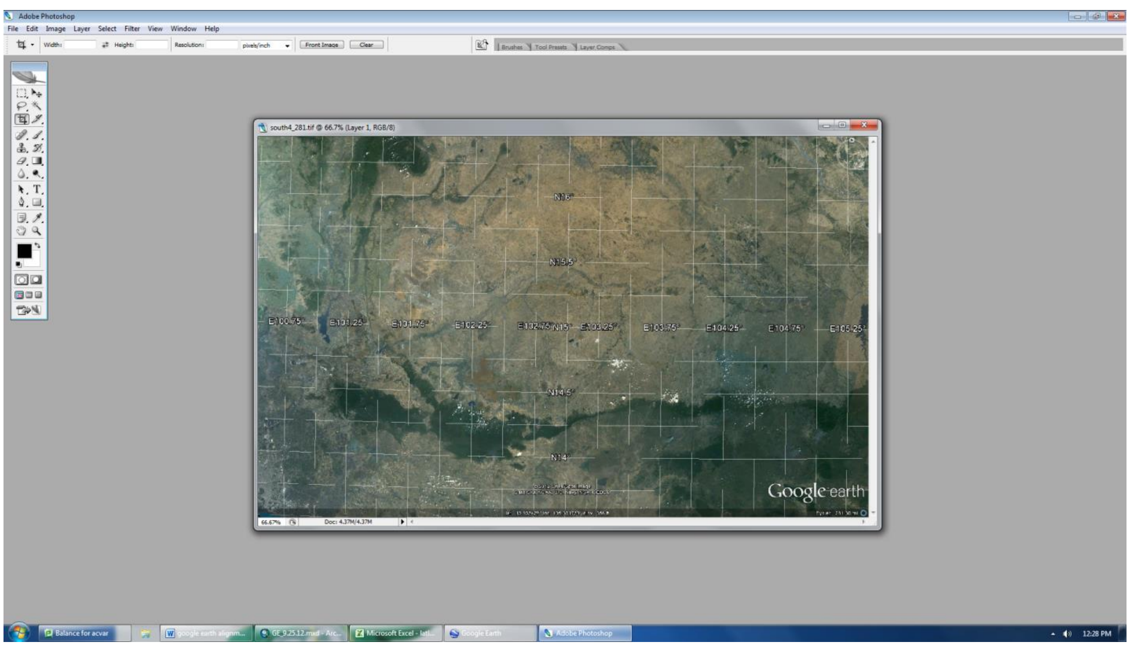



**FIGURE 4.4.4** - A screen capture from Google Earth is saved as a TIFF in Adobe Photoshop.

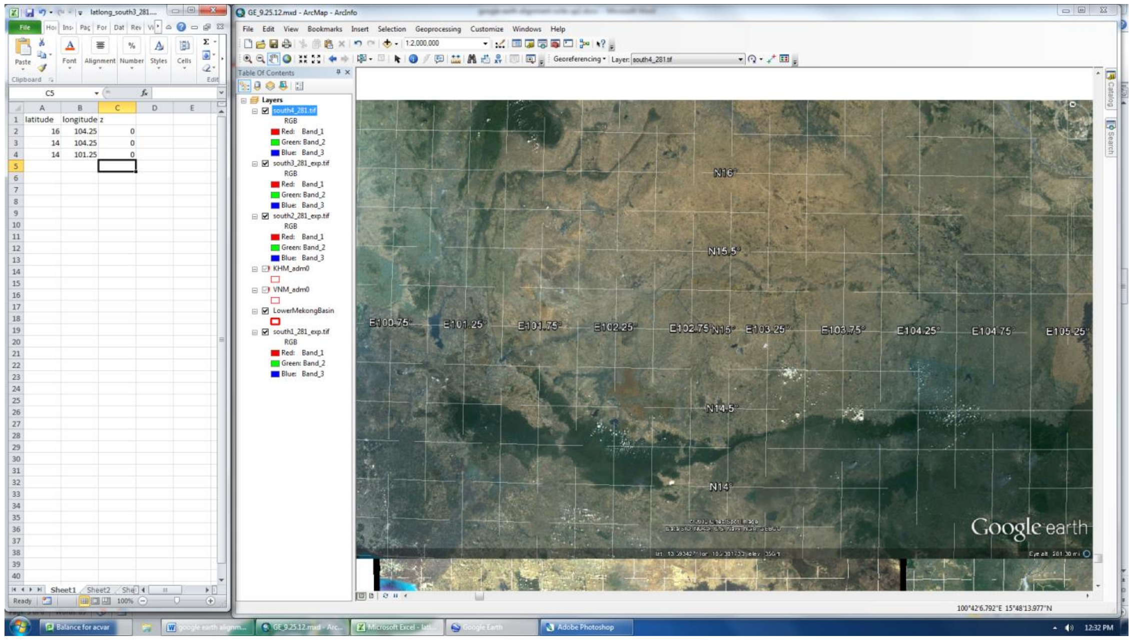
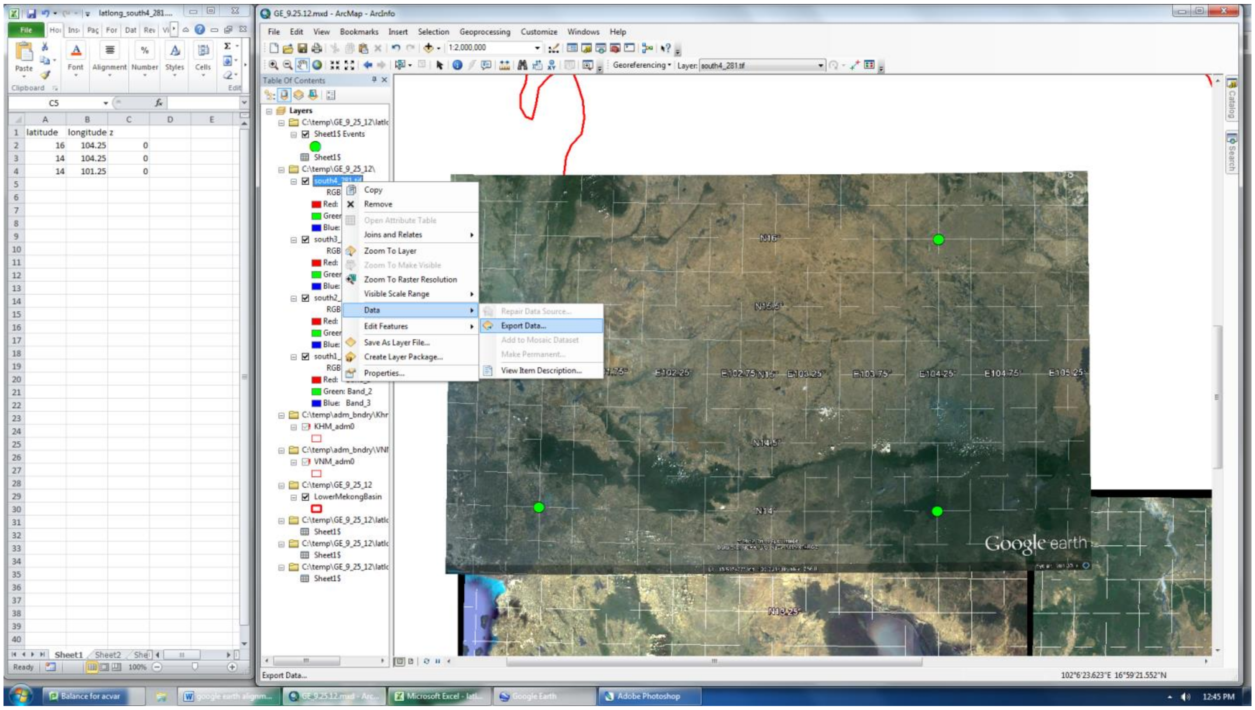


**FIGURE 4.4.5** - An ArcMap document is open on the right; a Microsoft Excel table is open on the left. Latitude and Longitude values are observed and entered into the Excel table. The Excel table is then utilized for the creation of reference points in ArcMap.



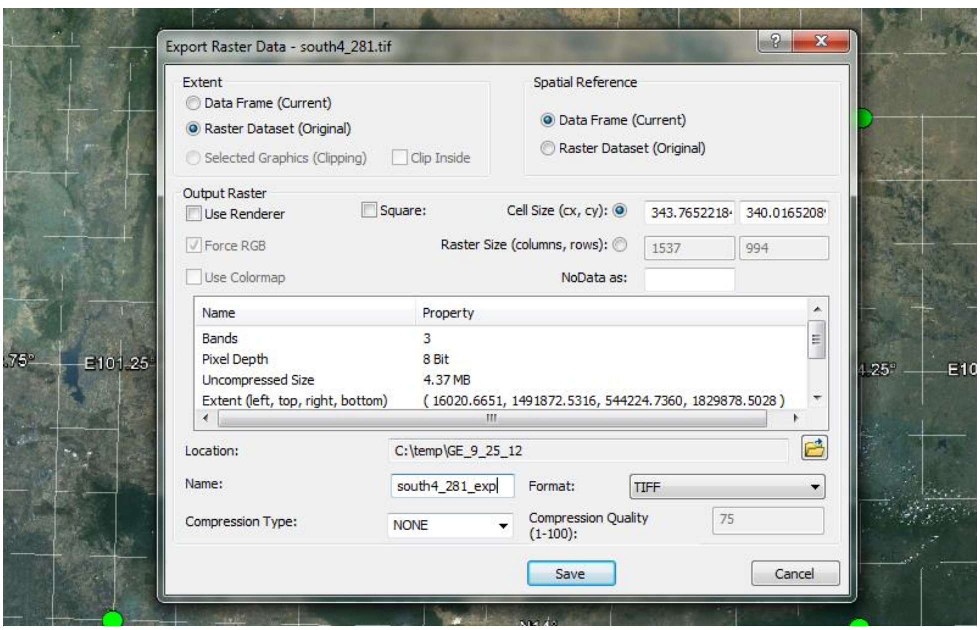



**FIGURE 4.4.6** - The image is georeferenced in ArcMap using the "Georeferencing Tools" based on three latitude/longitude points defined by the Excel table. The image is exported as a TIFF format georeferenced image using "Data – Export Data" tool in ArcMap.

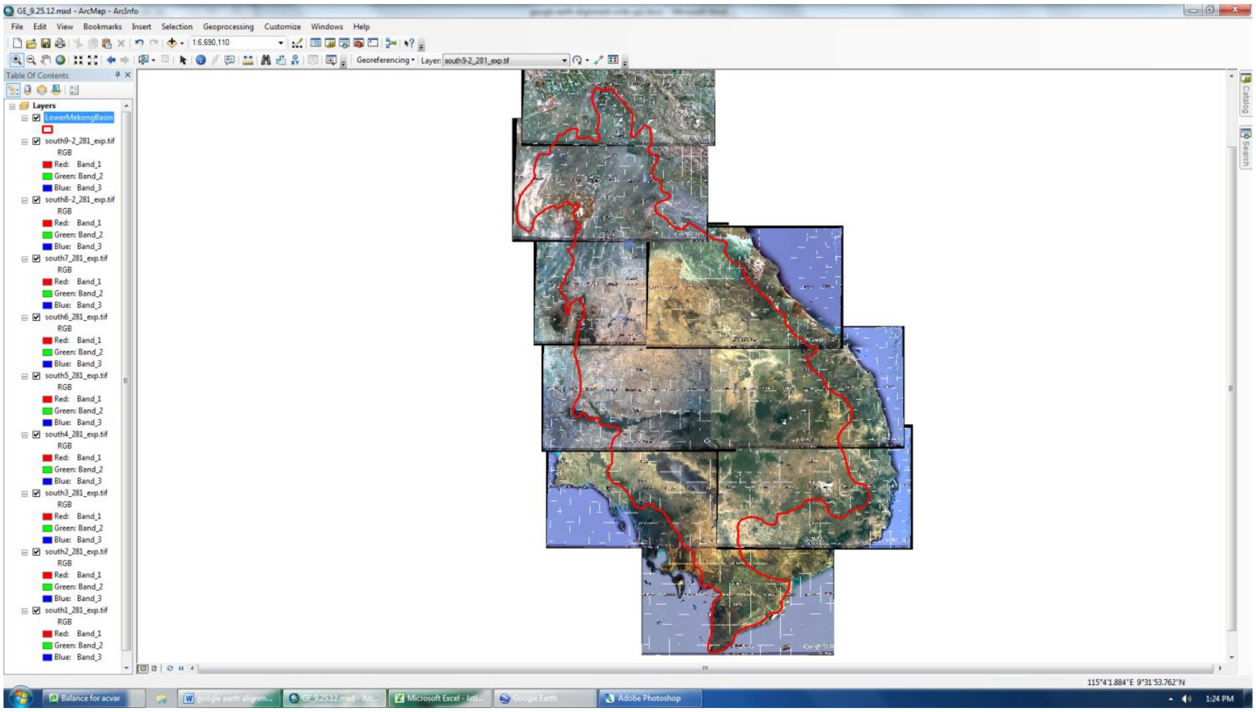


**FIGURE 4.4.7** – ArcMap view of composite moderate resolution satellite imagery of overall Lower Mekong Basin (outlined in red).

### 4.4.4 Finished Data Product – Satellite Imagery for Lower Mekong Basin

Moderate resolution (approx. 350 meter pixels) images from Google Earth have been georeferenced within ArcMap to create an overall satellite image of the Lower Mekong Basin. Once georeferenced, image panels have been combined using the ArcMap Data Management Tool “Mosaic to New Raster”. This composite satellite image was then extracted using the Lower Mekong Basin outline as a mask using the ArcMap Spatial Analyst Tool “Extract by Mask”.

The finished data product is shown in the following figure. The data product has been created in a georeferenced TIFF raster format, and can be utilized in open source GIS software as well as ArcGIS software, by Esri.

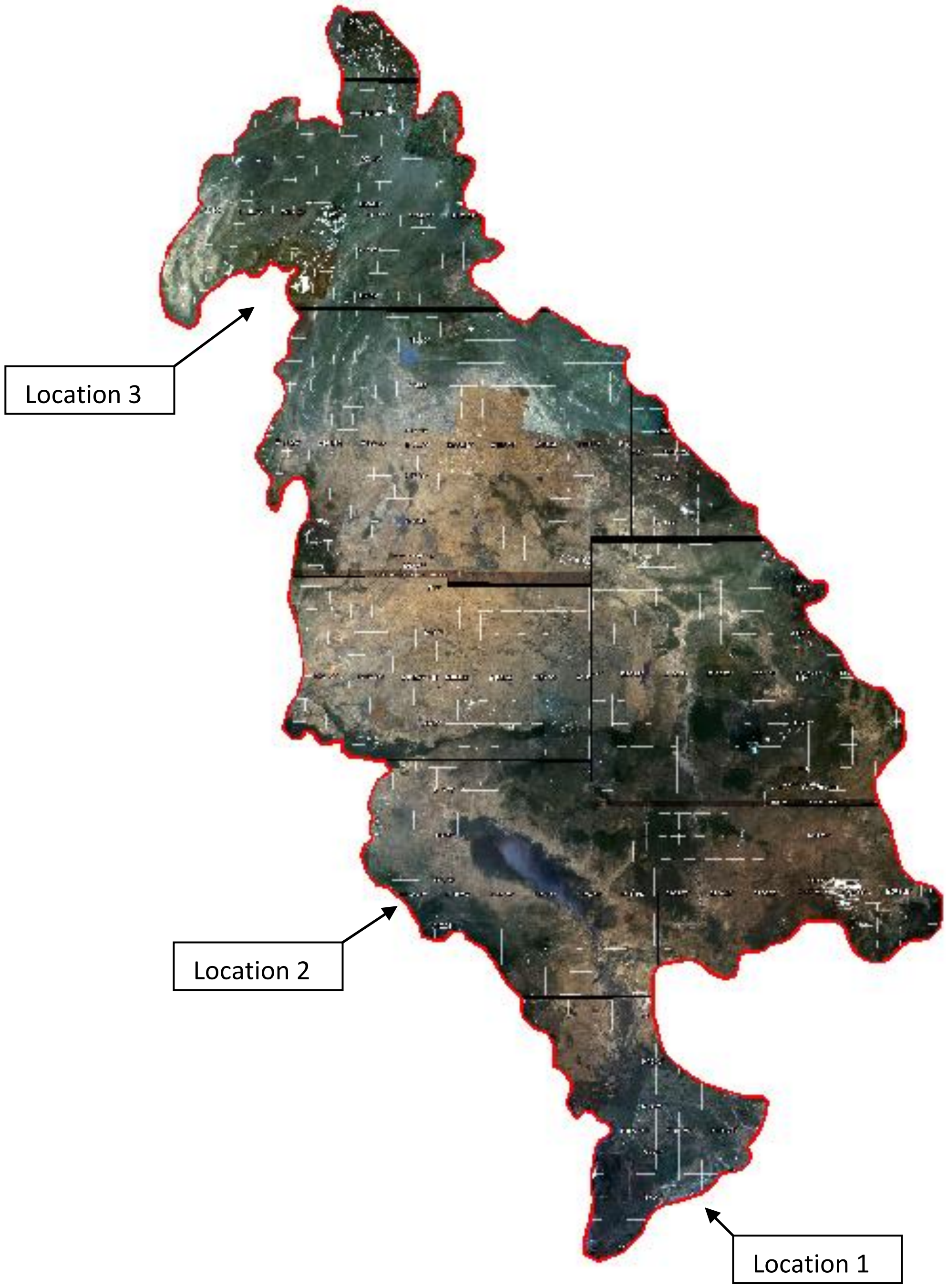



**FIGURE 4.4.8** – ArcMap view of moderate resolution (approx. 350 meter pixels) overall satellite imagery data for the Lower Mekong Basin.

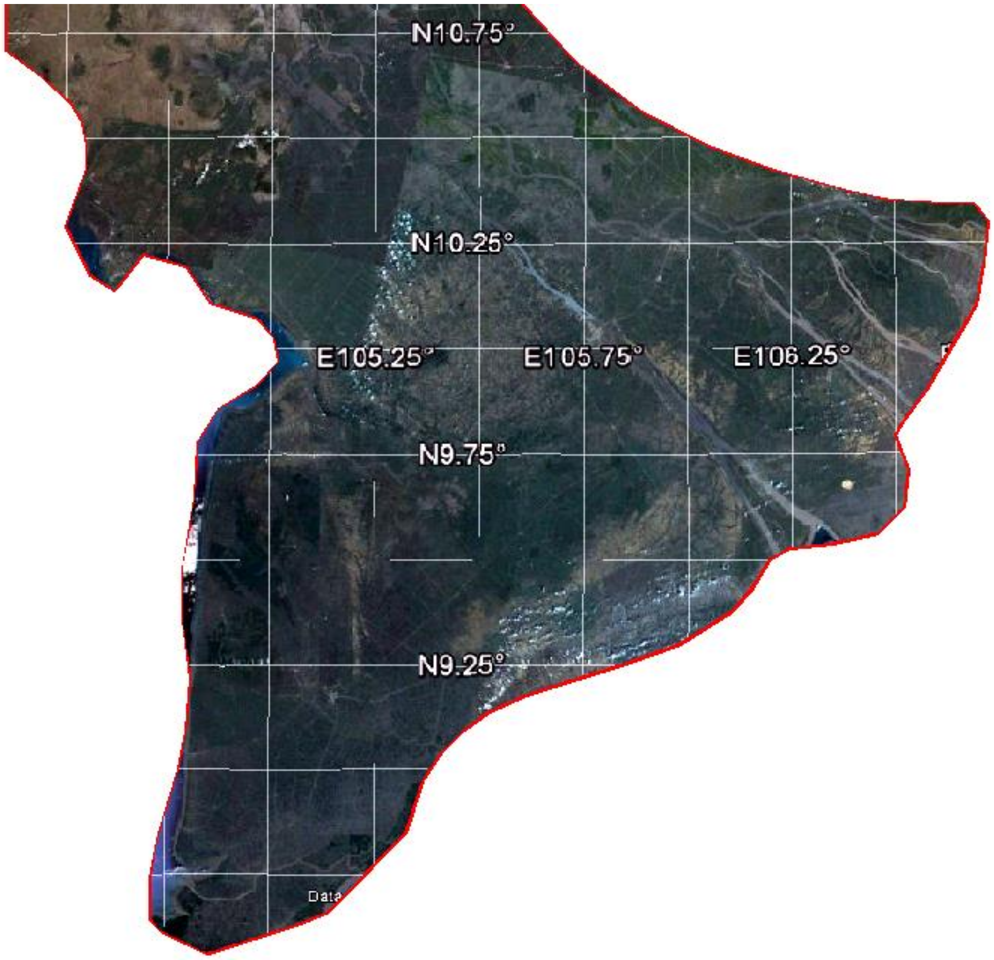



**FIGURE 4.4.9** – ArcMap view zoomed at location 1.


**FIGURE 4.4.10** – ArcMap view zoomed at location 2.

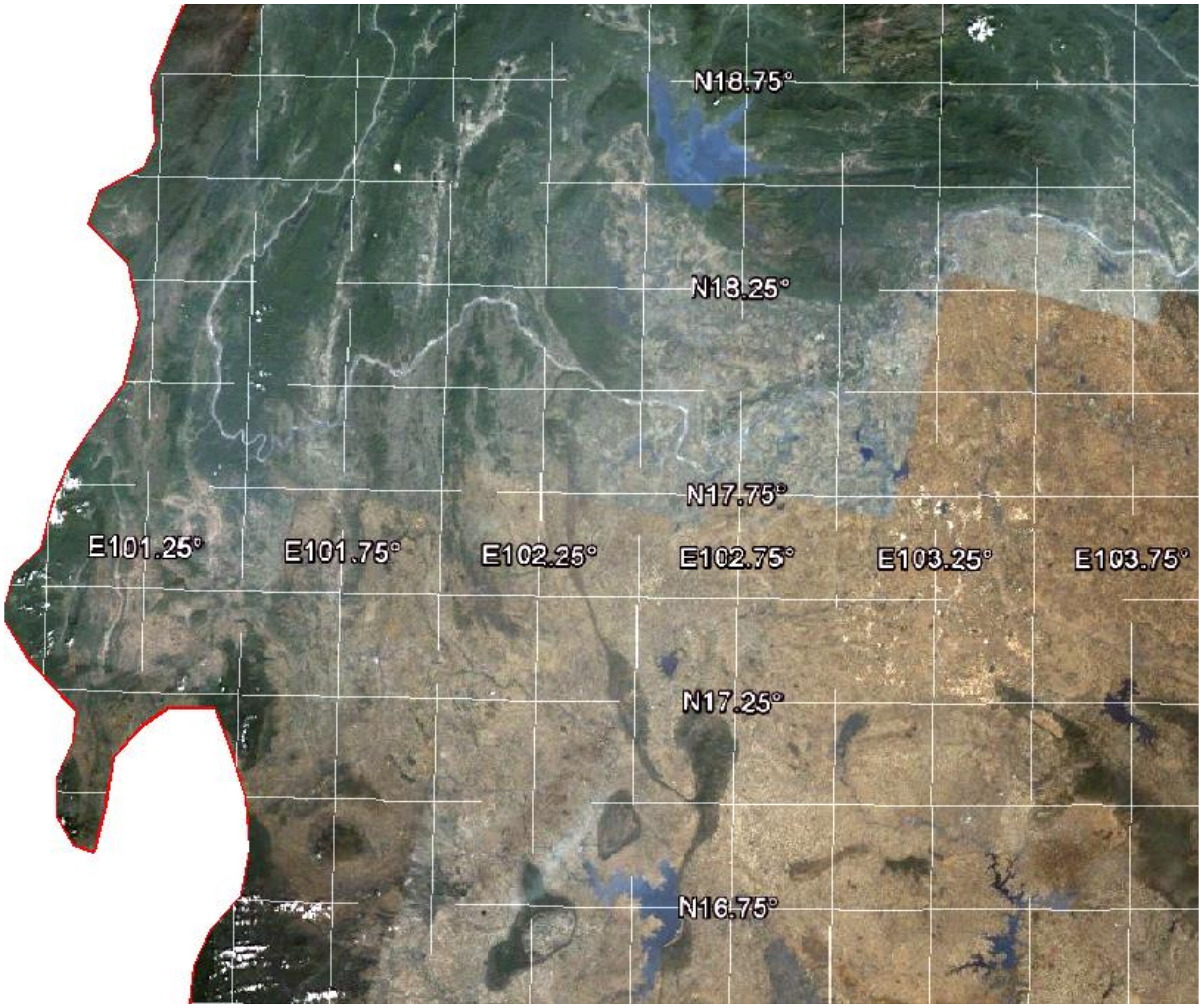



**FIGURE 4.4.11** – ArcMap view zoomed at location 3.

## 4.5 DATA PRODUCT RESEARCH CONCLUSIONS

### 4.5.1 Conclusions

This chapter of the research has demonstrated the use of ArcMap by Esri to create data products based on the SRTM data set. These data products have been created in a format which can be utilized in open source Geographic Information Systems (GIS). The open source GIS software Quantum GIS has been utilized to test the use of data products in a non-proprietary geographic information system.

The data products discussed in this chapter of the research are utilized as the base data source for the tools and models discussed in Chapter 5. Ten tools and models are discussed which utilize the geospatial data for the purposes of generating information pertinent to reservoir planning and decision support.

The high resolution digital elevation model (DEM) data product created in this research will be utilized for a number of purposes. The flow accumulation data product and the flowline elevation data product rely on the overall DEM as a basis for their creation. The DEM will be utilized for Geospatial terrain data (digital elevation models, SRTM data), which can be applied to reservoir planning for hydrologic studies, feasibility assessments, elevation comparisons for determining serviceable areas, etc.

The high resolution flow accumulation data product created in this research will be utilized for a peak flood flow estimation tool. This tool will be used to provide large scale approximations of peak flood flow at points within watersheds to estimate the flood control benefit of potential reservoir sites. The flow accumulation grid will also be utilized to create a basin yield estimation tool. This tool will be utilized for country scale feasibility studies to determine estimates of annual basin yield at potential reservoir sites.

The high resolution flowline elevation data product created in this research will be utilized in conjunction with the DEM data product for the creation of a reservoir feasibility tool. This tool will allow the user to compare potential reservoir sites to elevations of potential service points (villages, towns, cities, farm areas, etc.).

The perennial stream data product discussed in this chapter of the research will be utilized to support tools which will be used in a prototype decision support system for reservoir planning in developing nations. The user can zoom to areas of interest anywhere within the Lower Mekong Basin, and very quickly identify streams that are likely to flow on a perennial basis. The high resolution (30 x 30 meter grid cells) of this data product also can be utilized for estimating the waterway width. The user will be able to classify streams of interest by waterway width.

The basin population data product discussed in this chapter of the research will be utilized to support tools which will be used in a prototype decision support system for reservoir planning in developing nations. The end user will be able zoom to areas of interest anywhere within the Lower Mekong Basin, and very quickly quantify the potential population that will be served or affected by a potential reservoir site.

High resolution imagery has been combined with the SRTM Digital Elevation Model created in this research for the Lower Mekong Basin. High resolution imagery for the village of

Patumphon (southern Laos), the city of Vientiane (northern Laos), and the city of Phnom Penh (southern Cambodia) have been imported and georeferenced within an ArcMap document. The high resolution images have been created in a format which can be utilized in open source Geographic Information Systems (GIS).

Upon creation of the georeferenced high resolution imagery, a DEM can be overlaid in ArcMap to create elevation contours. This can then provide the user with a sense of topographic relief against the background of the high resolution satellite image. Chapter 5.4.3 displays the village of Patumphon with contours generated at an interval of 5 meters utilizing the Shuttle Radar Topography Mission (SRTM) digital elevation model. The data product has been created in a georeferenced TIFF format, and can be utilized in open source GIS software as well as ArcGIS software, by Esri.

Additionally, this chapter of the research has demonstrated the use of ArcMap by Esri to create a Moderate resolution (approx. 350 meter pixels) satellite image of the overall Lower Mekong Basin. The Data product has been created in a format which can be utilized in open source Geographic Information Systems (GIS). The open source GIS software Quantum GIS has been utilized to test the use of the data product.

The data product discussed in this chapter of the research will be utilized to support tools and models discussed in the subsequent chapter. The user can zoom to areas of interest anywhere within the Lower Mekong Basin, and very quickly gain a sense of terrain, land cover, natural, and man-made features.

The first hypothesis set forth in Chapter 2 has been supported within Chapter 4. The first research hypothesis was that data is now available to conduct country-scale water resource decision support in developing nations. The data products that have been discussed in Chapter 4 demonstrate that the data is indeed available, and can be readily utilized for country-scale water resource support in developing nations.

Chapter 4 uses the Lower Mekong Basin as a case study, and demonstrates utilization of the data to create a database for the Lower Mekong Basin. All data utilized is available over the world wide web and is global in nature. Thus, the type of database set up in this research using the Lower Mekong Basin as a case study could be re-created for any data limited area or developing nation in the world.

# 5.0 APPLICATION RESEARCH – CREATION OF TOOLS AND MODELS

### 5.0.1 Introduction

This chapter discusses tools and models that have been created to offer a decision maker the ability to manipulate and model the database represented by the Data Products discussed in the previous chapter. The tools and models presented in this chapter allow efficient means to create new information from the existing data. They provide the decision maker with the ability to conduct high level assessments on a regional scale and answer fundamental questions revolving around the reservoir planning process.

The database and tools that have been created in this research use the Lower Mekong River Basin as a case study. All data products, tools, and models created in this research are based on global data sets that are available for download on the world wide web. Thus, methodology outlined in this research could be duplicated for any region of the globe.

The second and third hypotheses introduced in Chapter 1 are the focus of the current chapter of the research. The second hypothesis, states that the digital data that has recently become available for utilization in a GIS-friendly format can now be exploited for much more efficient water resource planning in developing nations. The third hypothesis states that the newly available data and the utilization of capabilities in GIS can greatly aid in the assessment of flood controlling benefits of reservoirs in developing nations.

The tools and models discussed in this chapter have been created to address some of the key reservoir planning questions relating to both potential benefits that could be realized from the development of a reservoir, as well as the potential adverse impacts resulting from a planned reservoir.   The tools and models can be placed four categories:  general site assessment, adverse impact assessment, benefit assessment, and flood evaluation.

**General site assessment tools/models:**

- Perennial Stream Mapping Data Processing Tool
- Farmland Mapping Data Processing Tool
- Reservoir Storage Tool
- Annual Yield Model
- Flood Discharge Model

**Adverse impact assessment tools/models:**

- Population Displacement Tool
- Farmland Loss Tool
- Average Annual Flow Reduction Model

**Benefit assessment tools/models:**

- Irrigable Area Tool
- Serviceable Population Tool
- Hydropower Yield Model

**Flood Evaluation tools/Models**

- Flood Attenuation Model
- Water Surface Elevation Model/Population Inundation Tool

| Tool / Model | Description | Data Sets, and Data Products Utilized |
|---|---|---|
| 1-Perrenial Stream Mapping Data Processing Tool | Creates Perennial Stream Identification Map | Landsat Data Set |
| 2-Farmland Mapping Data Processing Tool | Creates Farmland Identification Map | Landsat Data Set |
| 3-Reservoir Storage Tool | Creates Reservoir Stage - Storage Rating Table at a Potential Reservoir Site | High Resolution DEM for Lower Mekong Basin |
| 4-Annual Yield Model | Estimates Annual Yield at a Potential Reservoir Site | High Resolution Flow Accumulation Grid for Lower Mekong Basin |
| 5-Flood Discharge Model | Estimates Flood Discharge at a User Specified Point in a Waterway | High Resolution Flow Accumulation Grid for Lower Mekong Basin |
| | | |
| 6-Population Displacement Tool | Estimates Population Displaced by a Proposed Reservoir | Population Map for Lower Mekong Basin |
| 7-Farmland Loss Tool | Estimates the Loss of Farmland Due to a Proposed Reservoir | Farmland Identification Grid for Lower Mekong Basin |
| 8-Ave. Annual Flow Reduction Model | Estimates the Reduction in Average Annual Flow Due to a Proposed Reservoir | High Resolution Flow Accumulation Grid for Lower Mekong Basin |
| | | |
| 9-Irrigable Area Tool | Estimates Irrigable Area Within a User Specified Radius of a Potential Reservoir Site | High Resolution DEM for Lower Mekong Basin;<br>Stream Flowline Elevation Grid For Lower Mekong Basin |
| 10-Serviceable Population Tool | Estimates Serviceable Population Within a User Specified Radius of a Potential Reservoir Site | Population Map for Lower Mekong Basin |
| 11-Hydropower Model | Estimates Hydropower Potential at a given Reservoir Site | High Resolution DEM for Lower Mekong Basin;<br>Stream Flowline Elevation Grid For Lower Mekong Basin |
| | | |
| 12-Flood Attenuation Model | Estimates Flood Attenuation / Reduction Benefits of a Potential Reservoir | Utilizes Data Created in Flood Discharge Model |
| 13-Water Surface Elevation Model / Population Inundation Tool | Estimates Population Inundated by a Flood Event | High Resolution DEM for Lower Mekong Basin; Landsat Data Set; Stream Flowline Elevation Grid For Lower Mekong Basin; Population Map for Lower Mekong Basin |

**TABLE 5.1.1**– Summary of Tools and Models.

Two modes of user interface have been selected to allow the user access to the Tools and Models as shown in the following figures. ArcMap, by ESRI, has been selected as the geographic information system to access and work with geospatial data. Arcmap is also used to work with the geospatial tools created in this research. Excel, by Microsoft, has been selected as the spreadsheet user interface for tools and models created in this research which process the geospatial data.

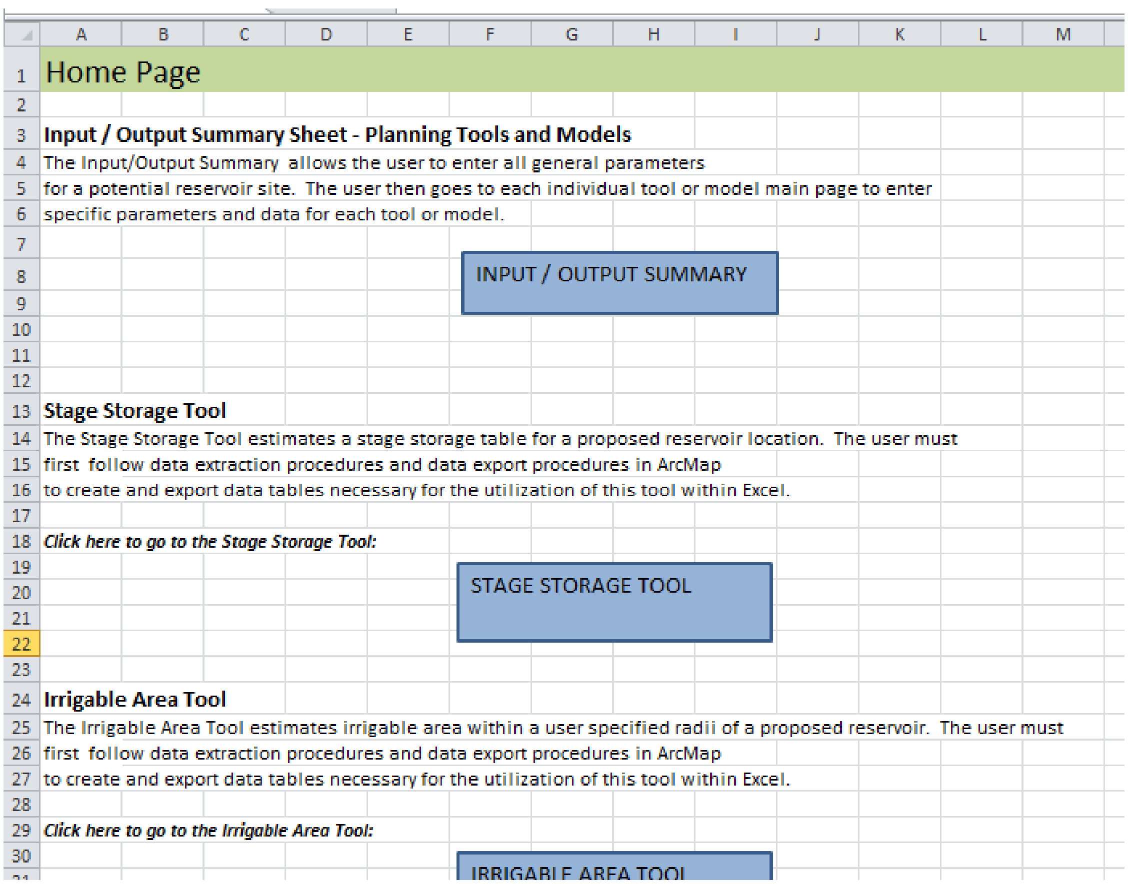



**FIGURE 5.1.2**– Spreadsheet user interface. The first three Tools/Models are shown in this figure. A total of ten Tools/Models is offered in the spreadsheet user interface.

## 5.1 GENERAL SITE ASSESSMENT TOOLS AND MODELS

### 5.1.1 Perennial Stream Mapping Tool

The perennial stream mapping methodology as discussed in Chapter 4, has been set up as a data processing tool in ArcMap. This tool has been created to assist in general site assessment, and provides a means to assess whether a potential reservoir site is located within a perennial waterway.

The Model Builder feature of ArcMap has been used to incorporate the water mapping methodology, and create a user friendly tool. This tool can be utilized by the user to quickly process Landsat data scenes and create composite perennial stream mapping of entire watersheds on a very large scale. This mapping is useful on a regional scale for the determination of streams and rivers that would be initially judged eligible for the placement of a reservoir.

The user begins with generating the required geospatial data by utilizing a tool set up in Model Builder within ArcMap, by ESRI. The tool creates three binary threshold maps based on the water mapping methodology outlined in Chapter 4. Utilizing a multiple index map equation within the Map Algebra function of ArcMap, a multiple index map is created as shown in the following figure. Dark grey indicates a value of 0 , light grey indicates a value of 1, light blue indicates a value of 2, and dark blue indicates a value of 3. A value of 0 indicates no water was present on any of the spectral indices, a value of 3 indicates water was present on all three of the spectral indices. The user is less sure of the presence of water with a value of 0 or 1 registering on the mapping, the user is somewhat sure of the presence of water with a value of 2, and fairly sure of the presence of water with a value of 3 registering on the mapping.

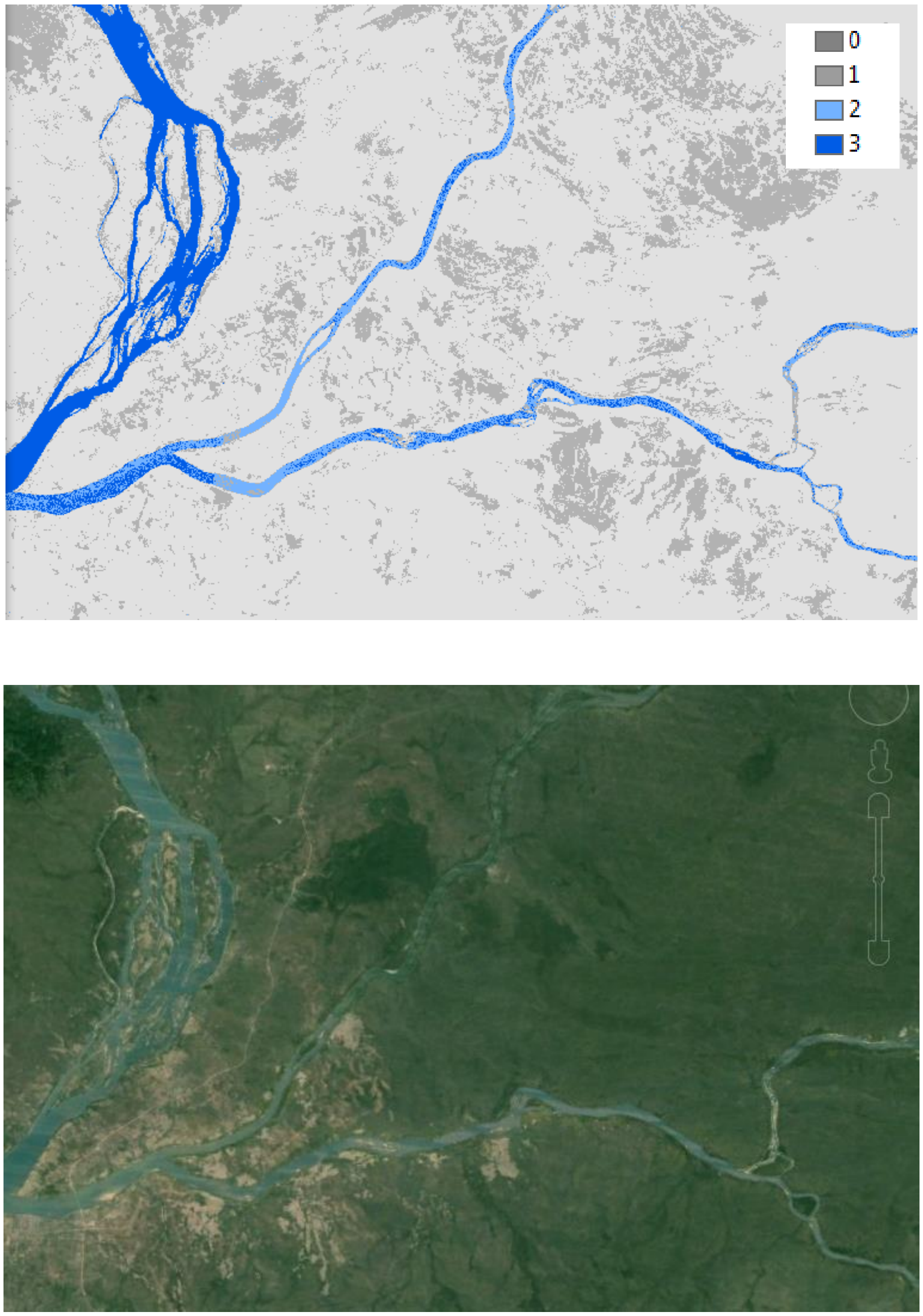
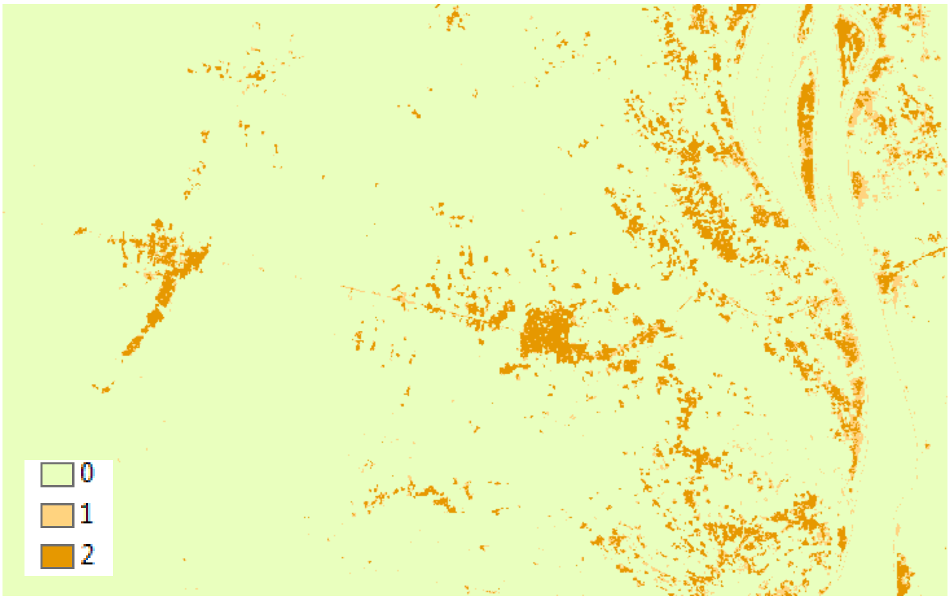



**FIGURE 5.1.1** – Perennial Stream Multiple Index Map (top frame), Google Earth Image of same scene (bottom frame).

### 5.1.2 Farmland Mapping Tool

The farmland mapping methodology as discussed in Chapter 4, has been set up as a data processing tool in ArcMap. This tool has been created to assist in general site assessment, and provides a means to evaluate existing farmland in the vicinity of a potential reservoir. The Model Builder feature of ArcMap has been used to incorporate the farmland mapping methodology, and create a user friendly tool. This tool can be utilized by the user to quickly process Landsat data scenes and create composite farmland mapping of entire watersheds on a very large scale.

The user begins with generating the required geospatial data by utilizing a tool set up in Model Builder within ArcMap, by ESRI. The tool creates two binary threshold maps based on the farmland mapping methodology outlined in Chapter 4. Utilizing a multiple index map equation within the Map Algebra function of ArcMap, a multiple index map is created as shown in the following figure. Light green indicates a value of 0 , light brown indicates a value of 1, and dark brown indicates a value of 2. A value of 0 indicates no farmland was present on any of the spectral indices, while a value of 2 indicates farmland was present in both of the spectral indices. The user is less sure of the presence of farmland with a value of 0 or 1 registering on the mapping, while the user is fairly sure of the presence of farmland with a value of 2.



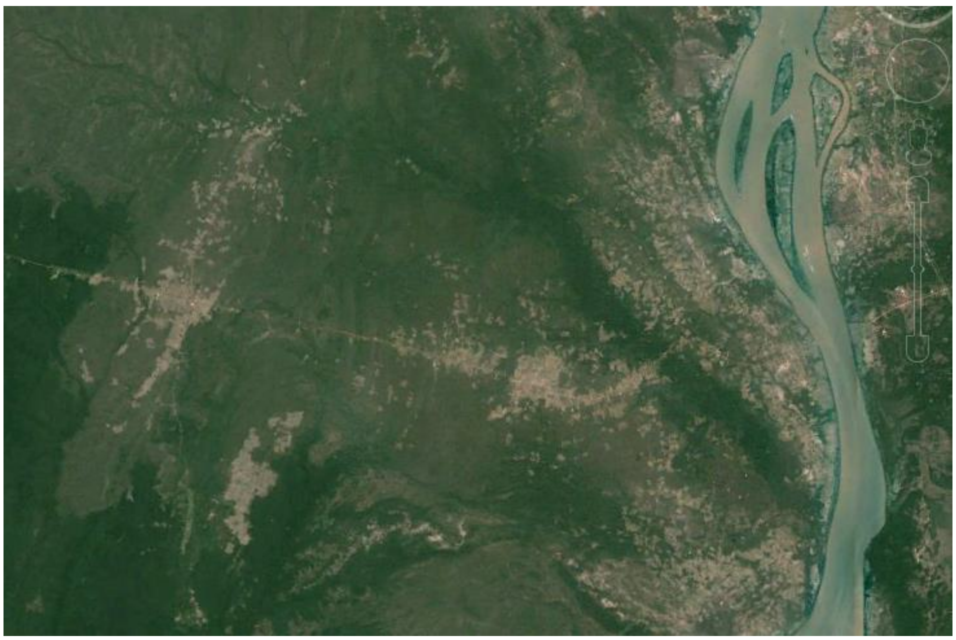



**FIGURE 5.1.2** – Farmland Multiple Index Map (top frame), Google Earth Image of same scene (bottom frame).

### 5.1.3 Stage-Storage Tool

The Stage-Storage Tool allows the user to create a stage-storage curve in tabular format for a potential reservoir site. The user first utilizes the "High Resolution DEM for Lower Mekong Basin" and the "High Resolution Stream Flowline Elevation Grid For Lower Mekong Basin" Data Products to generate the required geospatial data necessary. The user then uses the Stage-Storage Tool, created in a spreadsheet environment, to generate a tabular reservoir stage versus storage curve.

The Stage-Storage Tool combines geospatial data exported from ArcMap with the average end method for volume determination at each incremental stage of the reservoir. The main page of the Stage-Storage Tool is shown in the following figure.

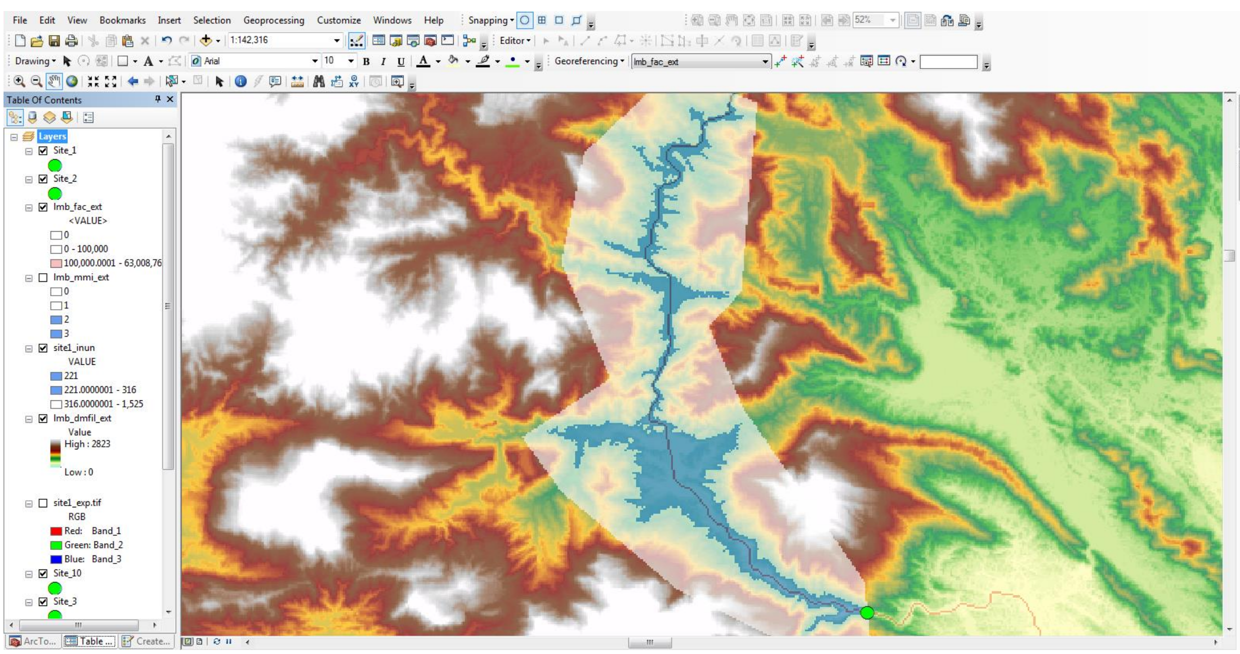



**FIGURE 5.1.3** – ArcMap View of DEM and inundation grid overlay.

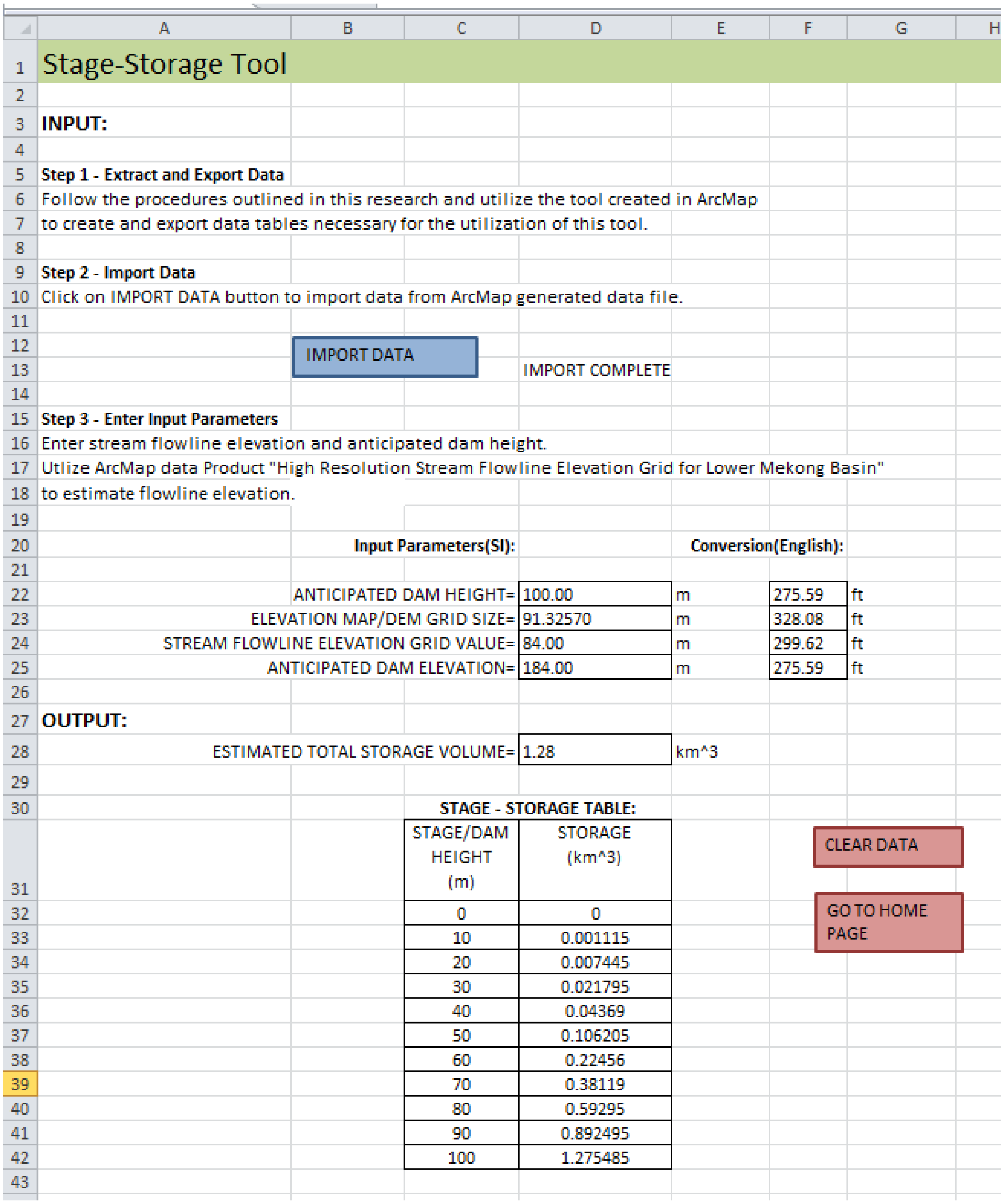



**FIGURE 5.1.4** – Stage-Storage Tool user interface sheet. The user follows steps outlined in the spreadsheet and obtains stage versus storage rating in tabular format for a given reservoir site. In this case, a total reservoir storage of 1.28 cubic kilometers radius could be obtained by the placement of a 100 meter dam.

### 5.1.4 Annual Yield Model

The Annual Yield Model estimates annual stream yield at a potential reservoir site. The user first utilizes the "High Resolution Flow Accumulation Grid for Lower Mekong Basin" Data Product created in this research to generate the required geospatial data necessary. The user then uses the Annual Yield Model created in a spreadsheet environment to estimate Annual Yield in cubic kilometers.

The user enters regional area-annual flow data from stream gage data in the Annual Yield Model spreadsheet interface. The spreadsheet processes this data and provides regional area-annual flow equation coefficients. These coefficients are then used to estimate annual stream/river yield at user specified points based on contributory watershed area.

The Lower Mekong Basin has been utilized as a case study in this research. Two annual average annual flow zones have been set up for the Lower Mekong Basin region based on gage data from the Mekong River Commission publication, "Annual Mekong Flood Report 2007" (MRC, 2007). Both zones are for tributaries to the main stem of the Mekong River. Thus, this model is intended to provide estimation of average annual flow for tributaries to the Mekong River only.

The user utilizes the "High Resolution Flow Accumulation Grid for Lower Mekong Basin" data product to identify contributory cells draining the potential reservoir location. The user enters the grid value and grid size in the Annual Yield Model. Upon completion of entering the input parameters required in the Annual Yield Model, the user is provided with an estimate of average annual flow in cubic meters per second and estimated annual yield in cubic kilometers as shown in the following figure.

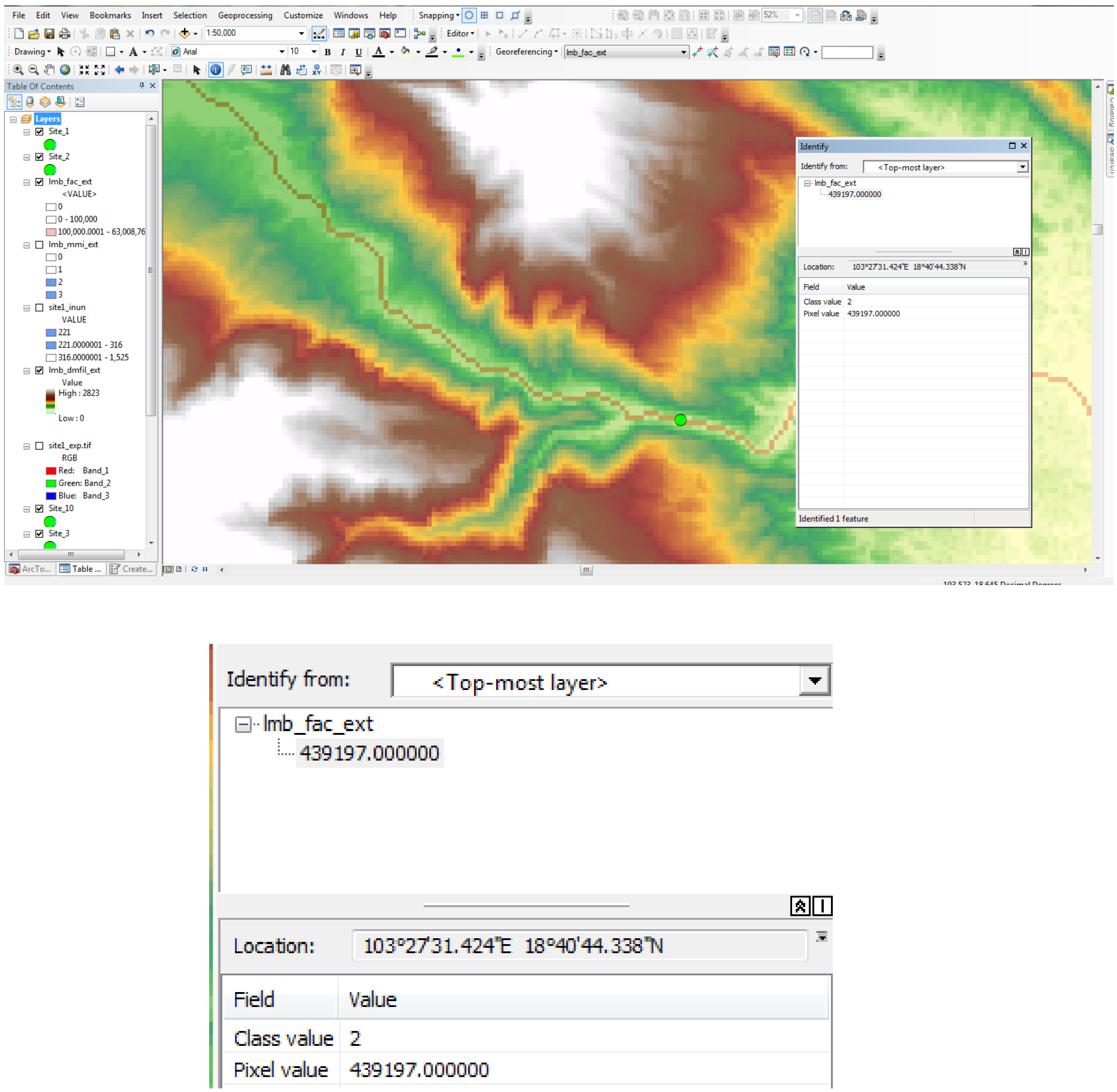



**FIGURE 5.1.5** – ArcMap view of High Resolution DEM data product and overlay with High Resolution Flow Accumulation data product. This enables the user to quickly assess watershed cells contributing to a point within a waterway and estimate average annual flow.

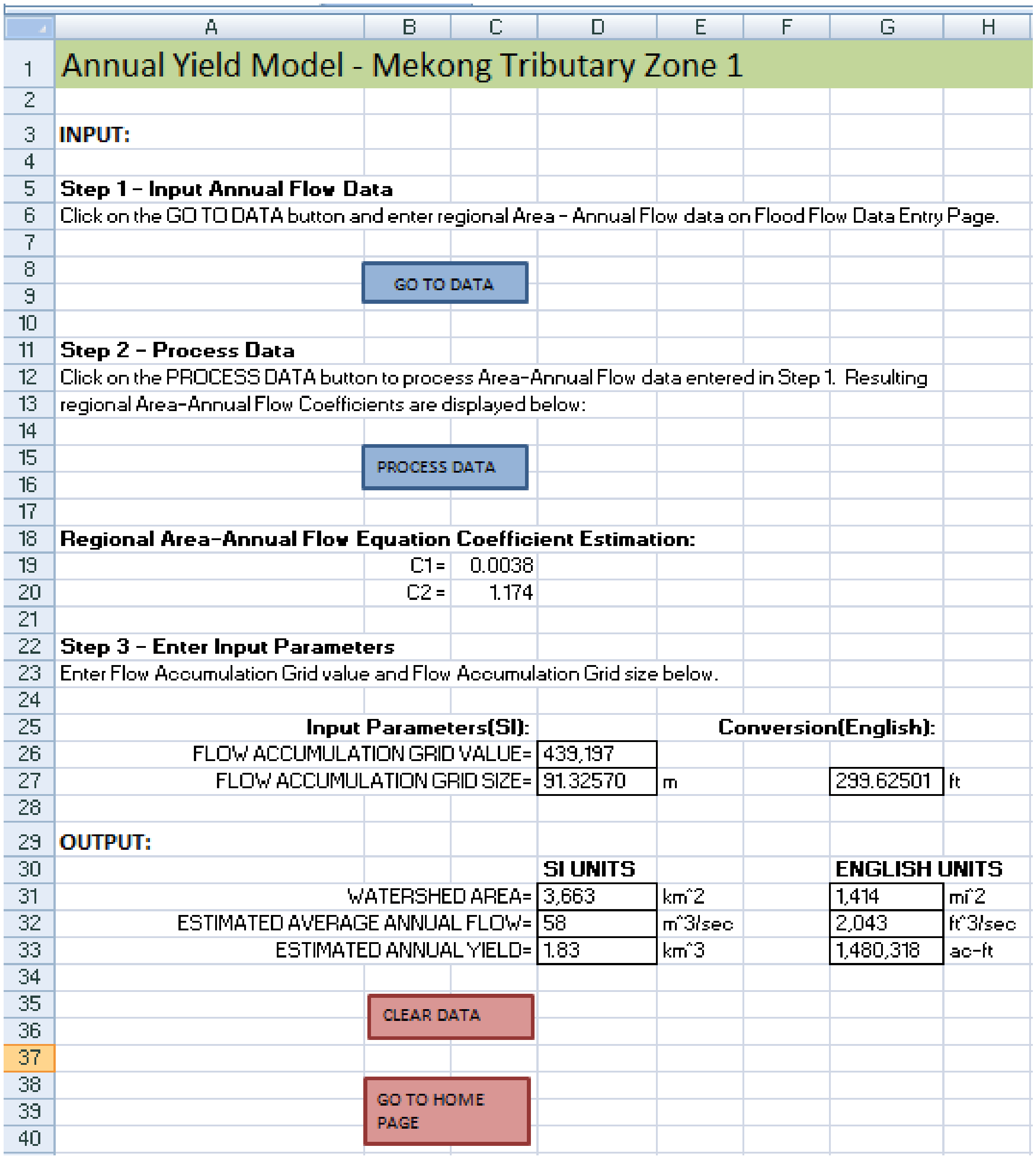



**FIGURE 5.1.6**– Annual Yield Model user interface sheet. The user follows the steps outlined in the spreadsheet and obtains estimated annual yield at a potential reservoir location. Based on the data and input parameters entered in this case, the Annual Yield Model provides the user with an estimated annual yield of 1.83 km^3.

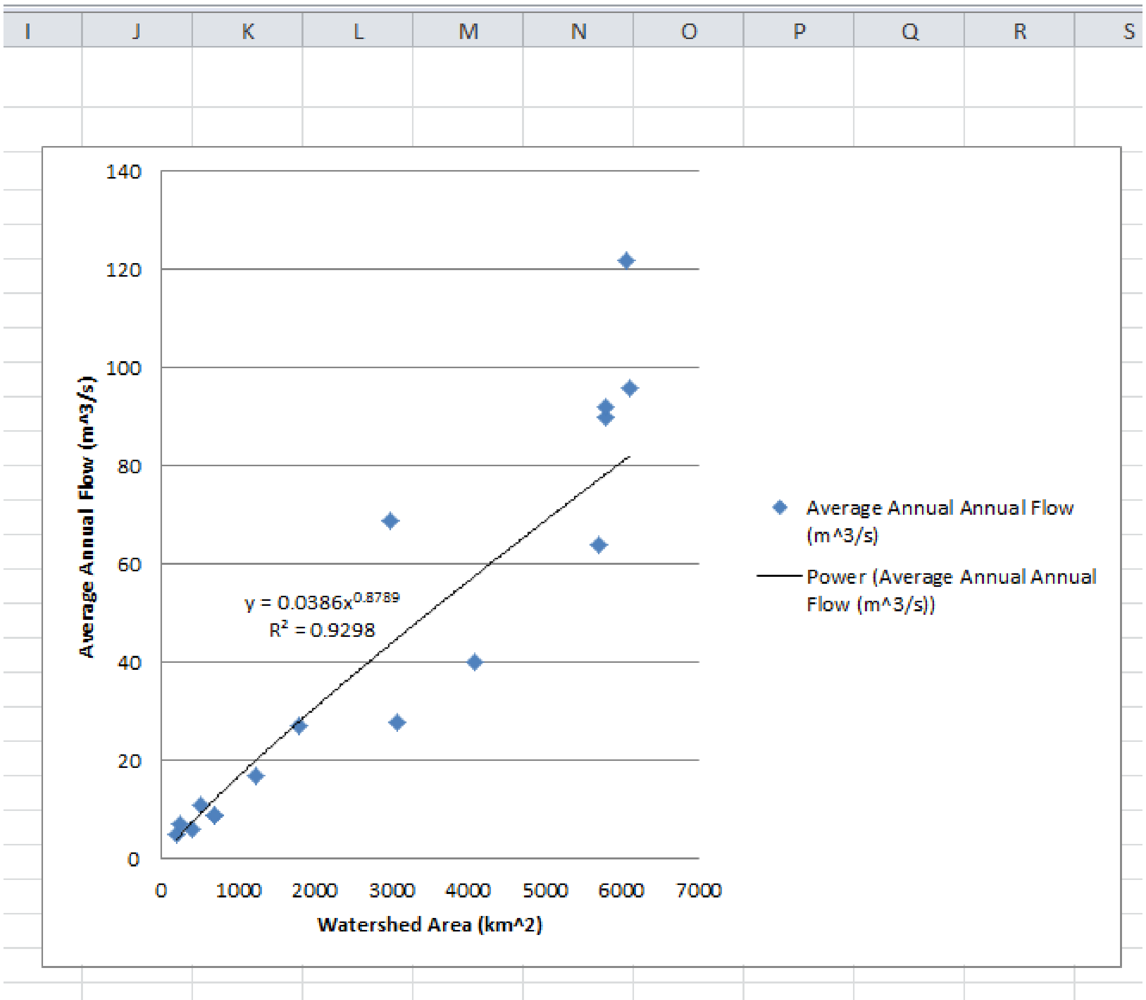



**FIGURE 5.1.7**– Data plot of average annual flow versus watershed area. The user can create such a plot within Microsoft Excel, and also utilize tools within Excel to display a power (or other) relation and the square of the correlation coefficient (R^2) for the data.

### 5.1.5 Flood Discharge Model

The Flood Discharge Model estimates peak flood discharge at a user specified location in a waterway. The user first utilizes the "High Resolution Flow Accumulation Grid for Lower Mekong Basin" Data Product created in this research to generate the required geospatial data necessary. The user then uses the Flood Discharge Model created in a spreadsheet environment to estimate peak flood discharge in cubic meters per second.

The user enters regional area-annual flow data from stream gage data in the Flood Discharge Model spreadsheet interface. The spreadsheet processes this data and provides regional area versus peak flood flow equation coefficients. These coefficients are then used to estimate peak flood flow at user specified points based on contributory watershed area.

The Lower Mekong Basin has been utilized as a case study in this research. Two peak flood flow models have been set up for the Lower Mekong Basin. Tributary Zone 1 has been set up for the main stem of the Mekong River; Tributary Zone 2 has been set up for tributary streams/rivers to the Mekong River. Data used in this example and for the case studies in Chapter 6 is synthetic and is based on regional regression equations obtained from the Mekong River Commission publication, "Annual Mekong Flood Report 2007" (MRC, 2007). The theme of this research is to create a tool that can be utilized to process the data and create an efficient user interface. Thus, the use of synthetic data for this portion of the research was felt to be adequate.

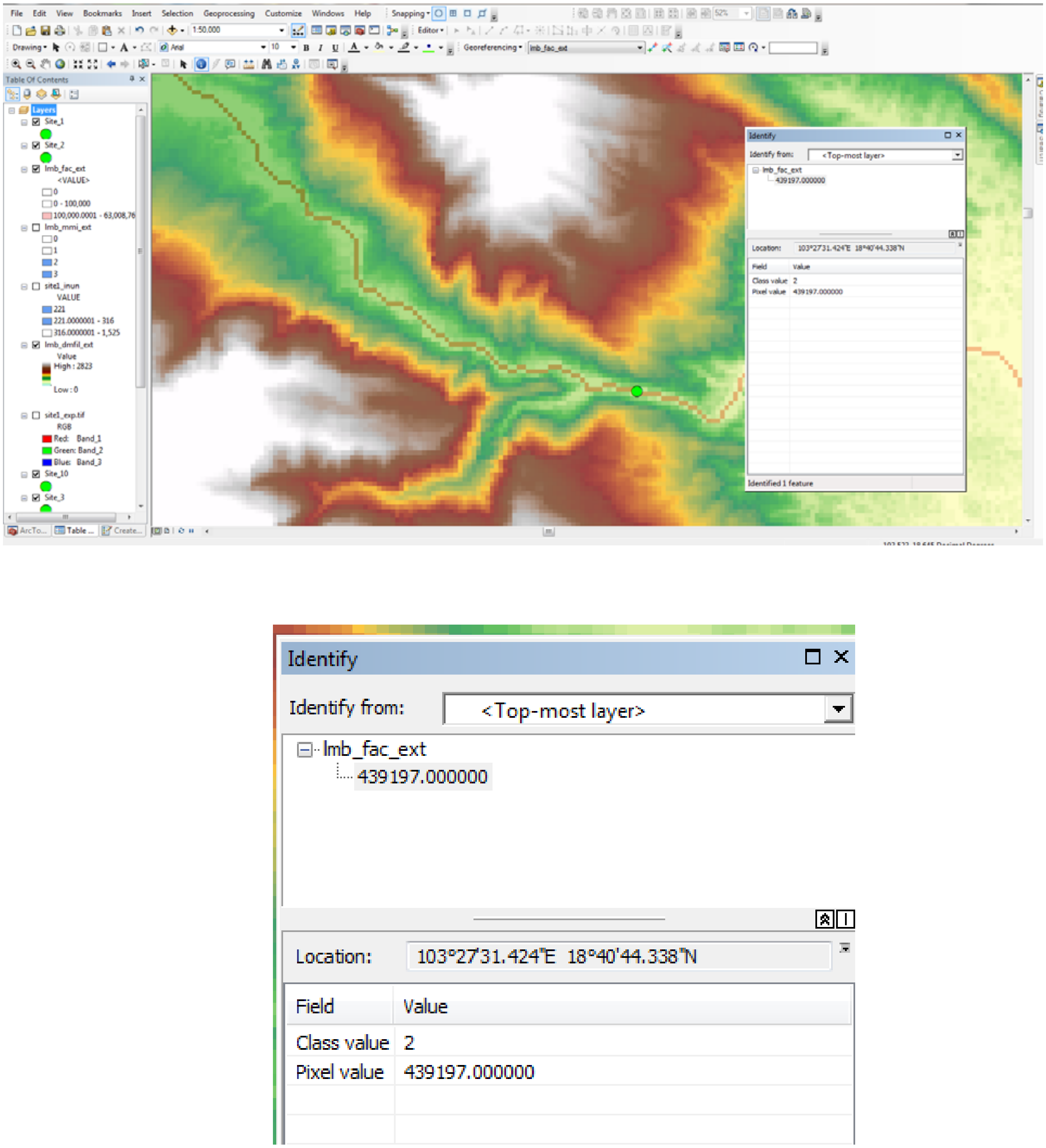



**FIGURE 5.1.8** – ArcMap view of High Resolution DEM data product and overlay with High Resolution Flow Accumulation data product. This enables the user to quickly assess watershed cells contributing to a point within a waterway and estimate peak average annual flood discharge.

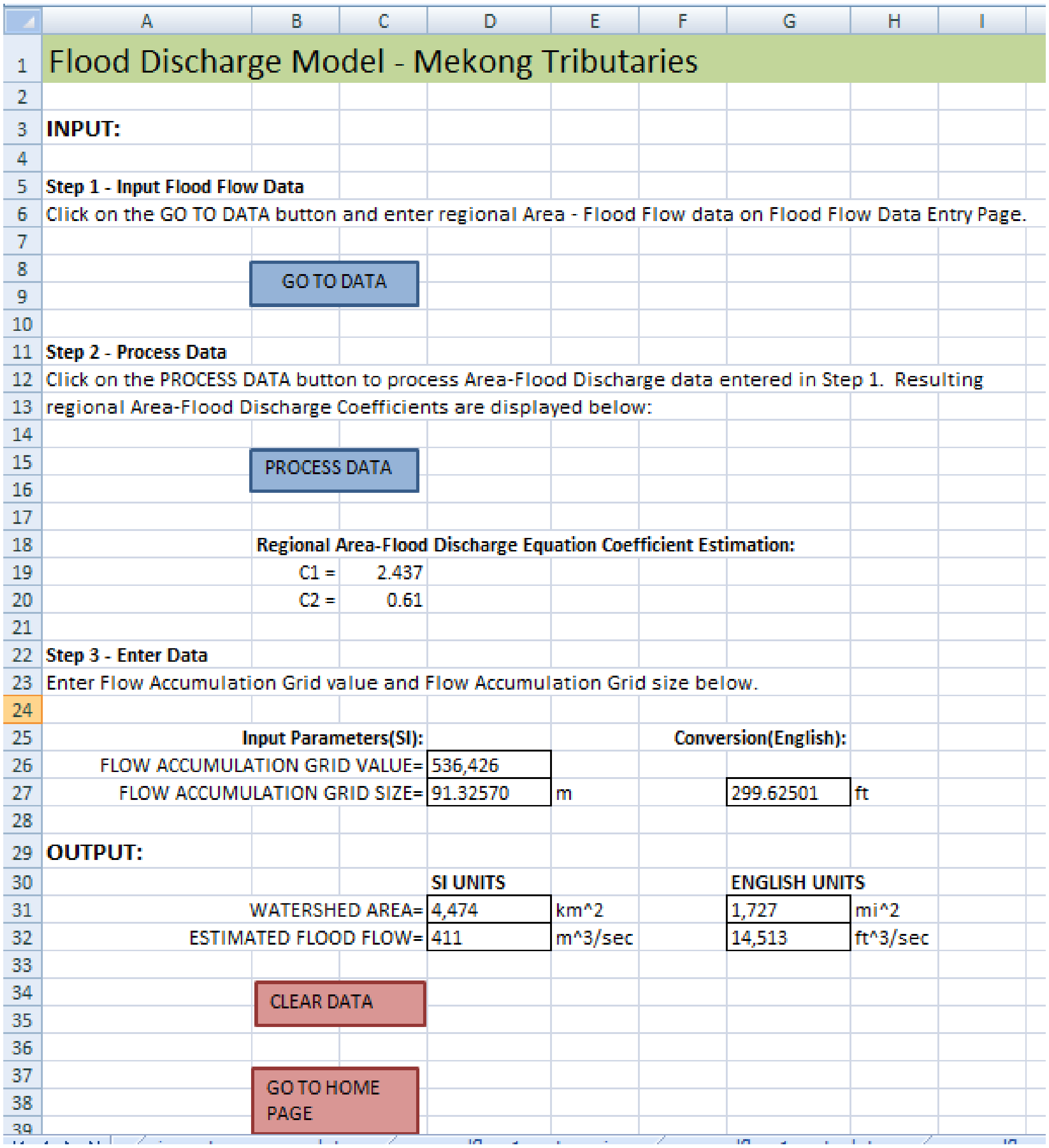



**FIGURE 5.1.9** – Flood Discharge Model user interface sheet. User follows steps outlined in the spreadsheet and obtains estimated food discharge at a user specified location within a waterway. In this case the tool estimates a peak flood discharge of 411 cubic meters per second for a watershed area of 4474 square kilometers

## 5.2 ADVERSE IMPACT ASSESSMENT TOOLS AND MODELS

### 5.2.1 Population Displacement Tool

The Population Displacement Tool estimates the number of persons potentially displaced by the development of a reservoir at a specific site. The user first utilizes the "Population Map for Lower Mekong Basin" Data Product overlayed with inundation mapping for a potential reservoir site generated while utilizing the "Stage Storage Tool", discussed previously, to generate the required geospatial data necessary. The user then uses the Population Displacement Tool created in a spreadsheet environment to estimate population map cells inundated, giving the number of persons potentially inundated by the placement of a proposed reservoir.

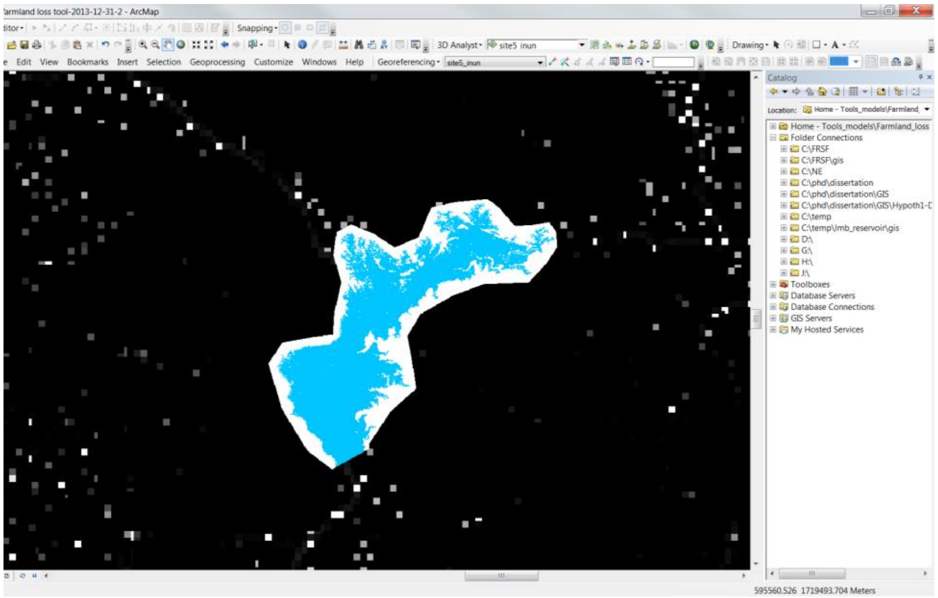


**Figure 5.2.1 –** ArcMap view of reservoir inundation map overlayed onto population map data product.

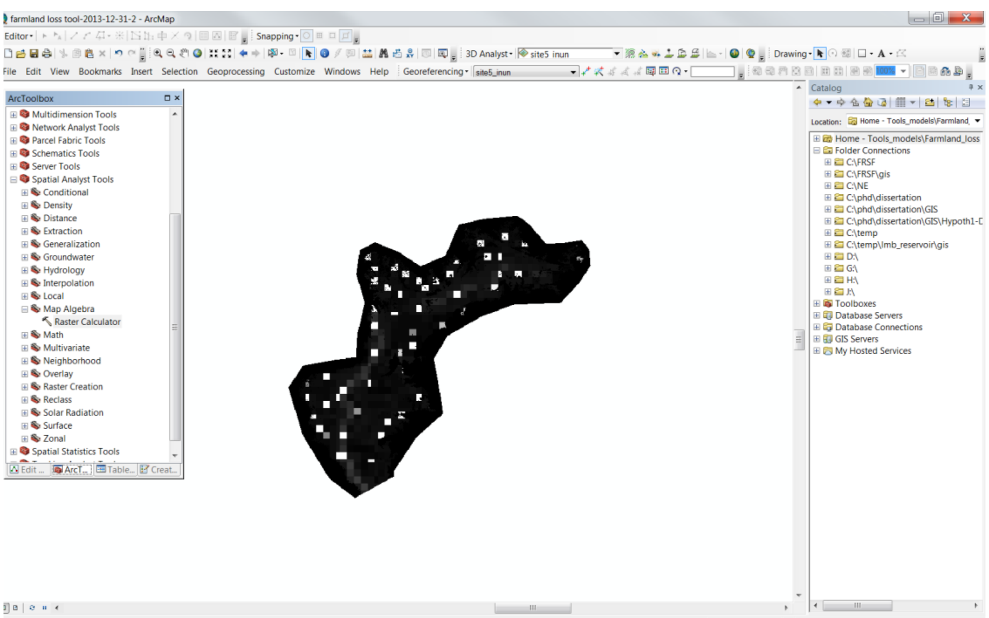


**Figure 5.2.2 –** ArcMap view of population inundated (white and grey cells) by a potential reservoir.

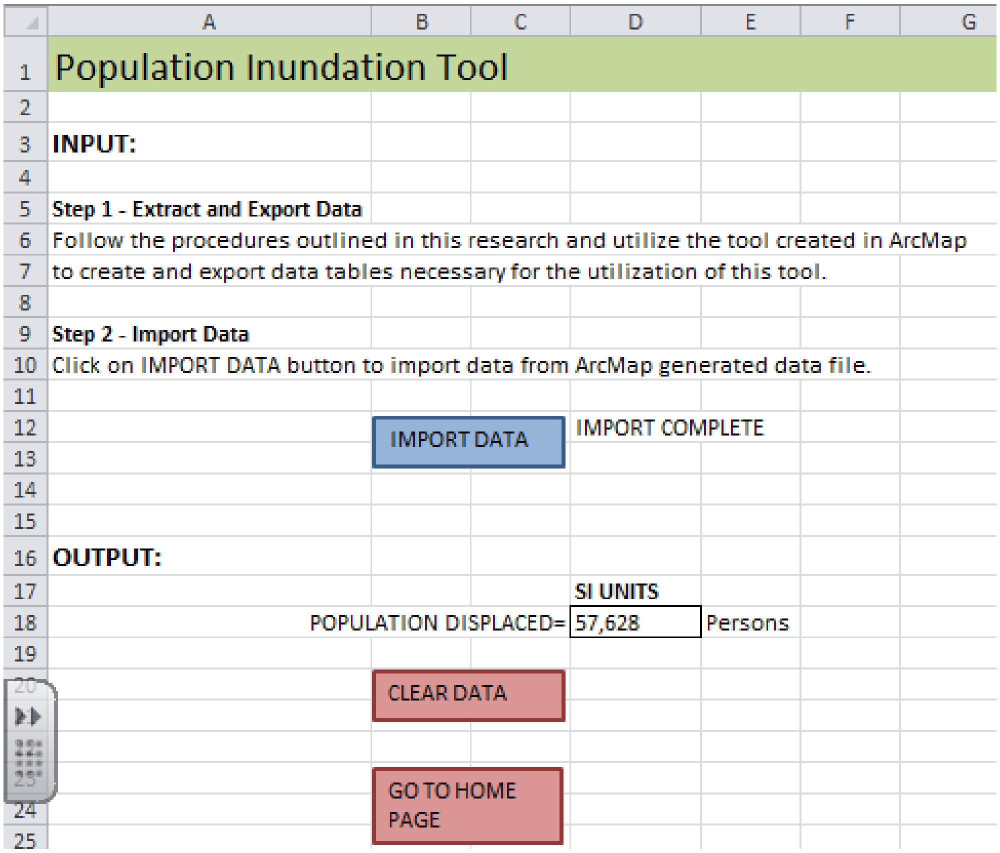



**FIGURE 5.2.3** – Population Inundation Tool user interface sheet. User follows steps outlined in the spreadsheet and obtains estimated number of persons inundation/displaced by the placement of a proposed reservoir. In this case the tool estimates 57,628 persons inundated by a potential reservoir.

### 5.2.2 Farmland Loss Tool

The Farmland Loss Tool estimates the potential loss of farmland due to the development of a reservoir at a specific site. The user first utilizes the "Farmland Identification Grid for Lower Mekong Basin" Data Product overlayed with inundation mapping for a potential reservoir site generated while utilizing the "Stage Storage Tool", discussed previously, to generate the required geospatial data necessary. The user then uses the Farmland Loss Tool created in a spreadsheet environment to estimate farmland map cells inundated, giving the number of square kilometers potentially inundated by the placement of a proposed reservoir.

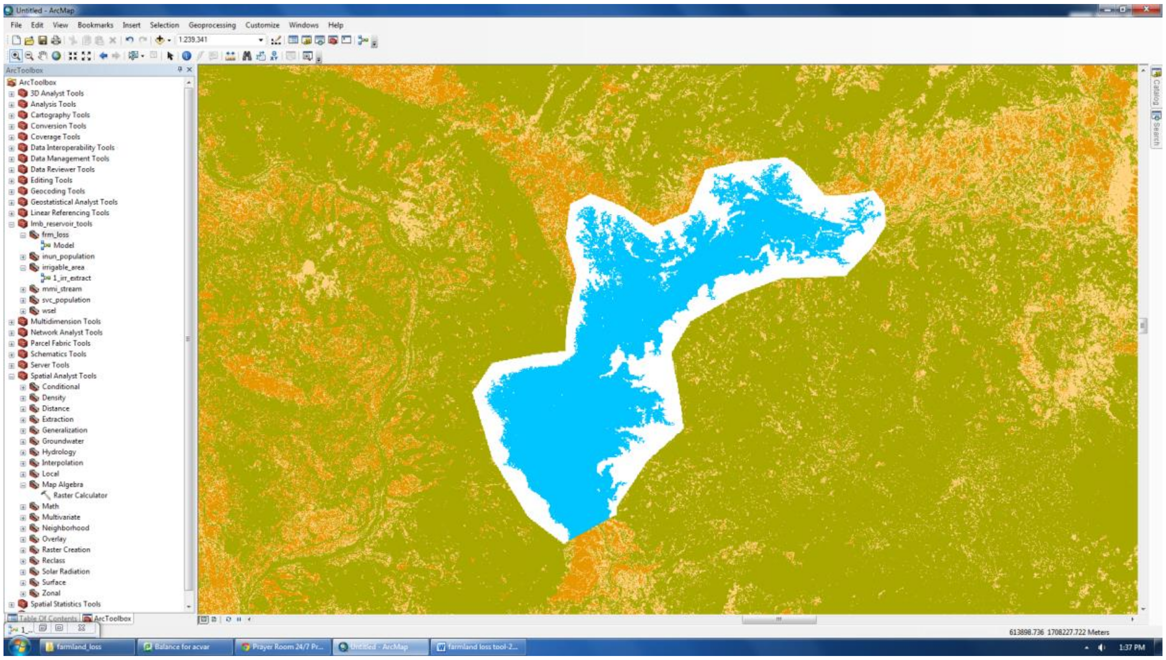



**Figure 5.2.4 –** ArcMap view of reservoir inundation map overlayed onto farmland map data product.

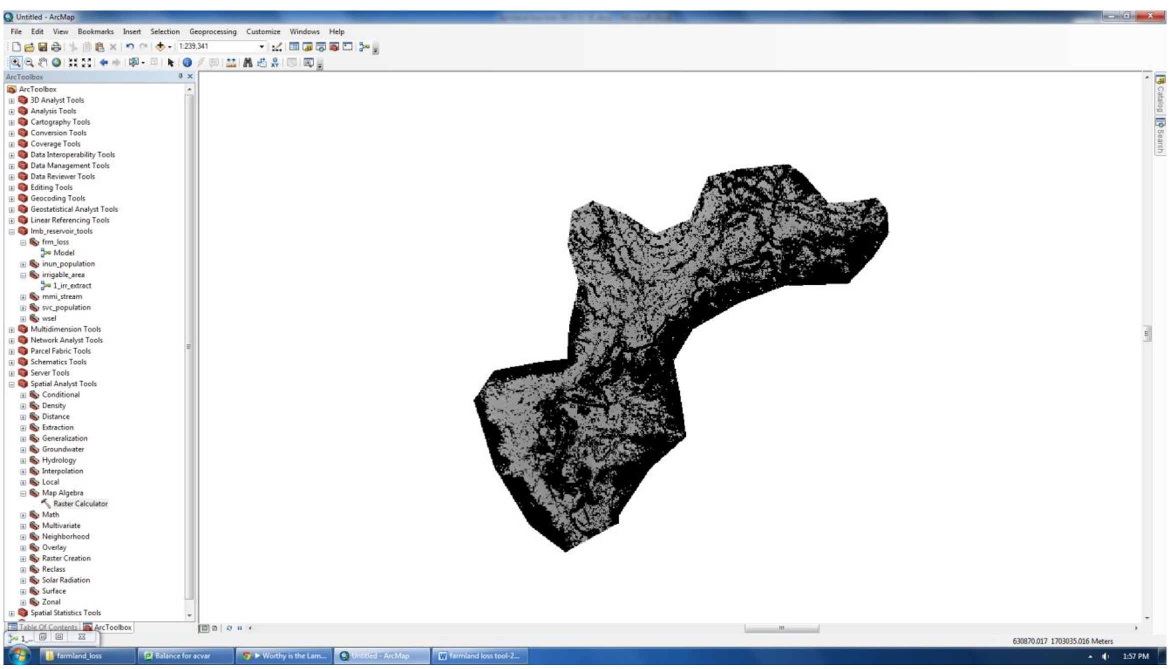



**Figure 5.2.5 –** ArcMap view of farmland inundated (light grey cells) by a potential reservoir.

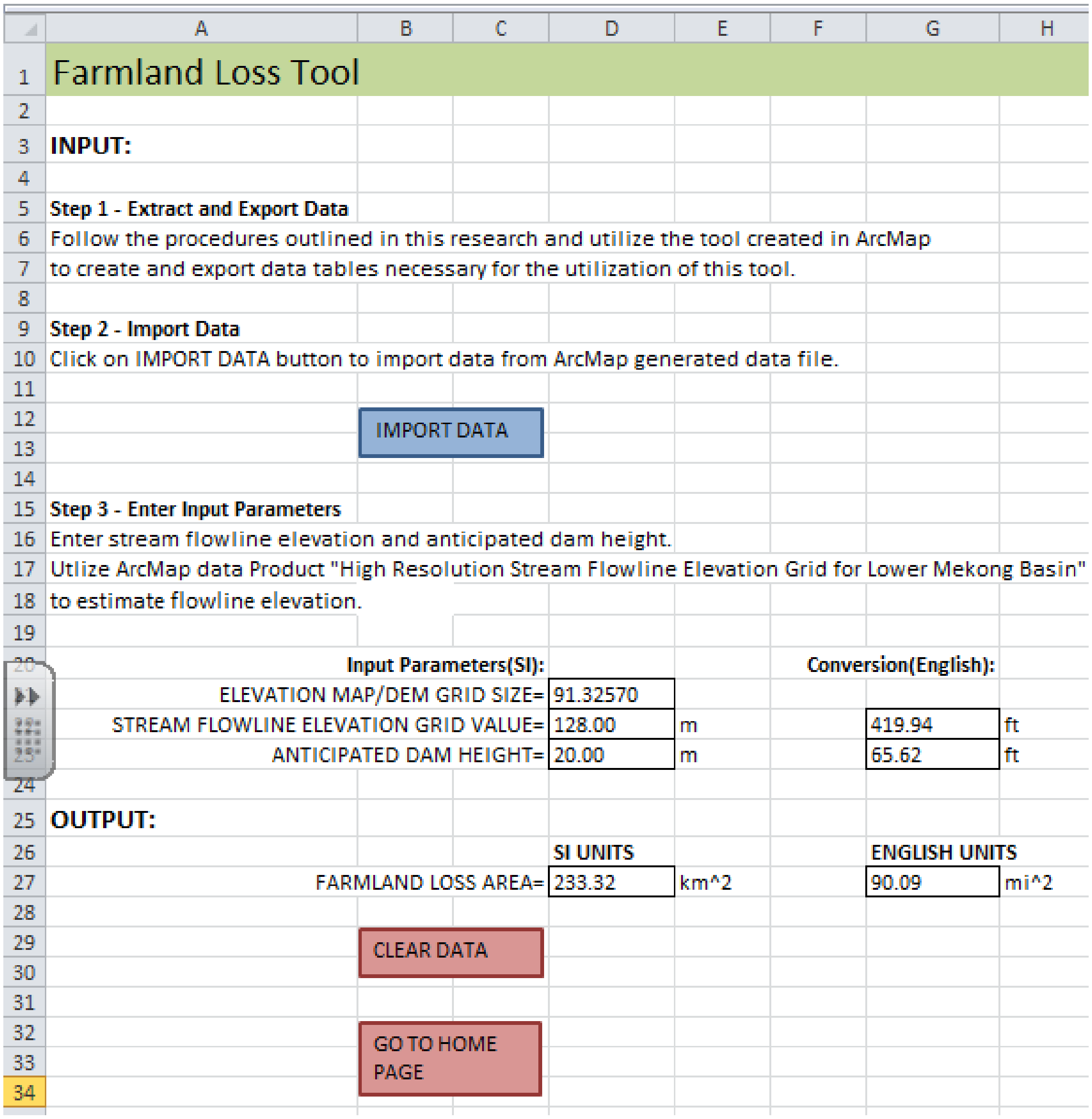



**FIGURE 5.2.6** – Farmland Loss Tool user interface sheet. User follows steps outlined in the spreadsheet and obtains estimated farmland inundation/loss by the placement of a proposed reservoir. In this case the tool estimates a farmland loss of 233.32 square kilometers.

### 5.2.3 Average Annual Flow Reduction Model

In the Average Annual Flow Reduction Model, an expert inputs locations downstream of a proposed reservoir that are "hotspots" for fisheries, environmentally sensitive areas, etc., and based on reduction in reduction of watershed area, estimates reduction of average annual flow, and a new average annual flow. The model takes the average annual flow equation generated in the "Annual Yield Model", discussed previously, and assumes as a worst case scenario that the maximum decrease in average annual flow would be represented by a proposed reservoir completely absorbing all runoff from an upstream watershed.

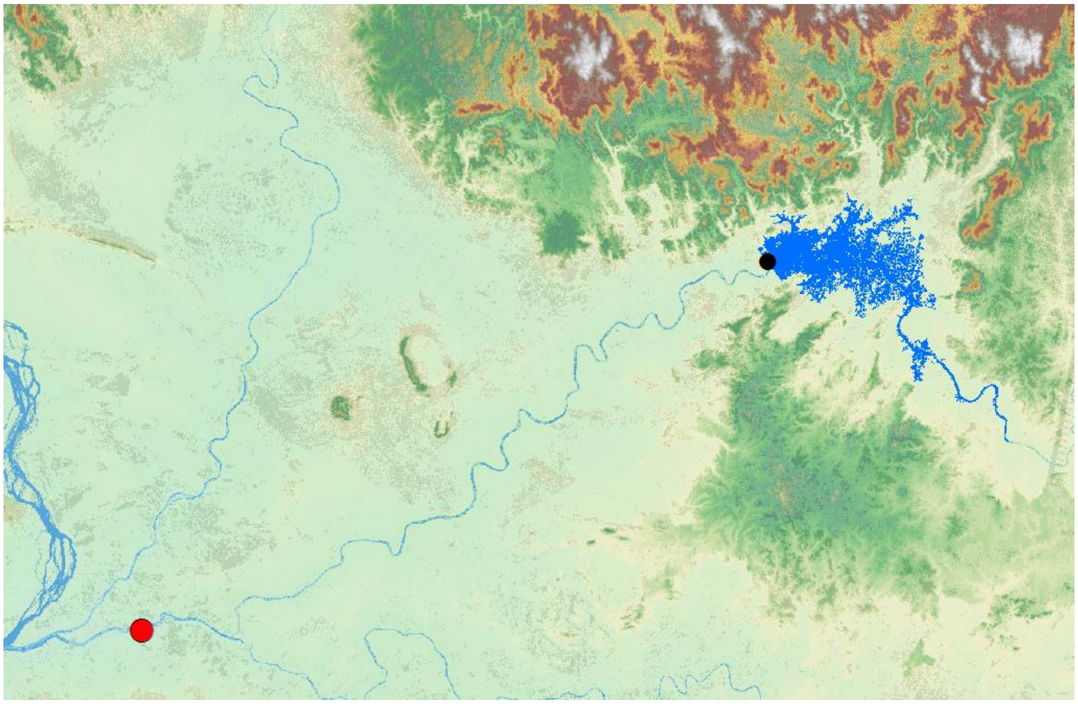
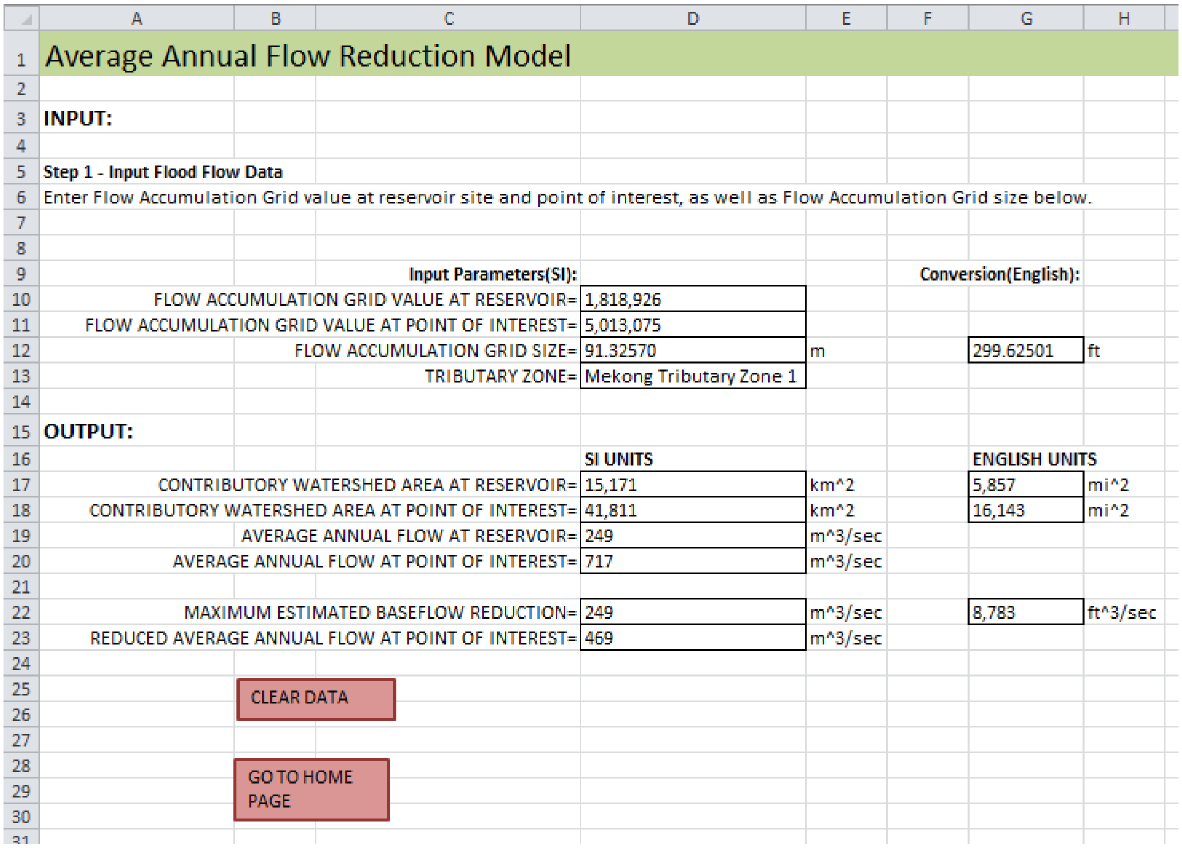


**FIGURE 5.2.7** – ArcMap view of High Resolution DEM data product, overlayed with High Resolution Flow Accumulation data product and the Perennial Stream Identification Grid. This enables the user to quickly assess watershed cells contributing to the proposed reservoir (black dot), and the point of interest (red dot). Through the spreadsheet interface, the user can estimate reduction in average annual flow at the point of interest.



# Average Annual Flow Reduction Model

**INPUT:**

**Step 1 - Input Flood Flow Data**

Enter Flow Accumulation Grid value at reservoir site and point of interest, as well as Flow Accumulation Grid size below.

| Input Parameters(SI): | | | Conversion(English): | |
|---|---|---|---|---|
| FLOW ACCUMULATION GRID VALUE AT RESERVOIR= | 1,818,926 | | | |
| FLOW ACCUMULATION GRID VALUE AT POINT OF INTEREST= | 5,013,075 | | | |
| FLOW ACCUMULATION GRID SIZE= | 91.32570 | m | 299.62501 | ft |
| TRIBUTARY ZONE= | Mekong Tributary Zone 1 | | | |

**OUTPUT:**

| | SI UNITS | | ENGLISH UNITS | |
|---|---|---|---|---|
| CONTRIBUTORY WATERSHED AREA AT RESERVOIR= | 15,171 | km^2 | 5,857 | mi^2 |
| CONTRIBUTORY WATERSHED AREA AT POINT OF INTEREST= | 41,811 | km^2 | 16,143 | mi^2 |
| AVERAGE ANNUAL FLOW AT RESERVOIR= | 249 | m^3/sec | | |
| AVERAGE ANNUAL FLOW AT POINT OF INTEREST= | 717 | m^3/sec | | |
| MAXIMUM ESTIMATED BASEFLOW REDUCTION= | 249 | m^3/sec | 8,783 | ft^3/sec |
| REDUCED AVERAGE ANNUAL FLOW AT POINT OF INTEREST= | 469 | m^3/sec | | |

CLEAR DATA

GO TO HOME PAGE

**FIGURE 5.2.8** – Average Annual Flow Reduction Model user interface sheet. User follows steps outlined in the spreadsheet and obtains a maximum estimated average annual flow reduction and reduced average annual flow due to the placement of a proposed reservoir. In this case the tool estimates a reduction in average annual flow of 249 cubic meters per second and a reduced average annual flow of 469 cubic meters per second.

## 5.3 BENEFIT ASSESSMENT TOOLS AND MODELS

### 5.3.1 Irrigable Area Tool

The Irrigable Area Tool estimates irrigable area within a user specified radius of a potential reservoir site. The user first utilizes the “High Resolution DEM for Lower Mekong Basin” and the “High Resolution Stream Flowline Elevation Grid For Lower Mekong Basin” Data Products in conjunction with the “irrigable_area_estimator” tool set up in ArcMap to generate the required geospatial data necessary. The user then uses the “Irrigable Area” Tool to estimate potential irrigable area in square kilometers within a user specified radius of the potential reservoir site.

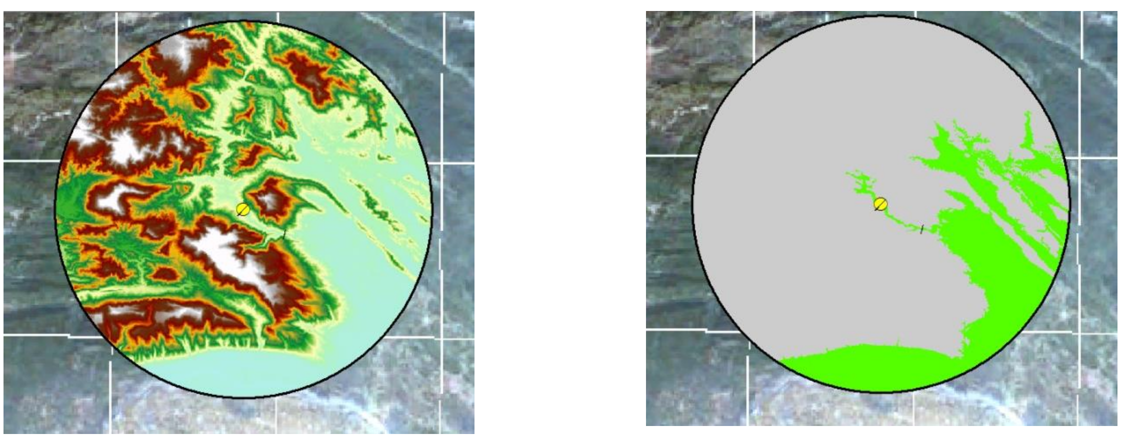


**FIGURE 5.3.1** – **Left Frame** - ArcMap view of potential reservoir location(Yellow Marker) and DEM cutout within user specified radius of potential reservoir site. Right Frame – ArcMap of irrigable area (shown in green) within the specified radius of a potential reservoir location.

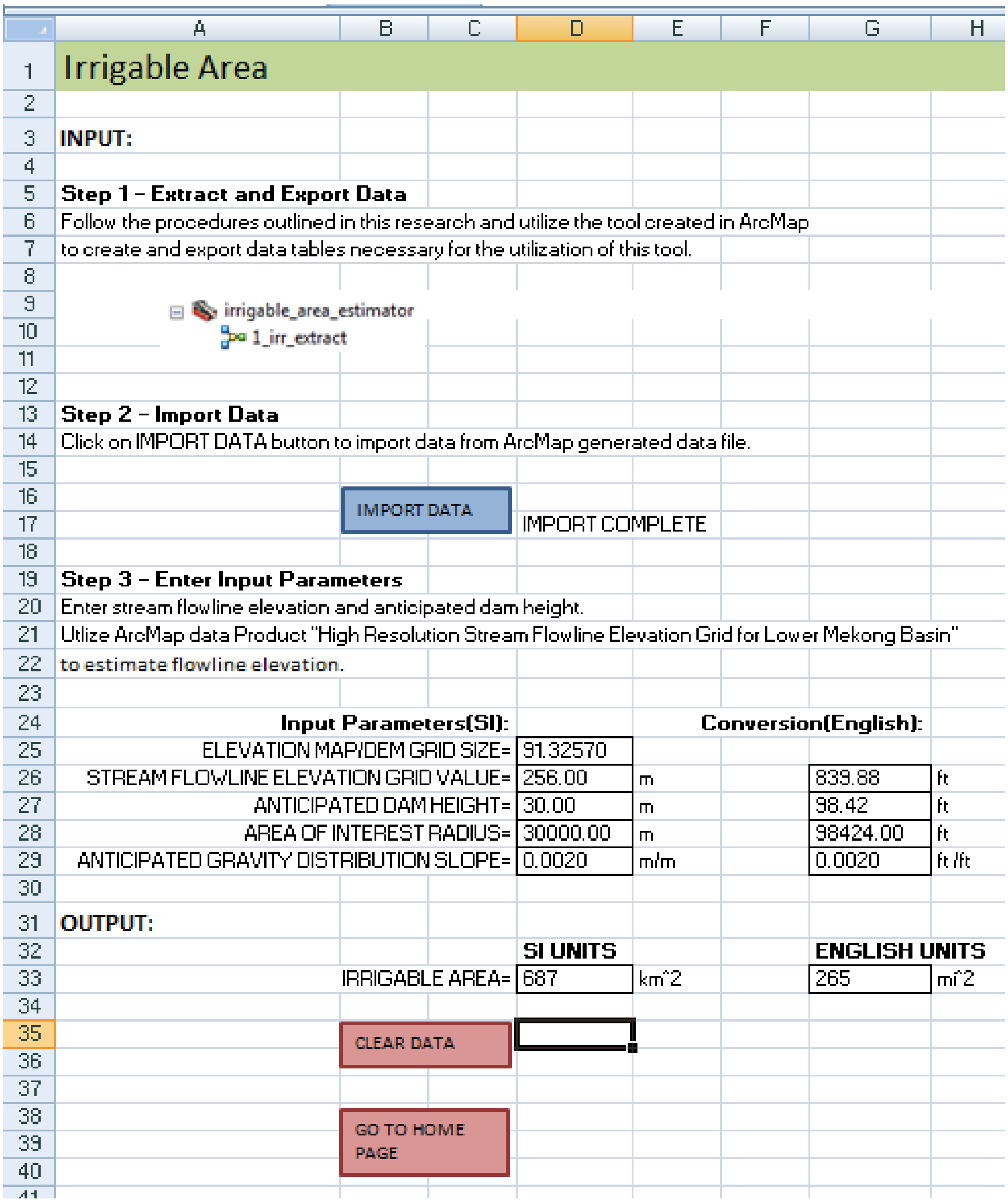



**FIGURE 5.3.2** – Irrigable Area Tool user interface sheet. The user follows steps outlined in the spreadsheet and obtains irrigable area within a specified radius of a potential reservoir

location. In this case an irrigable area of 687 km^2 is estimated within the 30 km radius specified by the user.

Upon completion of importing geospatial data from ArcMap and entering the input parameters and data, the Irrigable Area Tool provides the user with an estimate of irrigable area in both SI and English units (Square Kilometers and Square Miles).

### 5.3.2 Serviceable Population Tool

The Serviceable Population Tool estimates population within a user specified radius of a potential reservoir site. The user first utilizes the Population Map for Lower Mekong Basin Data Product to generate the required geospatial data necessary. The user then uses the" Serviceable Population Tool" (spreadsheet user interface), to estimate potential population within a user specified radius of the potential reservoir site. The tool accounts for elevation, and only considers population at or below the elevation of the top of potential dam. In doing so, the tool avoids counting population as serviceable that would require pumping.

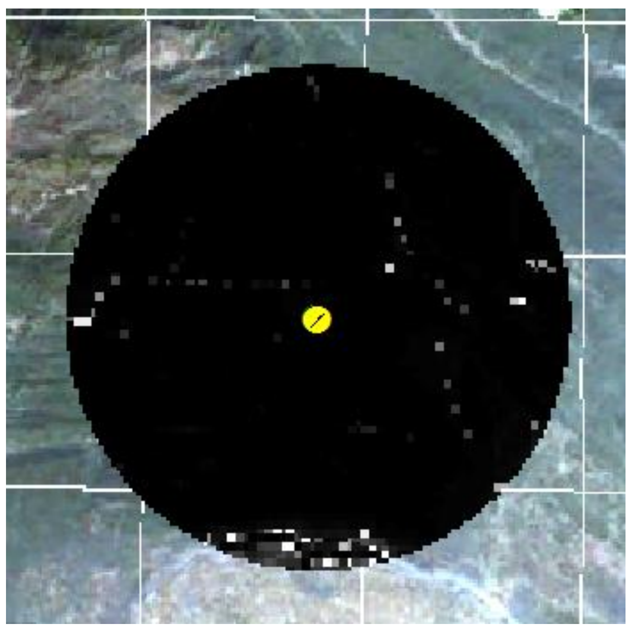


**FIGURE 5.3.3** – ArcMap view of potential reservoir location (yellow marker) and population map cutout within user specified radius. Cells shaded in white and grey indicate higher population (white shades indicate highest population, dark shade indicate lowest or no population within a cell).

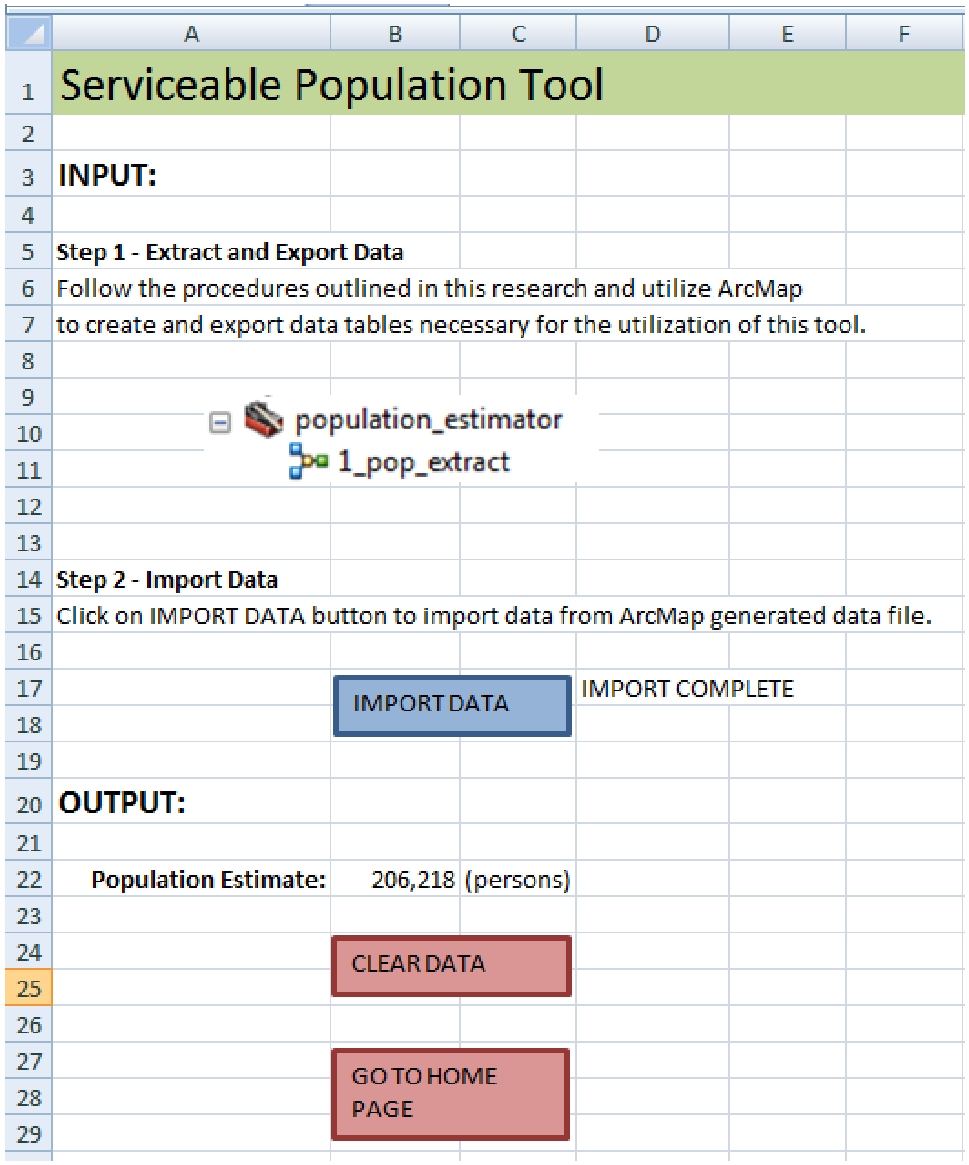



**FIGURE 5.3.4** – Serviceable Population Tool user interface sheet. User follows steps outlined in the spreadsheet and obtains estimated population within a user specified radius of a potential reservoir location. In this case, the tool estimates a population of 206,218 persons within a 30 kilometer radius of the potential reservoir location.

### 5.3.3 Hydropower Model

The Hydropower Model estimates the hydropower potential of a give reservoir site. This tool has been set up to answer question 6: What is the hydropower potential at a given reservoir site?

The user first utilizes the “High Resolution DEM for Lower Mekong Basin” and the “High Resolution Stream Flowline Elevation Grid for Lower Mekong Basin” Data Products to generate the required geospatial data. The user then uses the “Hydropower Model” (spreadsheet user interface), to estimate hydropower potential at a given reservoir site. The model utilizes dam height and average annual flow (estimated with the previously discussed “Annual Yield” Model) in order to estimate hydropower potential. The model estimates potential hydropower output in Megawatts (MW).

The possibility that over-estimation of hydropower potential at a reservoir site could occur due to the variability of inflow is recognized, and the spreadsheet user interface for the Hydropower Model accounts for variations in inflow as well as the potential variability of reservoir level by allowing the user to input a percentage of annual average flow and a percentage of maximum assumed reservoir level. Additionally, the Hydropower Model accounts for the likelihood that at a given reservoir site, a certain volume of flood control storage will be desired. The spreadsheet user interface for the Hydropower Model allows the user to input a portion of the reservoir level in meters above an assumed full active storage level to be assumed as dedicated to flood control volume. The user can input different values of reservoir level dedicated to flood storage in an iterative manner in order to achieve a sense of the trade-off between active storage volume and the hydropower potential of a site versus flood control storage.

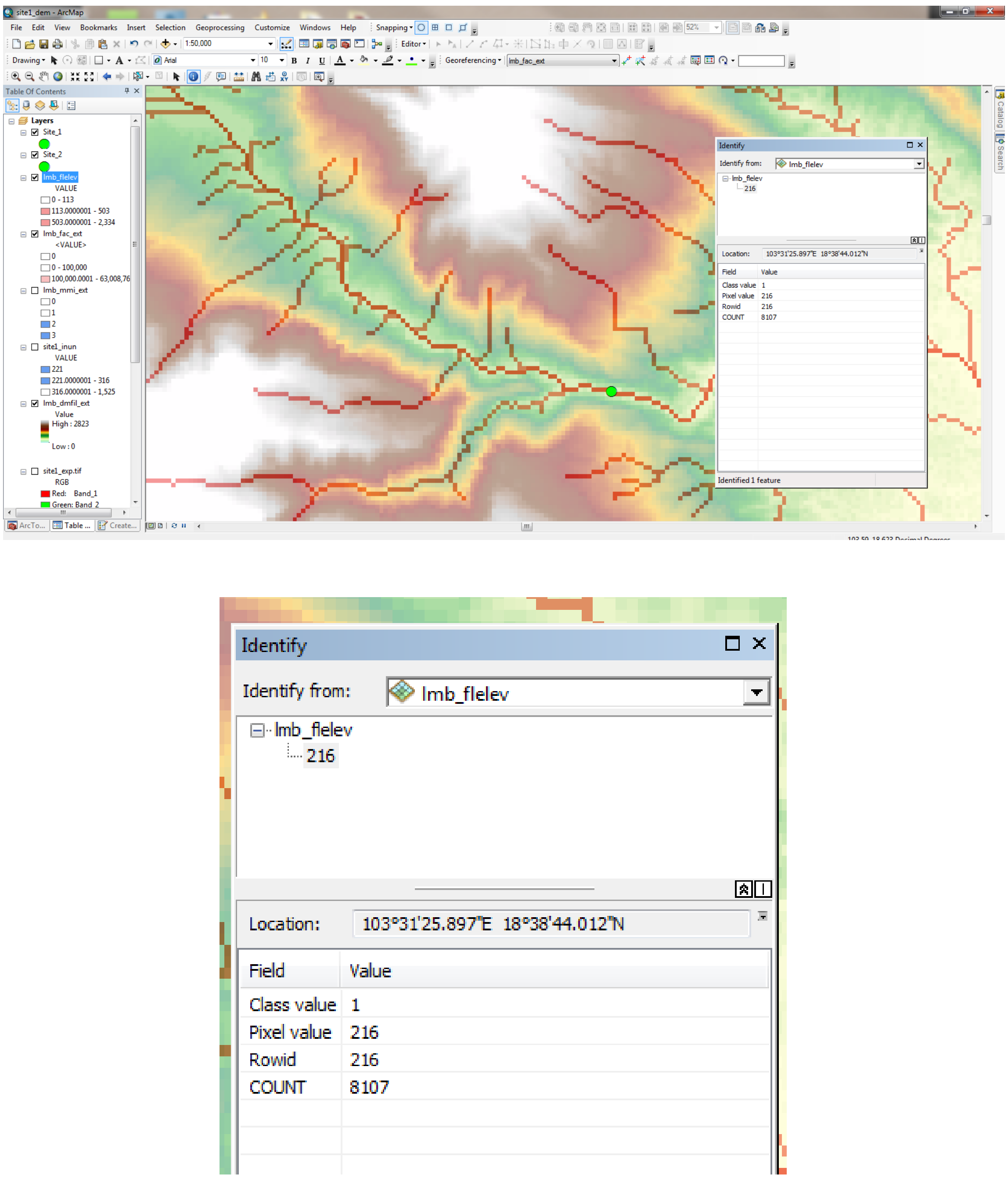



**FIGURE 5.3.5** – Hydropower Model ArcMap user interface.

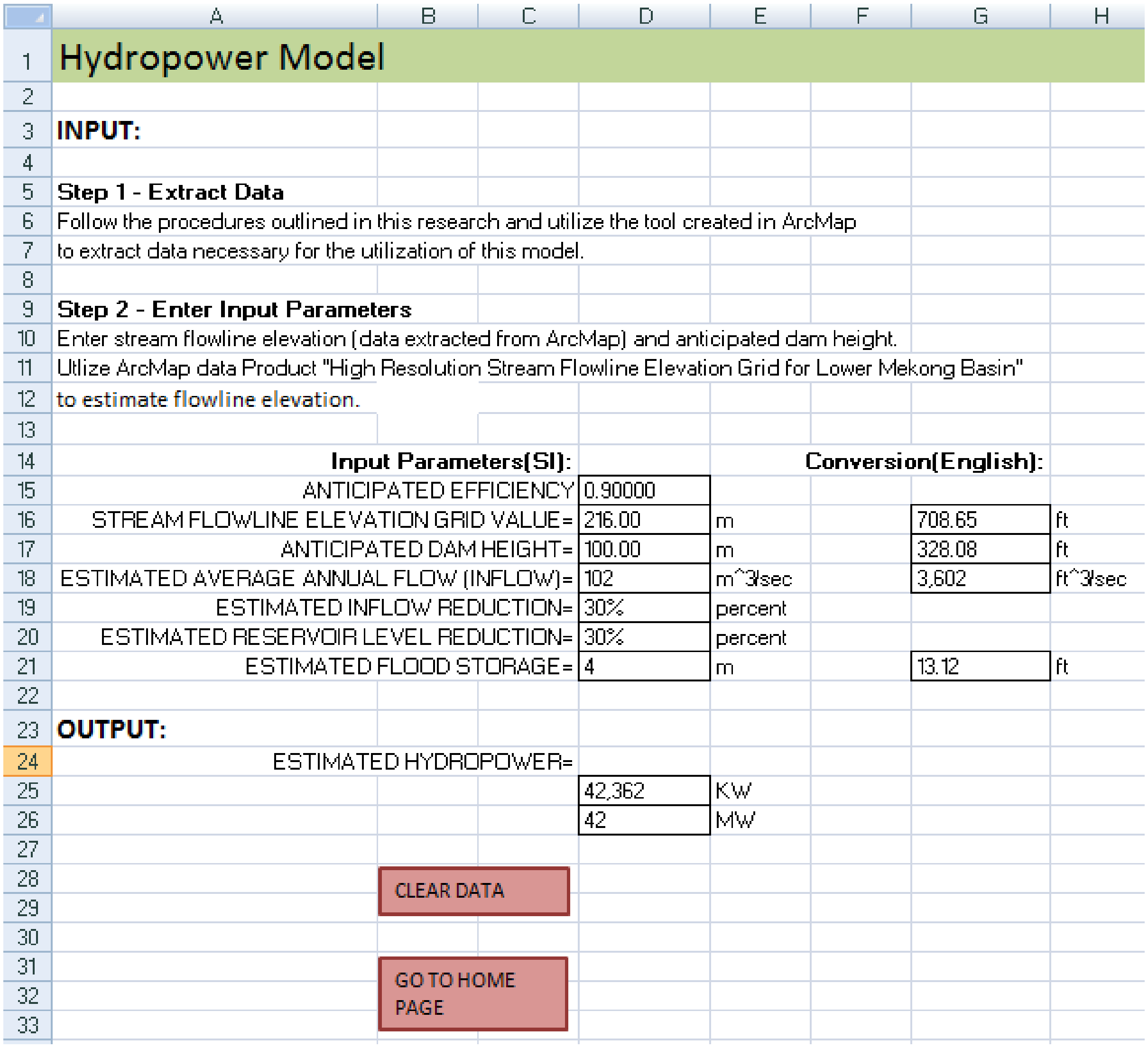



**FIGURE 5.3.6**– Hydropower Model user interface sheet. The user follows the steps outlined in the spreadsheet and obtains estimated hydropower potential reservoir location. Based on the data and input parameters entered in this case, the Hydropower Model provides the user with an estimated hydropower potential of 42 MW.

### 5.4.1 Flood Attenuation Model

The Flood Attenuation Model estimates the flood discharge attenuation that could potentially be realized by the placement of a reservoir at a user specified point in a waterway. This model requires that the user to first utilize the Flood Discharge Model to estimate a peak flood discharge. The model also requires the user to enter estimated flood duration. Based on these two parameters, the user can enter anticipated flood storage volume and obtain estimated attenuated flood discharge (reduced flood discharge).

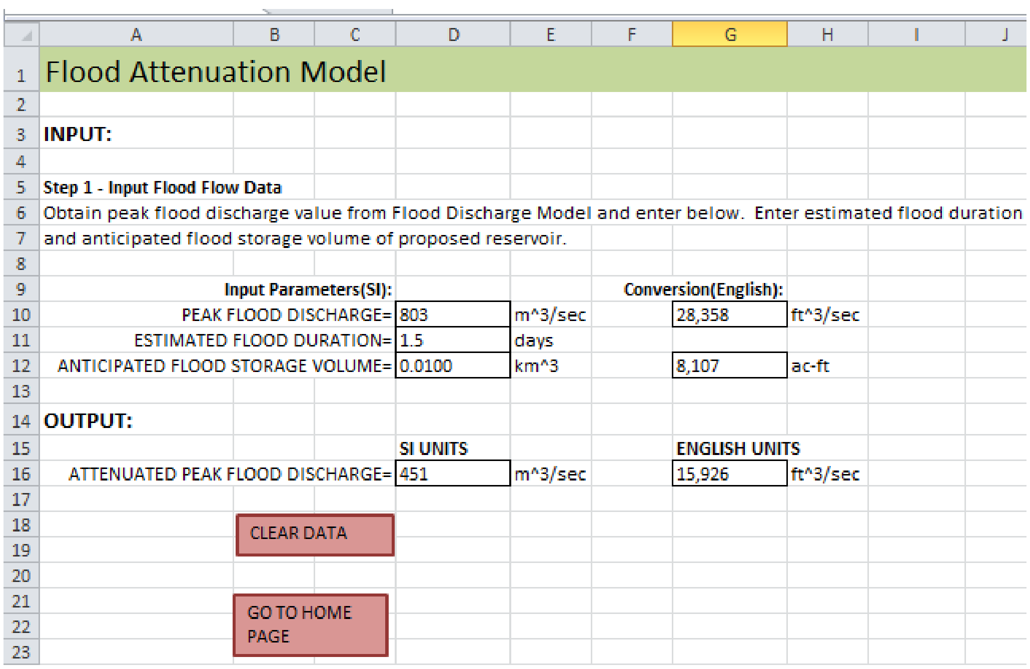



**FIGURE 5.4.1** – Flood Attenuation Model user interface sheet. The user enters peak flood discharge and estimated flood duration. Based on these two parameters, the user can enter anticipated flood storage volume and obtain estimated attenuated flood discharge

(reduced flood discharge). In this case the user entered an anticipated flood storage volume of 0.01 km^3 and was provided an estimated reduced peak flood discharge of 451 m^3/s.

### 5.4.2 Water Surface Elevation Model and Population Inundation Tool

The Water Surface Elevation Model estimates water surface elevation at a user specified reach along a waterway. The Population Inundation Tool takes the estimated water surface elevation from the Water Surface Elevation Model, and provides the user with a map of estimated inundation area and the estimated number of persons affected by flooding.

The focus of this chapter of the research is flood inundation and thus, the discharge utilized in the Water Surface Elevation Model is intended to be based on peak flood discharge. However, this model can be utilized for estimation of water surface elevation in scenarios other than peak flood discharge.

The user begins with generating the required geospatial data in ArcMap, using built in cross-section data extraction tools within ArcMap. The data is then imported in the Water Surface Elevation Model in spreadsheet format. The user first generates two topographic cross-chapters in ArcMap, and exports this data to a spreadsheet file format. An MMI cross-chapter is then sampled along the same line to allow segregation of Manning n-Value by two parts: areas within overbanks and areas outside of overbanks. This cross-chapter utilizes the "MMI Perennial Stream Identification Grid for Lower Mekong Basin" Data Product for the extraction of all necessary geospatial data in ArcMap.

The Water Surface Elevation Model, in spreadsheet format, is utilized to import all geospatial data (topographic cross-chapter, MMI cross-chapter). Once the data has been imported, the user can run the Water Surface Elevation Estimator Model to obtain an estimate of water surface elevation and depth of flow for a user specified flow rate.

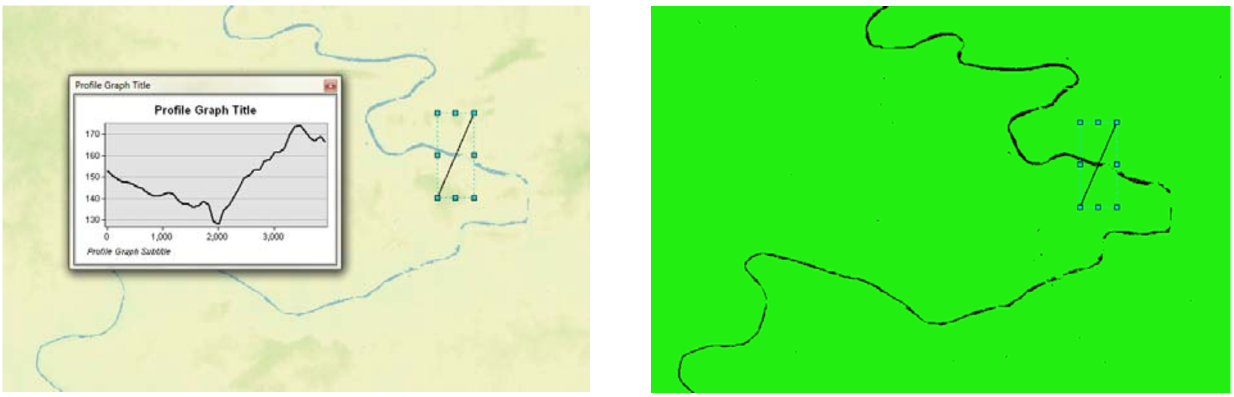



**FIGURE 5.4.2** – **Left Frame –** ArcMap view of Data Product "High Resolution DEM of Lower Mekong Basin". A Cross-chapter through the waterway is sampled using ArcMap. **Right Frame -** Overbank stationing map utilizing the Data Product "MMI Perennial Stream Identification Grid for Lower Mekong Basin". GIS data is exported and utilized used to readily identify overbank stationing.

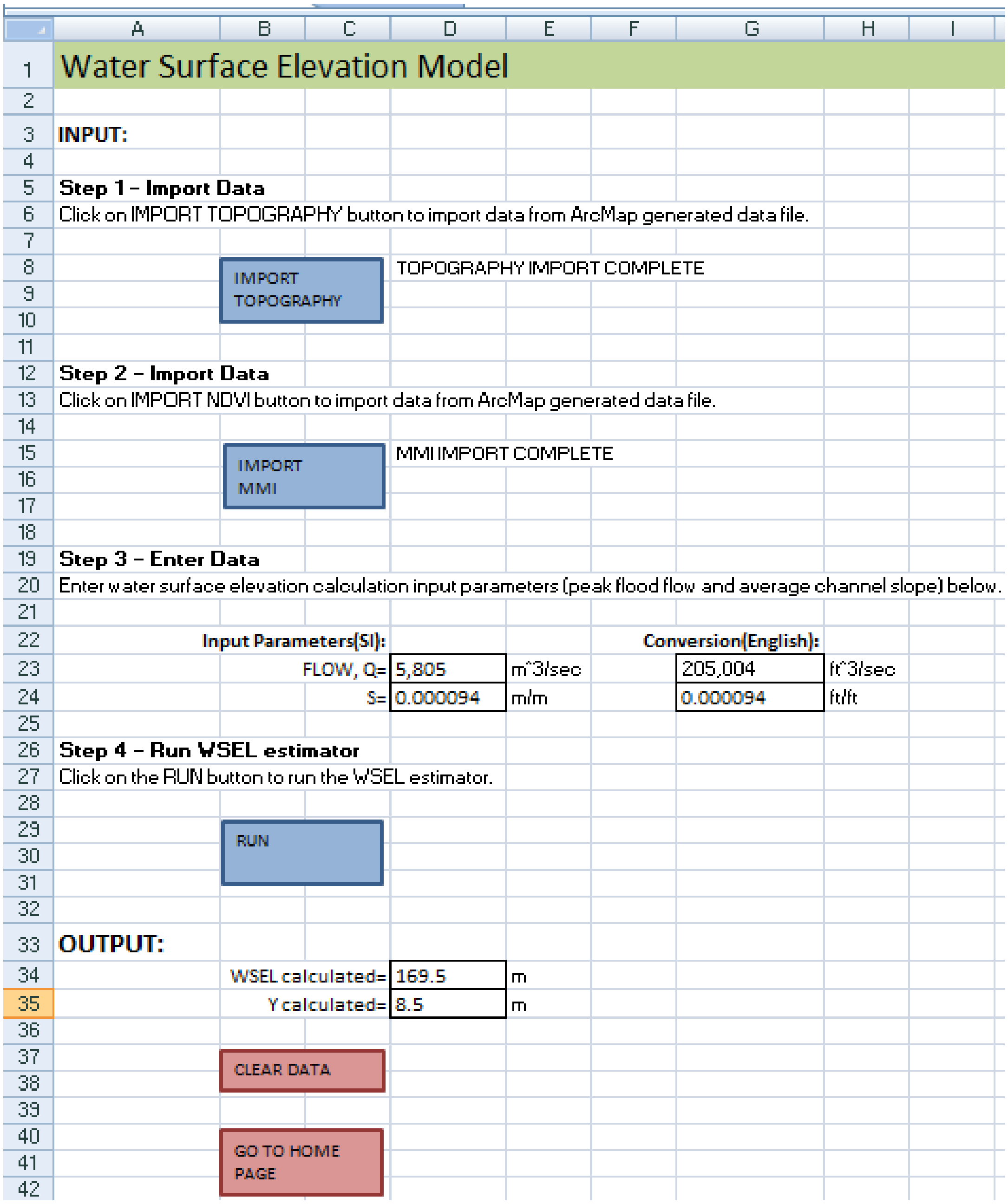



**FIGURE 5.4.3** – Water Surface Elevation Model user interface sheet. The User follows the steps outlined in the spreadsheet and obtains estimated water surface elevation for the reach specified by the user. In this case, the tool estimated an average water surface elevation of 169.5 meters above sea level, and a depth of flow of 8.5 meters.

Once a water surface elevation has been estimated with the Water Surface Elevation Model, the Population Inundation Mapping Tool created in ArcMap, is utilized to create a map of inundated population. Geospatial data is exported for use in the Population Inundation Tool, created in a spreadsheet environment, to estimate the number of persons affected by a flood event.

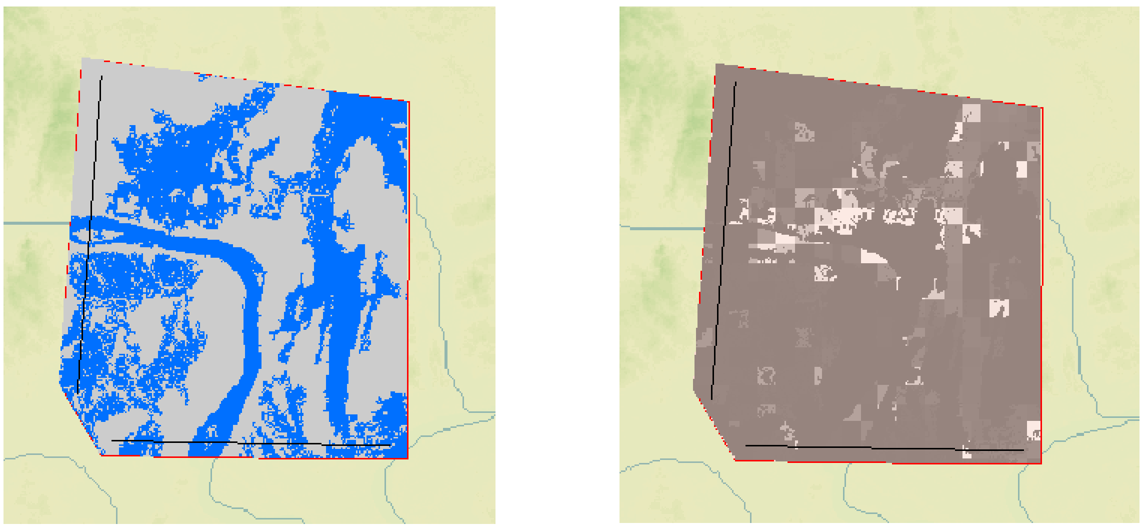


**FIGURE 5.4.4** – ArcMap views of flood inundation map (left frame), and population inundation map (right frame) created with the Population Inundation Tool. For the population inundation map, dark grey indicates zero inundation; lighter shades of grey and white indicate inundated population (the lighter the shade, the greater number of population is inundated).

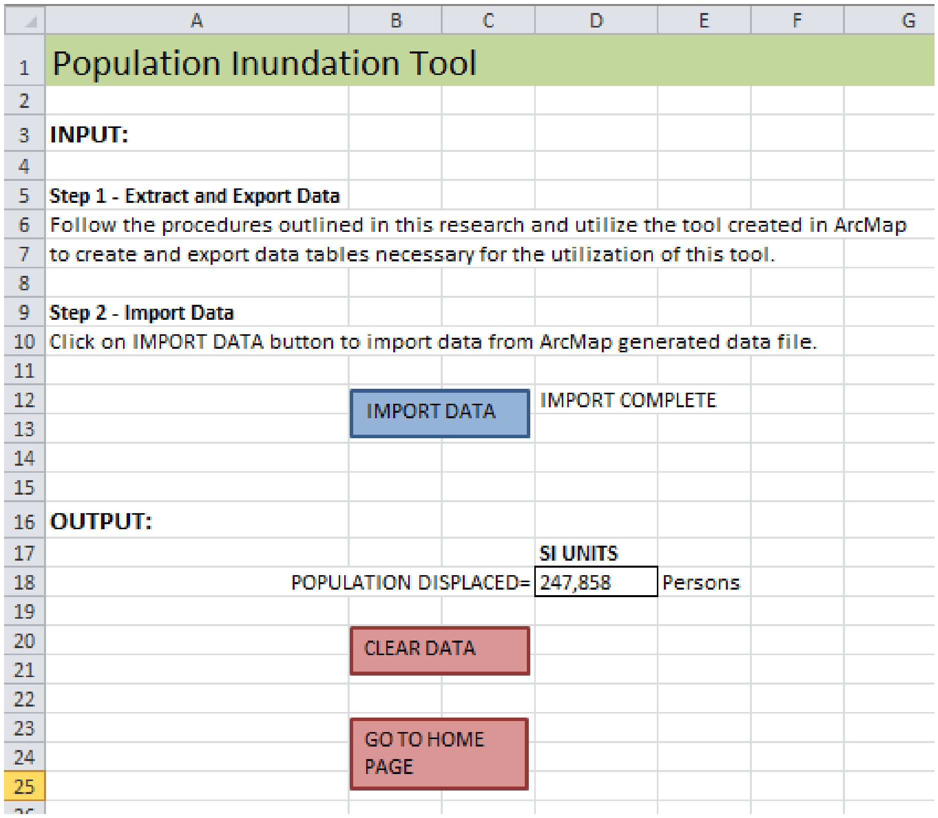



**FIGURE 5.4.5** – Population Inundation Tool spreadsheet user interface sheet. User follows steps outlined in the spreadsheet and obtains estimated population affected by a flood event. In this case the tool estimates 247,858 persons inundated by annual average flood in the user specified area.

The Population Inundation Tool can be used in conjunction with the Flood Attenuation Model to create inundation scenarios for reduction in flood discharge by the placement of an upstream flood control reservoir. The figure below shows, from left to right, inundation mapping for an upstream flood control volume of 0 (no flood control), 0.5 km^3, and 1.0 km^3.

The Population Inundation Tool was then utilized to estimate affected populations of 247,800, 96,000 and 29,000 persons in these flood control scenarios.

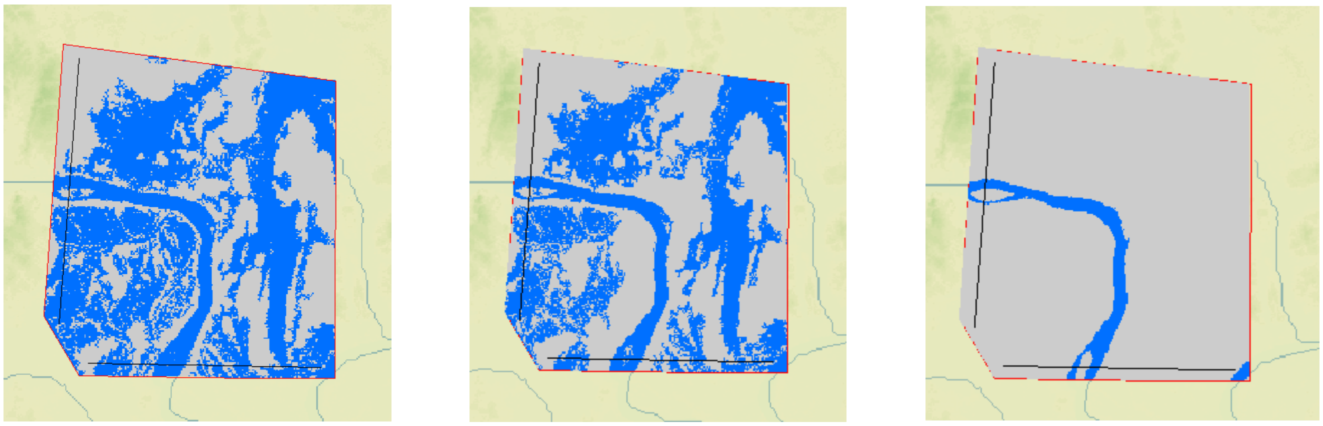


**FIGURE 5.4.6** –Population Inundation Tool used in conjunction with the Flood Attenuation Model to create inundation scenarios for reduction in flood discharge, and to estimate affected populations in these flood control scenarios.

## 5.5 APPLICATION RESEARCH CONCLUSIONS

### 5.5.1 Conclusions

The second and third hypotheses set forth in Chapter 2 have been supported within the current chapter of the research. The Tools and Models that have been created demonstrate that, as stated in the second hypothesis, the data now available in a GIS format can be utilized to conduct reservoir planning in data-limited areas. The data now available can, along with the tools and models created in this research, offer decision makers in developing nations the means to efficiently answer key reservoir planning questions and assess both potential adverse impacts along with potential benefits of alternative reservoir sites. The data that has been utilized to create a database for the Lower Mekong Basin is available through the internet and is global in nature. Thus, the type of database set up in this research using the Lower Mekong Basin as a case study could be re-created for any data limited area or developing nation in the world.

The third hypothesis, focused on regional high-level evaluation of flood control benefits of reservoirs, has been supported with the final Tools and Models presented in this research. These Tools and Models have been shown to offer decision makers in data-limited areas or developing nations the means to quickly and efficiently ascertain potential flood inundation, affected population and flood control benefits of reservoirs and the creation of new flood control attenuation.

# CHAPTER 6.0 – CASE STUDIES – DEMONSTRATION OF UTILIZATION OF DATA PRODUCTS, TOOLS, AND MODELS

## 6.1 Case Study 1 – Evaluation of Potential Tributary River Reservoir Sites

This chapter provides case studies demonstrating the use of the tools and models created. The case studies were conducted using the Lower Mekong Basin, in southeast Asia, as a testing ground. Data products have been set up for the majority of the Lower Mekong Basin (652,000 square kilometers), within the nations of Laos, Vietnam, Thailand, and Cambodia. The first case study involved the use of the tools and models in the reservoir planning spreadsheet. This, in conjunction with the data products, was used to conduct a screening study of multiple reservoir sites. The second case study involved the tools, models and data products to assess flood control effects of a potential reservoir with a flood control component.

The last sections of this chapter provide discussion of potential cost savings in utilizing the methodologies proposed in this research for the generation of data products, as well as use of the proposed tools and models. Additionally, comparison of the results of using the proposed tools and models with traditional methods is provided.

Three potential reservoir sites on rivers tributary to the Mekong River have been evaluated utilizing the data products, tools, and models created in this research. First, the data product “High Resolution DEM for the Lower Mekong Basin” has been overlayed with the data product “High Resolution Flow Accumulation Grid for the Lower Mekong Basin” in order to locate potential sites. An example in shown in the of the following figure. The left frame shows the flow accumulation data product (dark red lines), which provides the user with a guide for locating the flowlines of valleys potential streams and rivers.

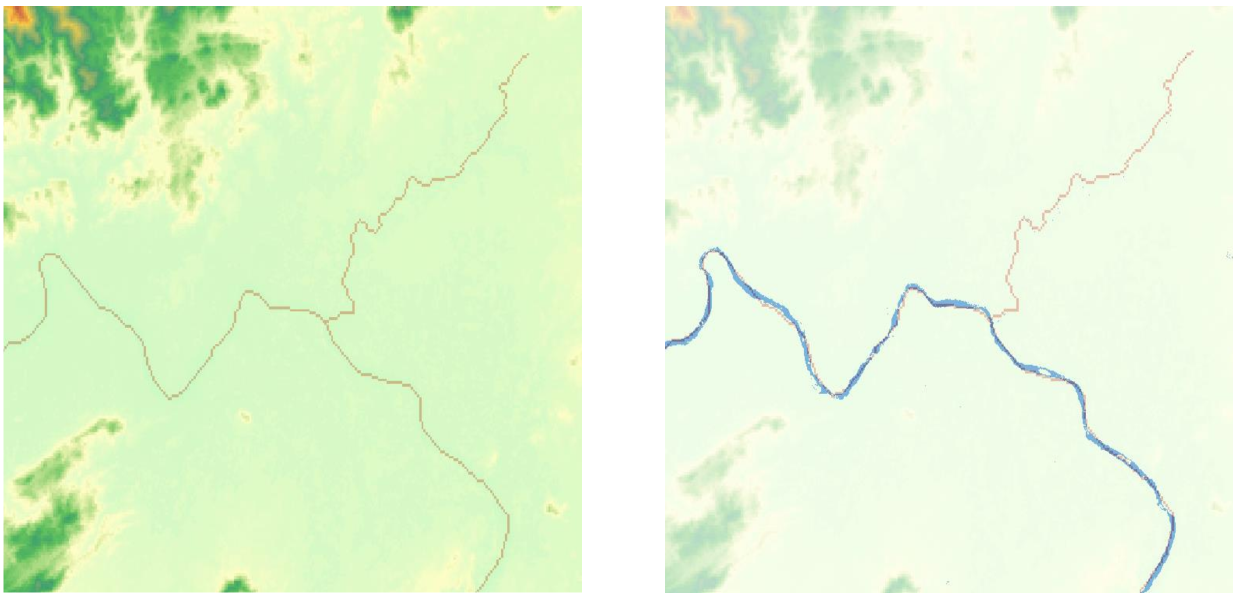


**FIGURE 6.1.1** – **Left Frame** - Overlay of data product "High Resolution DEM for the Lower Mekong Basin" (topographic color pattern) and "High Resolution Flow Accumulation Grid for Lower Mekong Basin" (dark red line) showing topography and valley flowline. **Right Frame** - Additional overlay of data product "Perennial Stream Identification Grid for Lower Mekong Basin" (blue color pattern), showing perennial stream flow, along one of the valley flowlines.

The flow accumulation data product has been set to only display a flowline if greater than 800 square kilometers of watershed drains to that point in the flowline. In doing so, flowlines with too little contributing watershed area are filtered out. As seen in Figure 6.1.1, the branch of the tributary in the upper right portion of the screen view ends at the point where the contributory watershed is less than this threshold.

The right frame in Figure 6.1.1 shows the additional overlay of the data product "MMI Perennial Stream Identification Grid for the Lower Mekong Basin", which allows the user to determine whether the stream or river has perennial flow characteristics. As shown in this frame, the branch of the tributary in the upper right does not display perennial flow characteristics, while the stream flowing through the middle does have perennial flow characteristics, which is indicated by the blue color pattern following the flowline.

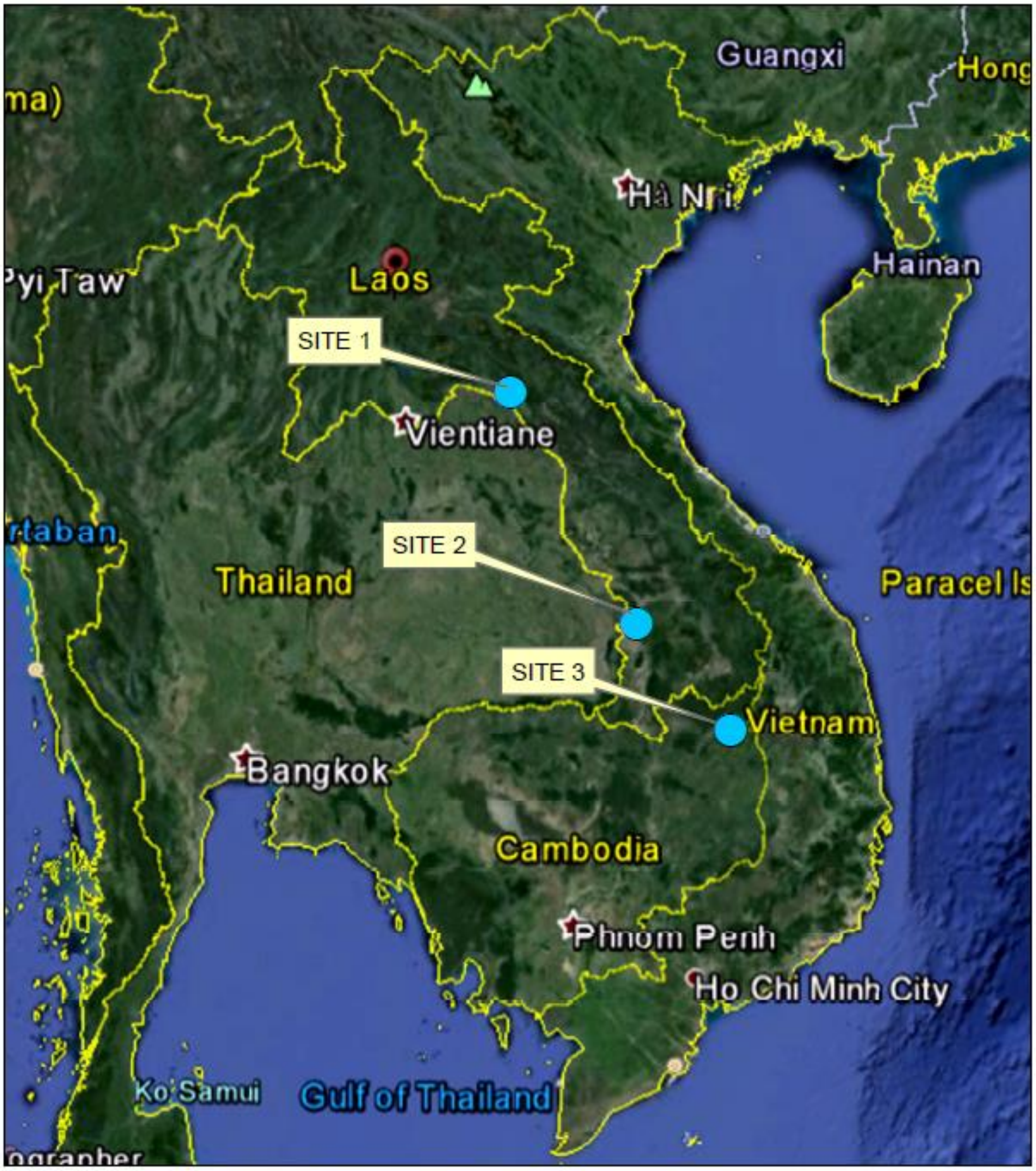
The sites screened in this case study were initially located using the methodology and two data products discussed above. In doing so the sites would, at a minimum, have a fairly large contributory watershed (greater than 800 square kilometers), and be shown to have perennial flow at the locations selected.

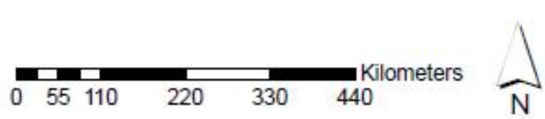
As discussed in Chapter 5, a spreadsheet interface has been utilized for user interaction with the tools and models created in this research. ArcGIS has been utilized for user interface for all data products created in this research. Following are maps created in ArcGIS with data products overlaying one another as background. Spreadsheet user interface summary tables follow map sets for each site.

It is noted that a maximum dam height of 100 meters was chosen for this case study. For some of the sites evaluated, particularly those in the southern portion of the Lower Mekong Basin where terrain is less mountainous, dam heights evaluated were less than 100 meters. A minimum dam height of was chosen as 15 meters in these areas.

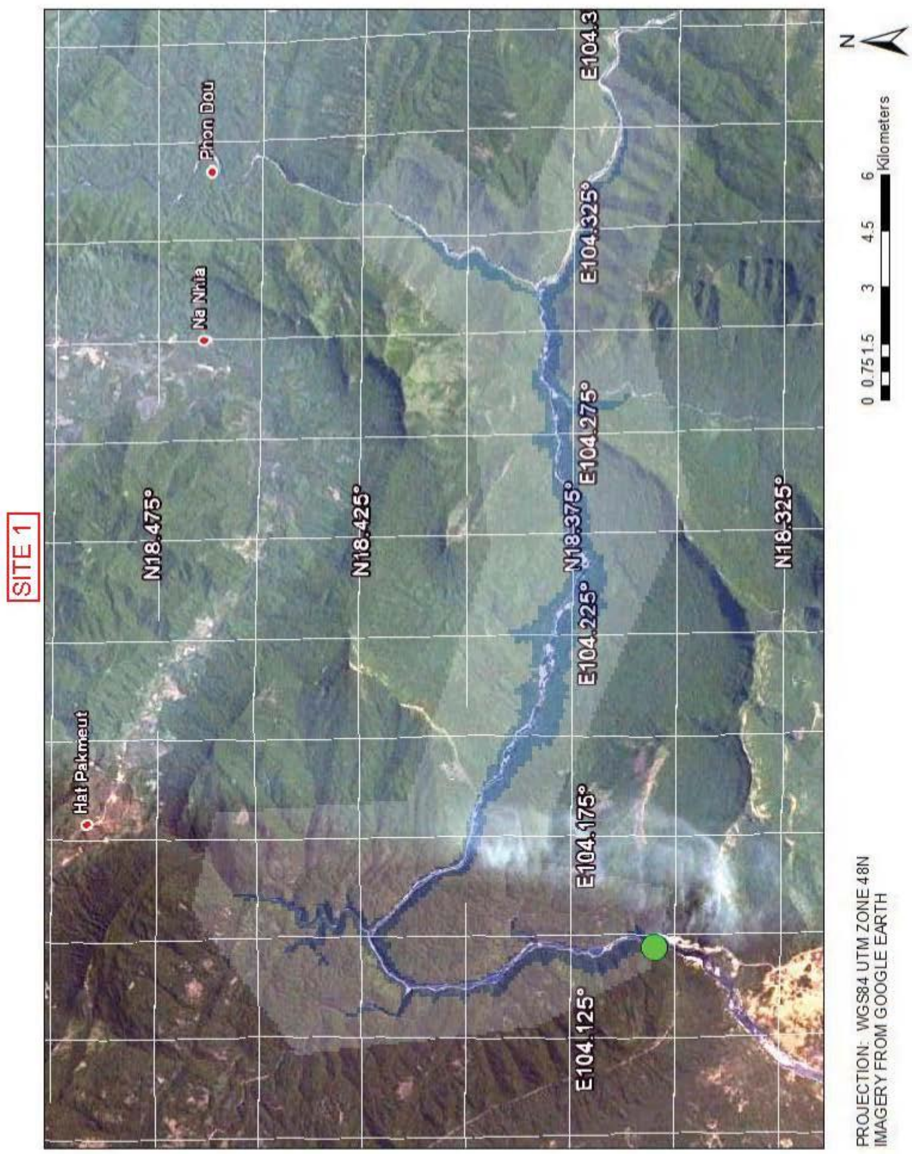
The following two figures provide an overview of the sites evaluated in this case study with first, a satellite imagery background, and second, a color coded terrain mapping (digital elevation model) background. Following these two overview maps, individual site maps are provided with higher resolution satellite imagery and terrain mapping backgrounds.

## OVERALL SITE MAP WITH GOOGLE EARTH IMAGERY OVERLAY

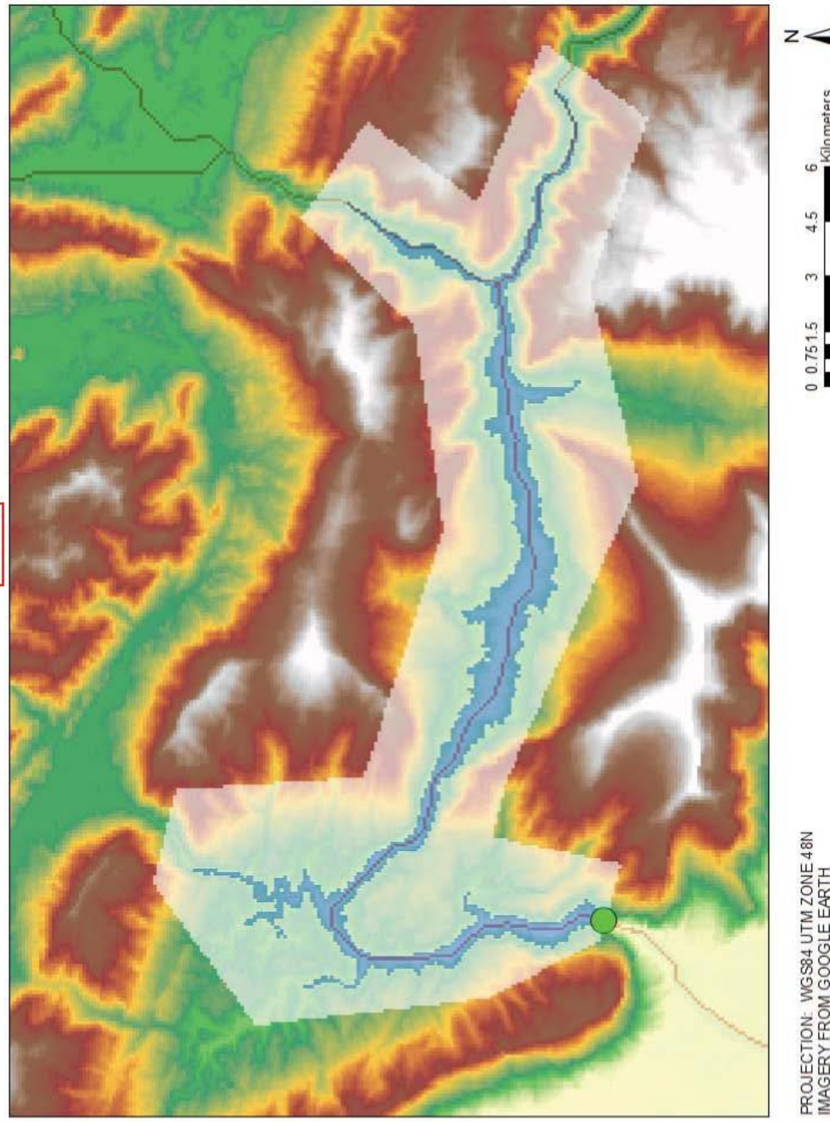



PROJECTION: WGS84 UTM ZONE 48N
IMAGERY OBTAINED FROM GOOGLE EARTH 1/8/14


SITE 1
Hat Pakmeut
Na Nhia
Phon Dou
N18.475°
N18.425°
N18.375°
N18.325°
E104.125°
E104.175°
E104.225°
E104.275°
E104.325°
E104.3
PROJECTION: WGS84 UTM ZONE 48N
IMAGERY FROM GOOGLE EARTH
0 0.75 1.5 3 4.5 6
Kilometers
N

SITE 1


N
0 0.75 1.5 3 4.5 6
Kilometers
PROJECTION: WGS84 UTM ZONE 48N
IMAGERY FROM GOOGLE EARTH

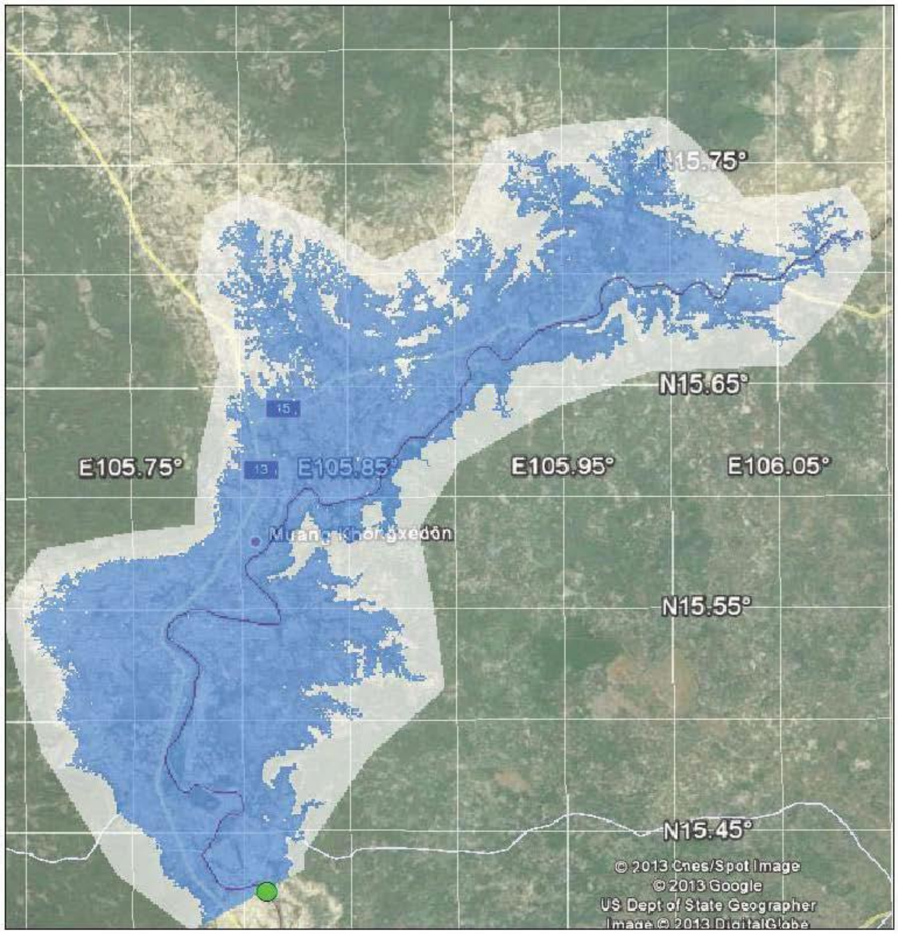
## Site 1 Summary

| | |
|---|---|
| **General Site Assessment** | |
| Proposed Dam Height (m): | 100 |
| Estimated Available Storage Volume at Specified Dam Height (km^3): | 0.86 |
| Estimated Watershed Area (km^2) | 13,627 |
| Estimated Annual Yield (km^3): | 7.27 |
| Estimated Average Annual Flood Discharge (m^3/s): | 789 |
| **Adverse Impact Assessment** | |
| Estimated Population Displaced (persons): | 7 |
| Estimated Farmland Loss Area (km^2): | 0.14 |
| Estimated Average Annual Flow Reduction (m^3/s): | 230 |
| **Benefit Assessment** | |
| Estimated Irrigable Area within 30 km radius (km^2): | 1803.62 |
| Estimated Serviceable Population within 30 km radius (persons): | 49,125 |
| Estimated Hydropower Potential (MW): | 390.68 |

**STAGE - STORAGE TABLE:**

| STAGE/DAM HEIGHT (m) | STORAGE (km^3) |
|---|---|
| 0 | 0 |
| 10 | 0.000291913 |
| 20 | 0.002877432 |
| 30 | 0.011051008 |
| 40 | 0.045788705 |
| 50 | 0.117098984 |
| 60 | 0.213430413 |
| 70 | 0.334324272 |
| 80 | 0.480030771 |
| 90 | 0.651759267 |
| 100 | 0.858183758 |

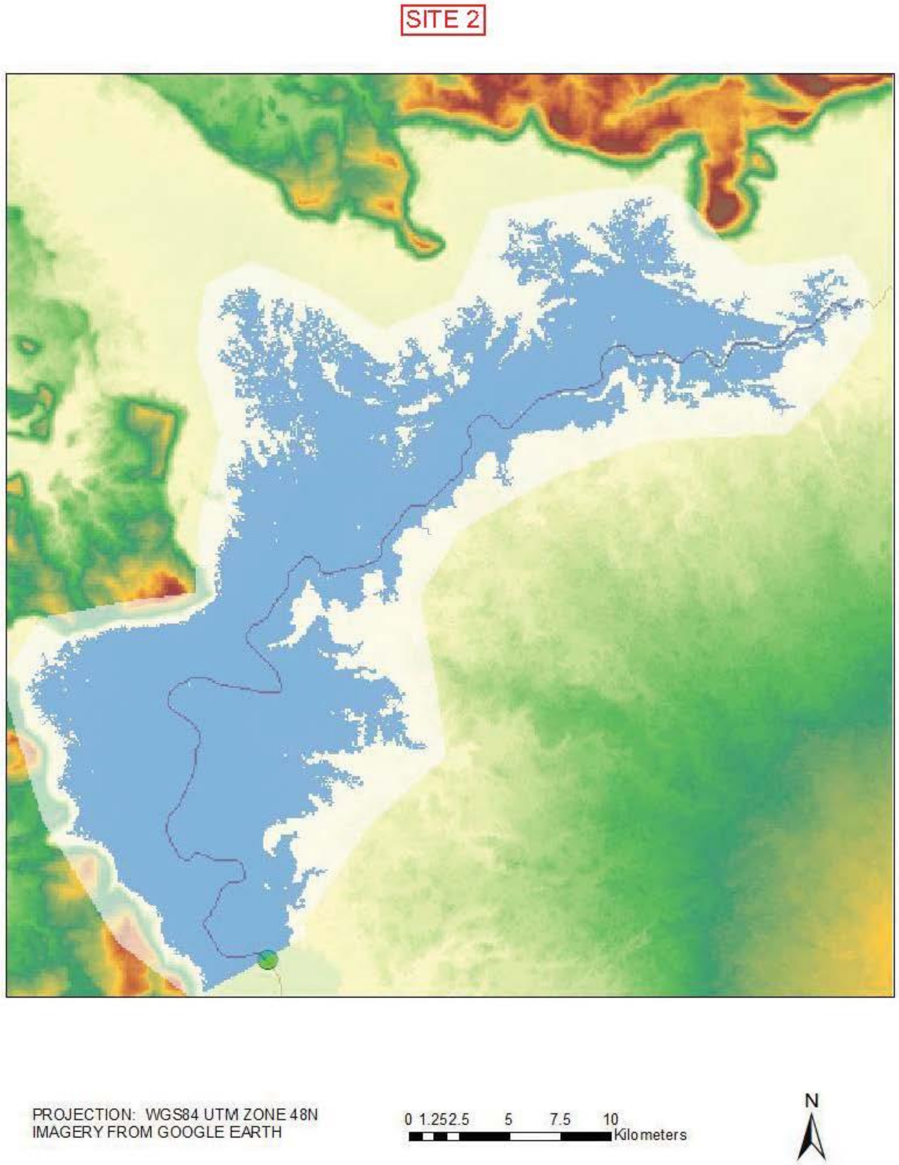
SITE 2




PROJECTION: WGS84 UTM ZONE 48N
IMAGERY FROM GOOGLE EARTH

0 1.25 2.5 5 7.5 10 Kilometers

N


SITE 2
PROJECTION: WGS84 UTM ZONE 48N
IMAGERY FROM GOOGLE EARTH
0 1.25 2.5 5 7.5 10
Kilometers
N

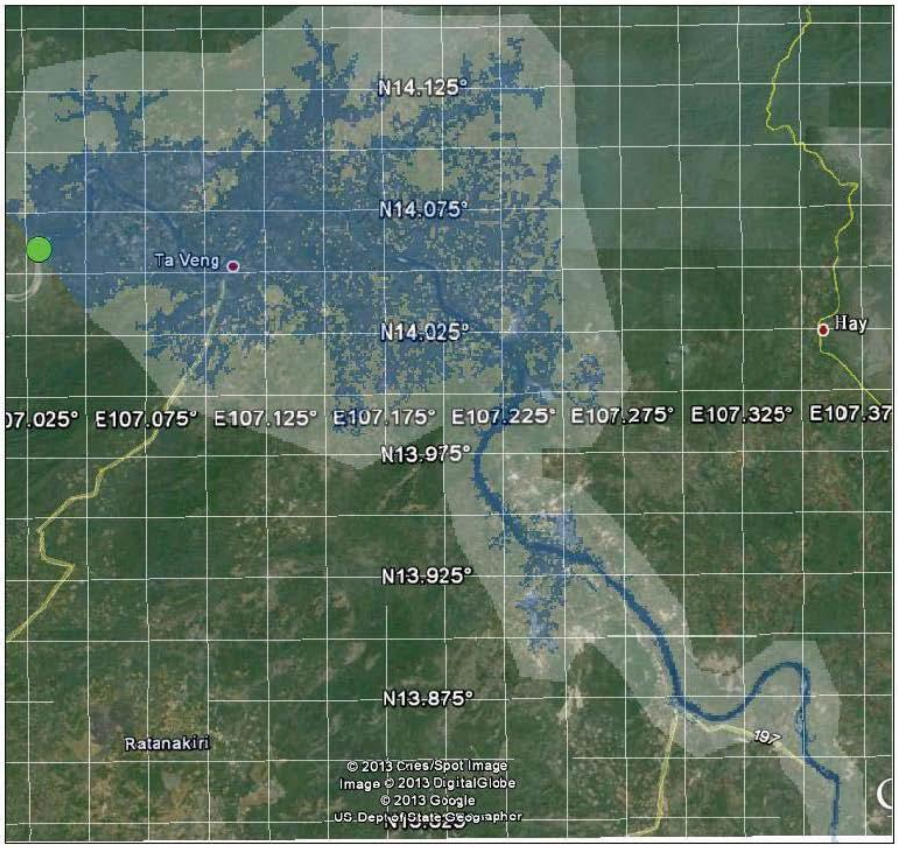
# Site 2 Summary

| | |
|---|---|
| **General Site Assessment** | |
| Proposed Dam Height (m): | 20 |
| Estimated Available Storage Volume at Specified Dam Height (km^3): | 3.59 |
| Estimated Watershed Area (km^2) | 5,689 |
| Estimated Annual Yield (km^3): | 2.81 |
| Estimated Average Annual Flood Discharge (m^3/s): | 463 |
| **Adverse Impact Assessment** | |
| Estimated Population Displaced (persons): | 57,628 |
| Estimated Farmland Loss Area (km^2): | 233.32 |
| Estimated Average Annual Flow Reduction (m^3/s): | 89 |
| **Benefit Assessment** | |
| Estimated Irrigable Area within 30 km radius (km^2): | 16.30 |
| Estimated Serviceable Population within 30 km radius (persons): | 66,919 |
| Estimated Hydropower Potential (MW): | 30.16 |

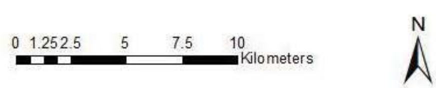
**STAGE - STORAGE TABLE:**

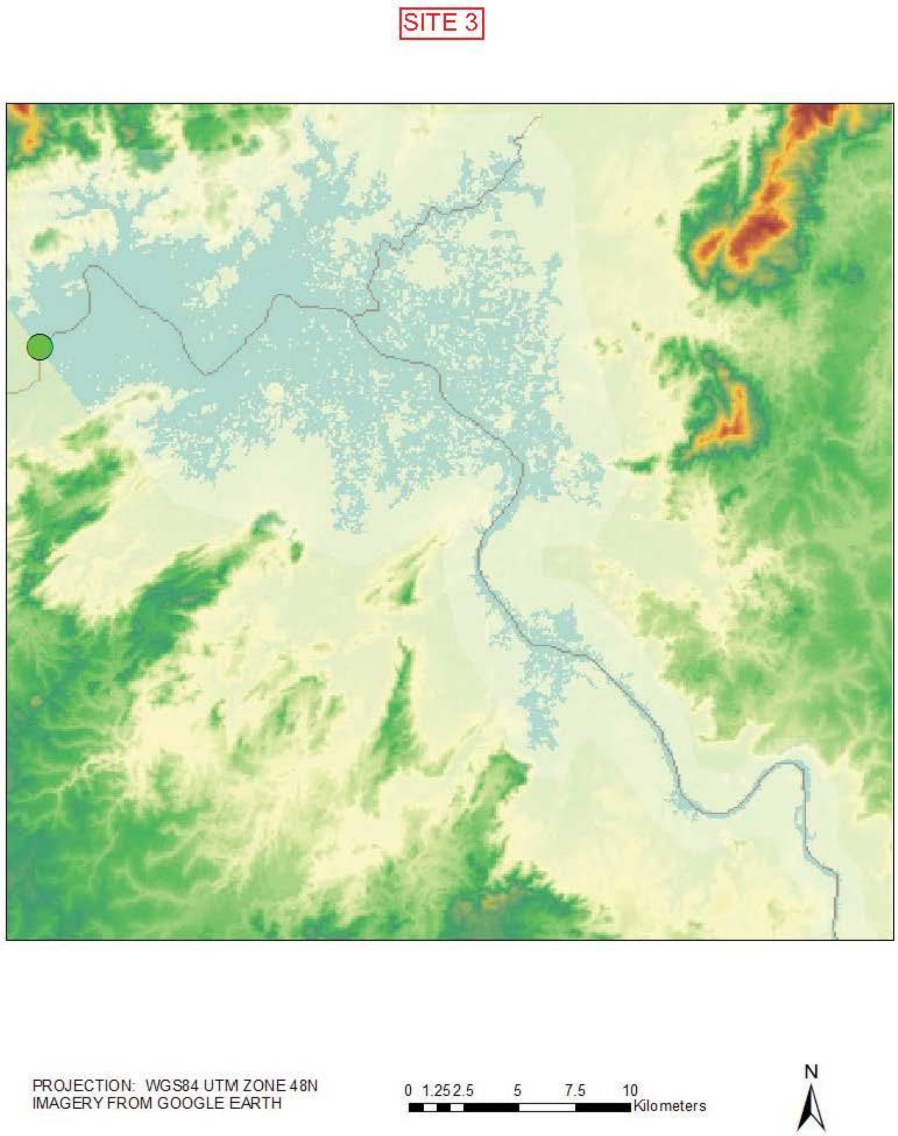
| STAGE/DAM HEIGHT (m) | STORAGE (km^3) |
|---|---|
| 0 | 0 |
| 5 | 0.08417532 |
| 10 | 0.607054812 |
| 15 | 1.798645399 |
| 20 | 3.585822772 |
| | |
| | |
| | |
| | |
| | |
| | |

SITE 3




PROJECTION: WGS84 UTM ZONE 48N
IMAGERY FROM GOOGLE EARTH




SITE 3
PROJECTION: WGS84 UTM ZONE 48N
IMAGERY FROM GOOGLE EARTH
0 1.25 2.5 5 7.5 10
Kilometers
N

## Site 3 Summary

| | |
|---|---|
| **General Site Assessment** | |
| Proposed Dam Height (m): | 20 |
| Estimated Available Storage Volume at Specified Dam Height (km^3): | 1.36 |
| Estimated Watershed Area (km^2) | 15,171 |
| Estimated Annual Yield (km^3): | 8.17 |
| Estimated Average Annual Flood Discharge (m^3/s): | 842 |
| **Adverse Impact Assessment** | |
| Estimated Population Displaced (persons): | 2,292 |
| Estimated Farmland Loss Area (km^2): | 8.04 |
| Estimated Average Annual Flow Reduction (m^3/s): | 259 |
| **Benefit Assessment** | |
| Estimated Irrigable Area within 30 km radius (km^2): | 4.43 |
| Estimated Serviceable Population within 30 km radius (persons): | 21,017 |
| Estimated Hydropower Potential (MW): | 87.83 |

**STAGE - STORAGE TABLE:**

| STAGE/DAM HEIGHT (m) | STORAGE (km^3) |
|---|---|
| 0 | 0 |
| 5 | 0.026647525 |
| 10 | 0.167182987 |
| 15 | 0.558138463 |
| 20 | 1.35693869 |
| | |
| | |
| | |
| | |
| | |
| | |

## 6.2 Case Study 2 – Evaluation of Flood Control Benefits

The City of Vientiane, located on the Lower Mekong River in northern Laos has been selected for this case study to demonstrate the evaluation of flood control benefits of a potential reservoir utilizing the Data Products, Tools and Models created in this research.


**FIGURE 6.2.1** – City of Vientiane, Laos, located on the Lower Mekong River.

A hypothetical reservoir has been placed just upstream of the City of Vientiane. The flood attenuation model estimates flood attenuation benefits for potential reservoirs and hypothetical flood storage volume provided by a reservoir. The Water Surface Elevation Model estimates water surface elevation at a user specified reach along a waterway. The Population Inundation Tool takes the estimated water surface elevation from the Water Surface Elevation Model, and provides the user with a map of estimated inundation area and the estimated number of persons affected by flooding.

The user begins with generating the required geospatial data in by utilizing the methodology within ArcMap as outlined in Chapter 5. Data is then imported in the Water Surface Elevation Model in spreadsheet format. The user first generates two topographic cross-sections in ArcMap, and exports this data to a spreadsheet file format. An MMI cross-section is then sampled along the same line to allow segregation of Manning n-Value by two parts: areas within overbanks and areas outside of overbanks.

The Water Surface Elevation Model, in spreadsheet format, is utilized to import all GIS data (topographic cross-section, MMI cross-section). Once all necessary data has been imported, the user can run the Water Surface Elevation Estimator Model to obtain an estimate of water surface elevation and depth of flow for a user specified flow rate.

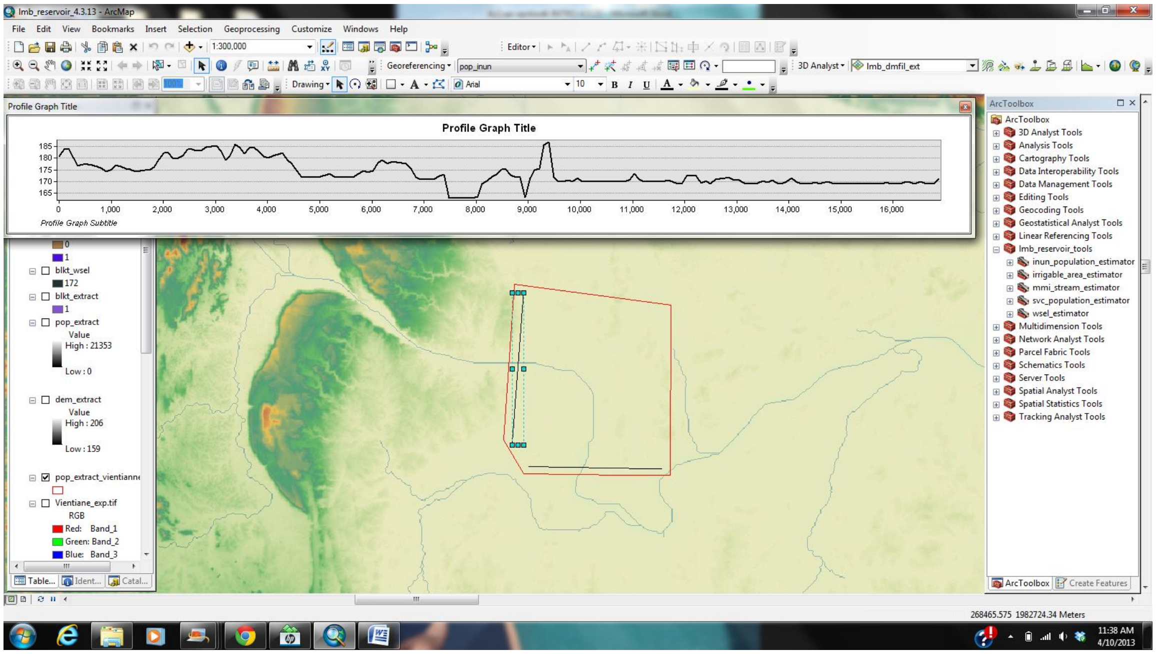



**FIGURE 6.2.2** – ArcMap view of area of inundation to be mapped (outlined in red) and data product "High Resolution DEM of Lower Mekong Basin" in background. Black lines represent cross-section cut lines. A profile view of the upstream cross section is displayed in the upper portion of the screen.

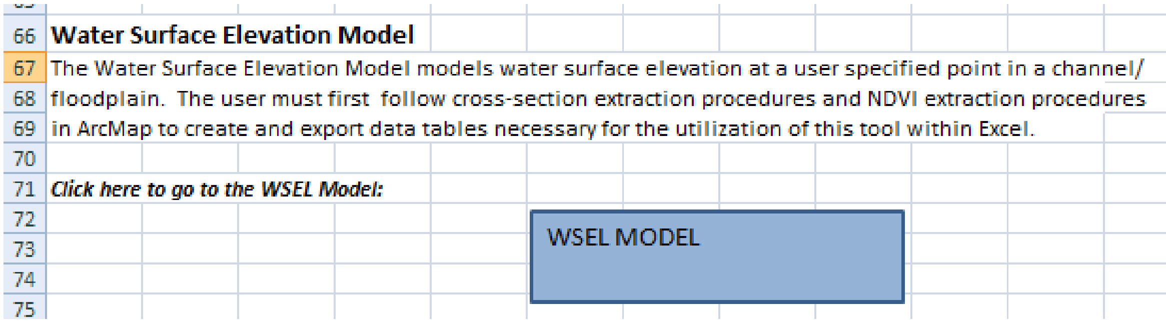



**FIGURE 6.2.3** – Zoomed view of Home Page of “lmb_reservoir” spreadsheet and the Water Surface Elevation Model. The user clicks on the WSEL Model button to go to the user interface page.

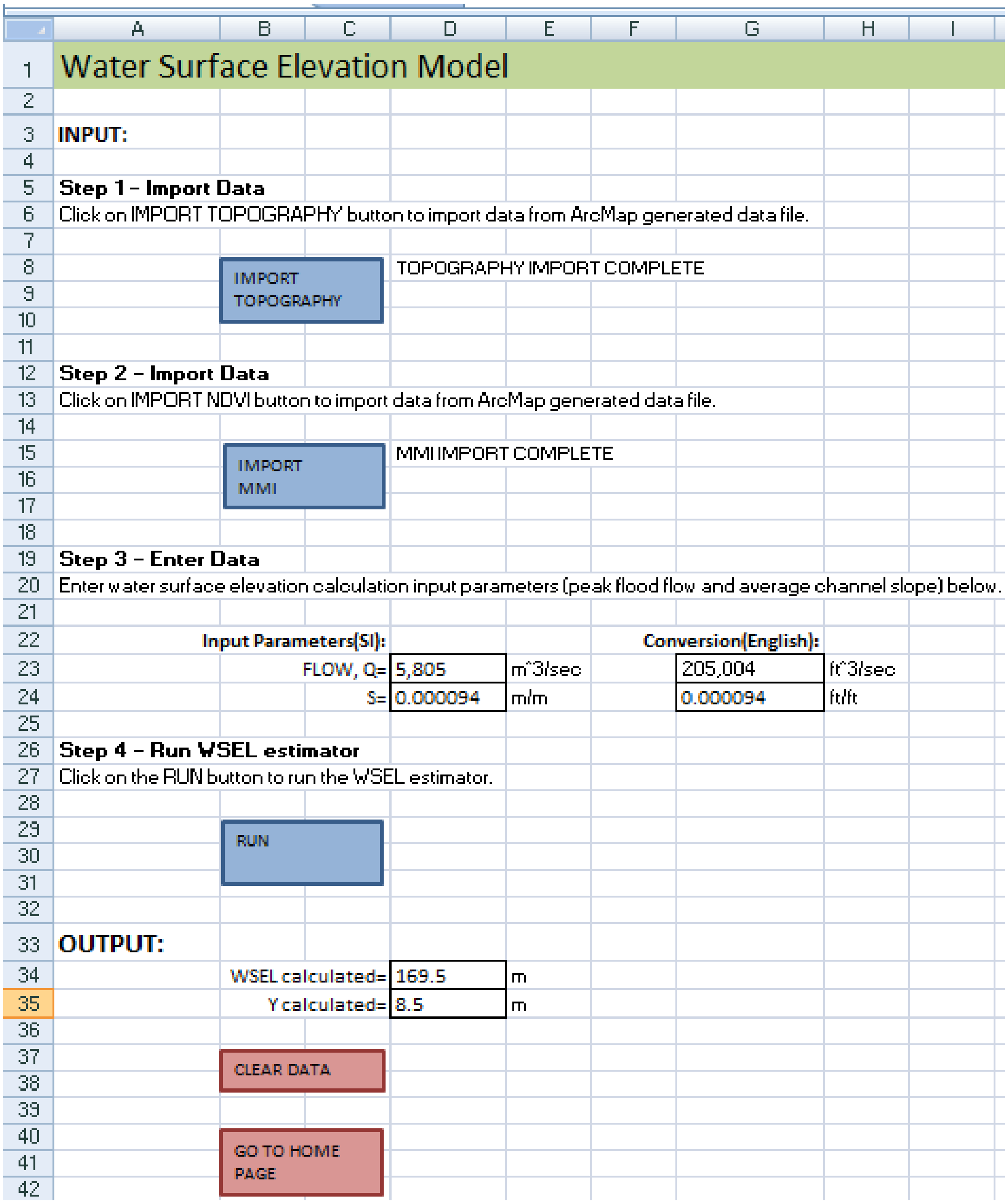



**FIGURE 6.2.4** – Water Surface Elevation Model user interface sheet. The User follows the steps outlined in the spreadsheet and obtains estimated water surface elevation for the reach specified by the user. In this case, the tool estimated an average water surface elevation of 169.5 meters above sea level, and a depth of flow of 8.5 meters.

The Flood Attenuation Model estimates the flood discharge attenuation that could potentially be realized by the placement of a reservoir at a user specified point in a waterway. This model requires that the user to first utilize the Flood Discharge Model to estimate a peak flood discharge. The model also requires the user to enter estimated flood duration. Based on these two parameters, the user can enter anticipated flood storage volume and obtain estimated attenuated flood discharge (reduced flood discharge).

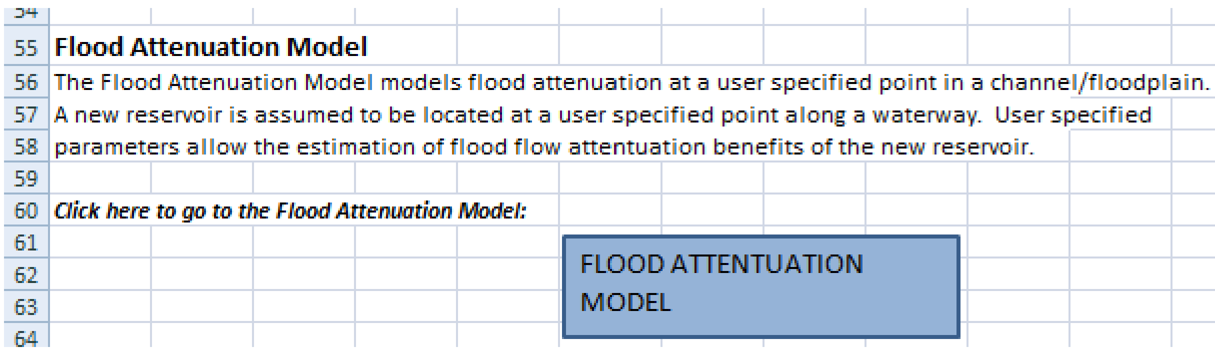



**FIGURE 6.2.5** – Zoomed view of Home Page of “lmb_reservoir” spreadsheet and the Flood Attenuation Model. The user clicks on the Flood Attenuation Model button to go to the user interface page.

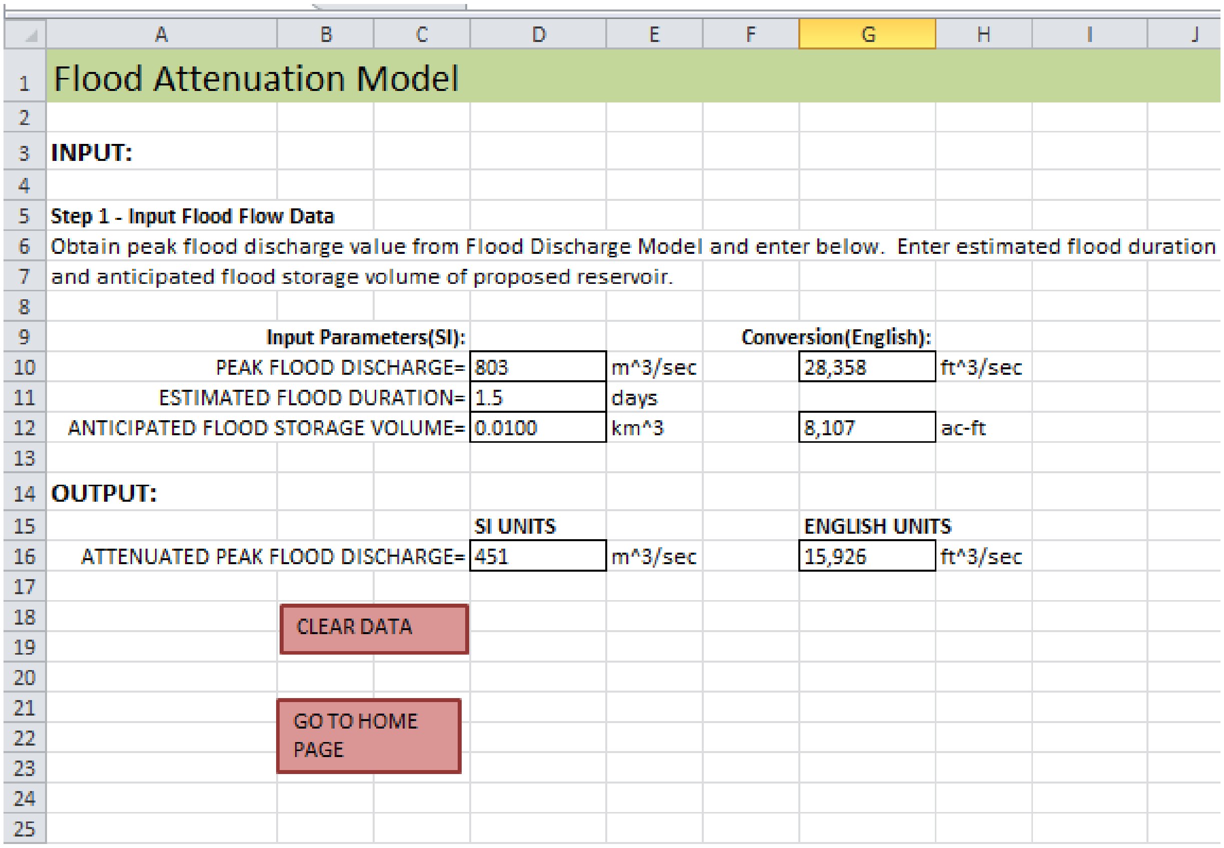



**FIGURE 6.2.6** – Flood Attenuation Model user interface sheet. The user enters peak flood discharge and an estimated flood duration. Based on these two parameters, the user can enter anticipated flood storage volume and obtain estimated attenuated flood discharge (reduced flood discharge). In this case the user entered an anticipated flood storage volume of 0.01 km^3 and was provided an estimated reduced peak flood discharge of 451 m^3/s.

Once a water surface elevation has been estimated and hypothetical flood attenuation volumes and reduced flood flows have been computed, the methodology outlined in Chapter 5 for ArcMap is utilized to create a map of inundated population. Geospatial data is exported for use in the Population Inundation Tool, created in a spreadsheet environment, to estimate the number of persons affected by a flood event.

A binary map is created with the Population Inundation Mapping Tool. All cells below the estimated water surface elevation are set to a value of 1 (shown in blue in the following figure); all cells above are set to a value of 0 (shown in grey in the following figure). Thus, blue cells represent estimated inundation to the nearest vertical meter, and set up the basis for the Population Inundation Tool.

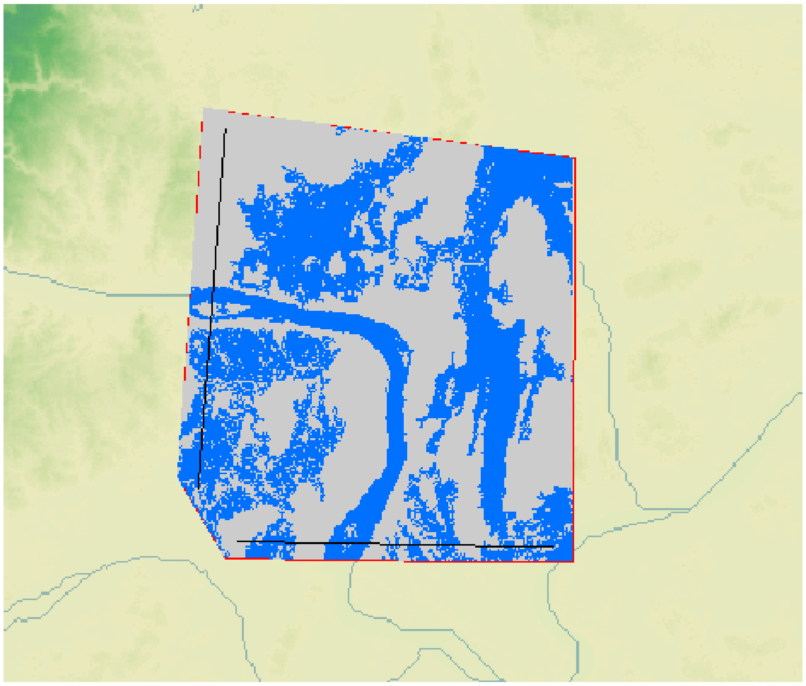


**FIGURE 6.2.7** – Binary map created using the Inundation Mapping Tool. Blue cells represent estimated inundation to the nearest vertical meter.

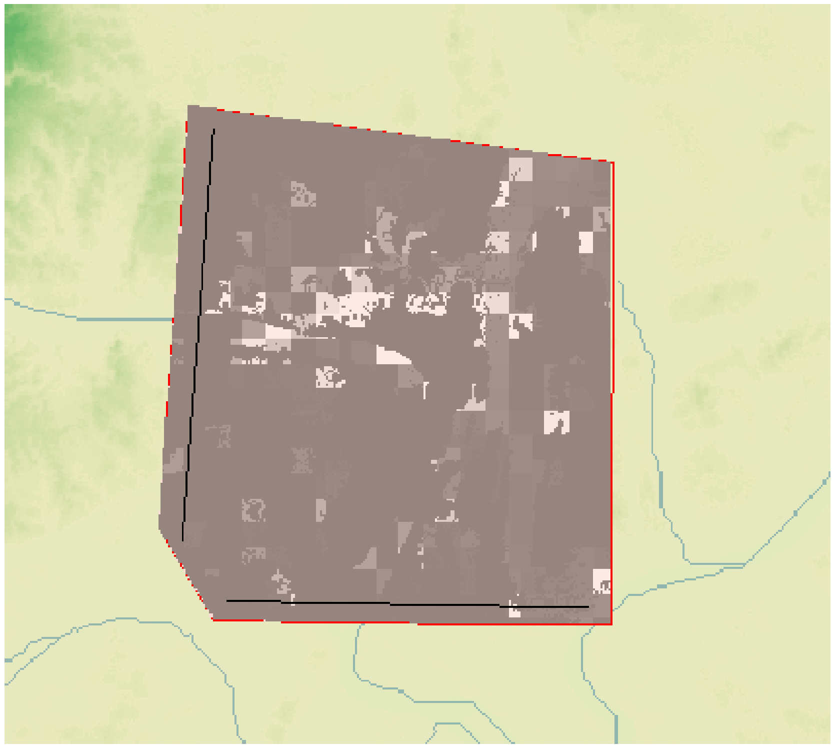


**FIGURE 6.2.8** – Map resulting from the operation [binary inundation map] * [extracted population map]. All binary inundation map cells that = 0 result in registering a 0 population inundation value. All binary inundation map cells that = 1 result in registering the population value in the extracted population map.

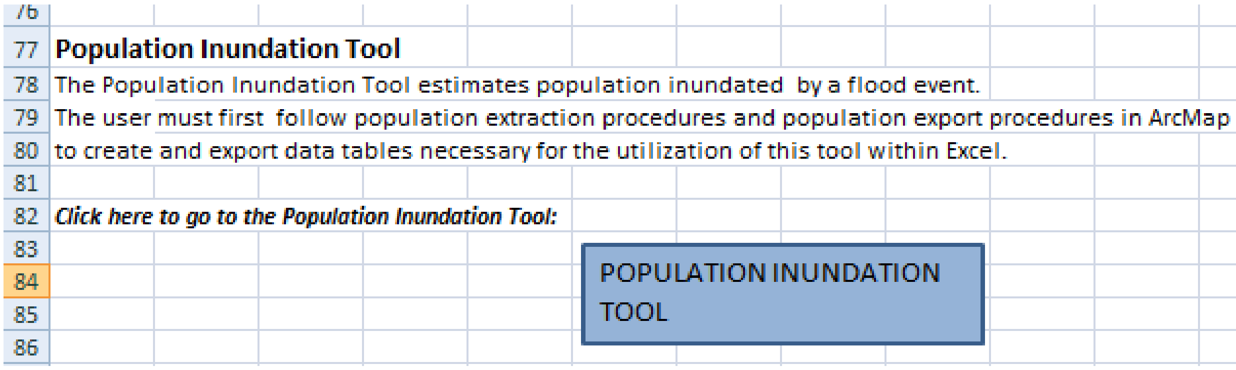



**FIGURE 6.2.9** – Zoomed view of Home Page of "lmb_reservoir" spreadsheet and the Population Inundation Tool. The user clicks on the Population Inundation Tool button to go to the user interface page.

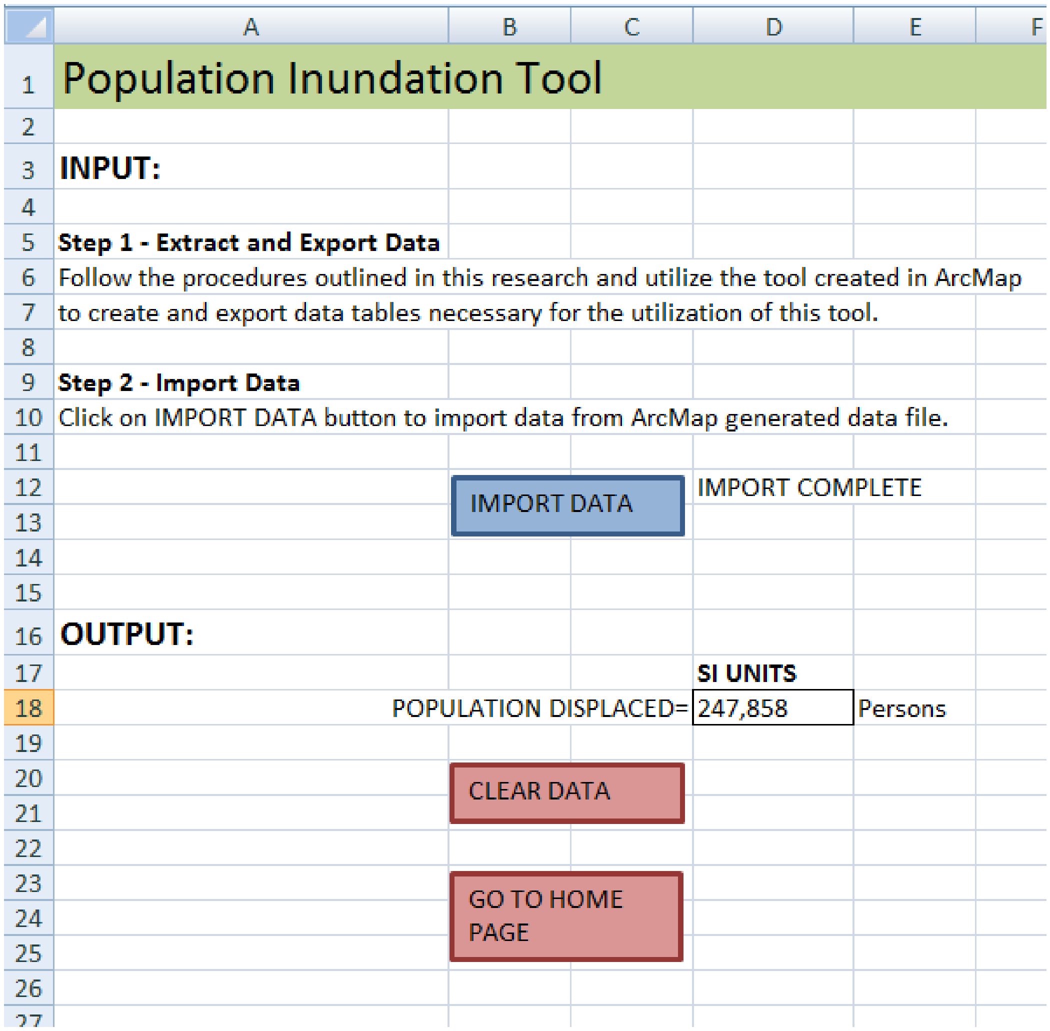



**FIGURE 6.2.10** – Population Inundation Tool user interface sheet. User follows steps outlined in the spreadsheet and obtains estimated population affected by a flood event. In this case the tool estimates 247,858 persons affected by flooding of the user specified area shown in Figure 6.2.7.

The Population Inundation Tool is used in conjunction with the Flood Attenuation Model to create inundation scenarios for reduction in flood discharge by the placement of an upstream flood control reservoir. The figure below shows, from left to right, inundation mapping for flood control volumes of 0 (no flood control), 0.5 km^3, and 1.0 km^3. These flood control scenarios resulted in estimated attenuated flood flows of 12845 m^3/s (no flood control), 5805 m^3/s, and 2889 m^3/s. The Population Inundation Tool was then utilized to estimate affected populations of 247,800, 96,000 and 29,000 persons in these flood control scenarios.

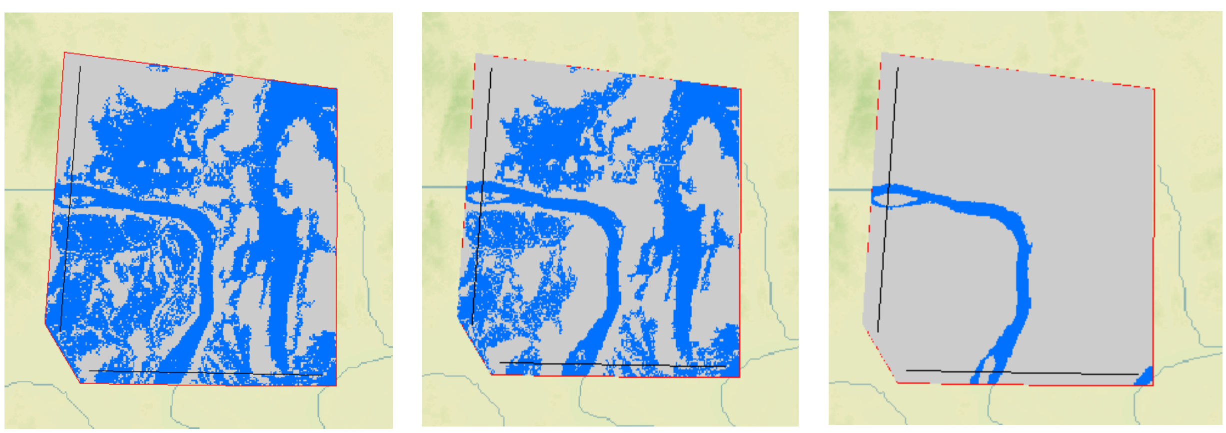


**FIGURE 6.2.11** –Population Inundation Tool used in conjunction with the Flood Attenuation Model to create three attenuation/inundation scenarios for reduction in flood discharge, and to estimate affected populations in these flood control scenarios. From left to right, affected populations of 247,800, 96,000 and 29,000 persons were estimated in the three attenuation/inundation scenarios.

### 6.3 Cost Comparisons

The Data Products, Tools, and Models created in this research can provide enormous savings in monetary terms, time and manpower. The following table lists each Tool/Model and the data required for the Tool/Model, along with traditional versus new data sources as proposed in this research.

Comparison the cost to conduct studies on a site by site basis is very difficult because the overall theme of this research is to provide an end user with a means to screen potential reservoir sites on a very large scale. Once the Data Products have been set up for a large scale region, such as the Lower Mekong Basin, the time and money spent evaluating individual sites is miniscule, which can be seen in the following cost comparison table. Following are monetary cost comparisons for the creation of the information generated with this research versus traditional methods for generating this data for a single site. This cost comparison is based on the four basic data sets required to conduct evaluation with the ten Tools and Models created in this research.

| Tool/Model | Data Required | Traditional Data Source | Research Data Source |
|---|---|---|---|
| 1-Perrenial Stream Mapping Data Processing Tool | Land Cover Mapping | Stream Monitoring Station | Landsat Data Set |
| 2-Farmland Mapping Data Processing Tool | Farmland Mapping | Aerial Imagery | Landsat Data Set |
| 3-Reservoir Storage Tool | Topographic Mapping | Aerial Photogrammetric Survey | SRTM Data Set |
| 4-Annual Yield Model | Streamflow Data | Aerial Photogrammetric Survey; Regional Streamflow Data | SRTM Data Set; Regional Streamflow Data |
| 5-Flood Discharge Model | Streamflow Data | Aerial Photogrammetric Survey; Regional Streamflow Data | SRTM Data Set; Regional Streamflow Data |
| | | | |
| 6-Population Displacement Tool | Population Data; Topographic Mapping | Census Data Compilation; Aerial Photogrammetric Survey | SRTM Data Set; Landscan Data Set |
| 7-Farmland Loss Tool | Land Cover Mapping | Aerial Imagery; Aerial Photogrammetric Survey | SRTM Data Set; Landsat Data Set |
| 8-Ave. Annual Flow Reduction Model | Topographic Mapping | Aerial Photogrammetric Survey; Regional Streamflow Data | SRTM Data Set; Regional Streamflow Data |
| | | | |
| 9-Irrigable Area Tool | Topographic Mapping | Aerial Photogrammetric Survey | SRTM Data Set |
| 10-Serviceable Population Tool | Population Data | Census Data Compilation | SRTM Data Set; Landscan Data Set |
| 11-Hydropower Model | Topographic Mapping; Streamflow Data | Aerial Photogrammetric Survey; Regional Streamflow Data | SRTM Data Set; Regional Streamflow Data |
| | | | |
| 12-Flood Attenuation Model | Topographic Mapping | Aerial Photogrammetric Survey | SRTM Data Set |
| 13-Water Surface Elevation Model / Population Inundation Tool | Topographic Mapping; Population Data | Aerial Photogrammetric Survey; Census Data Compilation | SRTM Data Set; Landscan Data Set |

**TABLE 6.3.1** – Tool/Model data requirement summary

| **Traditional Data Gathering Method** | | **Newly Proposed Data Gathering Method** | |
|---|---|---|---|
| **Data Source** | **Cost for Site 1** | **Data Source** | **Cost for Site 1** |
| Stream Monitoring Station | $15,000 initial installation, $10,000 annual cost | Landsat Data Set | 1 hour @ $140/hr = $140 |
| Aerial Photogrammetric Survey | $1.8 Million | SRTM Data Set | 2 hours @ $140/hr = $280 |
| Census Data Compilation | 20 hours @ $140/hr = $2800 | SRTM Data Set; Landscan Data Set | .5 hour @ $140/hr = $70 |
| Aerial Photography | $870,000 | Google Earth Imagery | .5 hour @ $140/hr = $70 |

**TABLE 6.3.2** – Data Cost Summary

The costs in the above table for Aerial Photogrammetric Surveying and Aerial Photography are based upon averaged cost estimates from discussions with U.S. consulting firms specializing in Aerial reconnaissance. The author held these discussions via phone conversation in the month of June 2013. Costs assume a U.S. project; therefore, some fluctuation would be anticipated depending on the country or developing nation that such data would be gathered in. The author framed the context of discussions with a project that he had done as a professional consultant in northern Colorado. The project was to assemble aerial topographic data and aerial imagery using traditional methods for a floodplain hydrology and hydraulic study of a roughly 20 square mile area. Based on this context, the author scaled up costs for the current study area considered, “Site 1”.

The costs listed for a stream monitoring station is based on the averaged cost of installation and the annual operational cost found from several online news articles (www.mariettatimes.com, April 26, 2013), (thegazette.com Jun 20, 2013), (billingsgazette.com Jun 20, 2013).

It is noted that the costs listed for Site 1 within the "Newly Proposed Data Gathering Method" column assume that the overall Data Products as discussed in this research have been assembled. It is assumed that the user would then simply pull the relevant data from the Data Products for Site 1.

Some countries may have such expertise and local consulting firms would be able to provide the data. However, it is anticipated that in many developing nations, an outside consulting firm would need to be brought into the country in order to provide such services.

As seen in the above table, there is considerable savings in monetary terms comparing traditional data gathering methods to the newly proposed data gathering methods with this research. A cost saving of roughly $2.7 million U.S. Dollars could be realized for the screening level evaluation of a single site. Considering the cost to assemble the data required for Sites 1 through 10, it becomes very apparent that it would be cost prohibitive to conduct the type of large-scale screening study that the Data Products, Tools, and Models created with this research offer to a developing nation.

Also it is noted that there is significant savings in time and manpower not specifically noted, but eluded to in the above table. Costs listed for Site 1 within the "Newly Proposed Data Gathering Method" column show time estimates for a user and assume that the Data Products have been assembled for an area according to the methodology proposed in this research. As shown, a single water ministry staff person, consultant, etc. would spend roughly 4 hours evaluating a site. Using traditional methods, teams of consultants, field crews, pilots, etc. would need to be assembled. The time frame to obtain results for an evaluation site would be in terms of months and years.

### 6.4 Comparison of Results

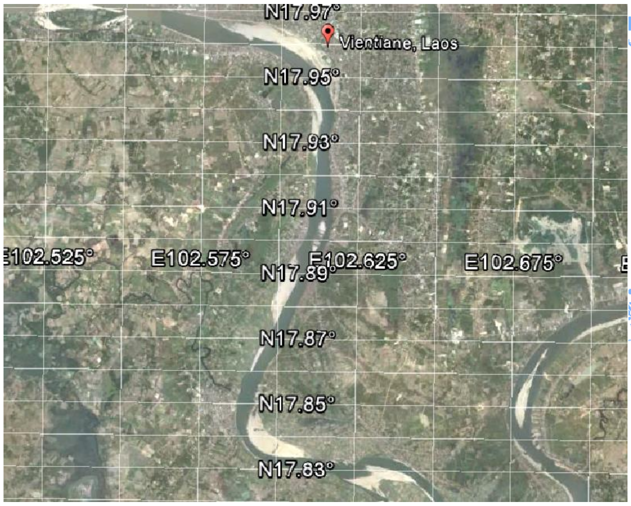
This chapter compares the results of several of the Tools and Models created in this research to other sources. Due to the originality of several of the Tools and Models, they cannot be compared to another source. The following table summarizes the comparisons that were completed for the ten Tools and Models created in this research.

| Tool/Model | Comparison | Difference |
|---|---|---|
| 1-Perennial Stream Mapping Data Processing Tool | Graphical Comparison | Graphical Results Show Minimal Differences |
| 2-Farmland Mapping Data Processing Tool | No Comparison | N/A |
| 3-Reservoir Storage Tool | Engineering project | 1% |
| 4-Annual Yield Model | Reconnaissance Report (United Nations 1969) | 33% |
| 5-Flood Discharge Model | Gage Data | 1% to 24% |
| | | |
| 6-Population Displacement Tool | No Comparison | N/A |
| 7-Farmland Loss Tool | No Comparison | N/A |
| 8-Ave.Annual Flow Reduction Model | No Comparison | N/A |
| | | |
| 9-Irrigable Area Tool | No Comparison | N/A |
| 10-Serviceable Population Tool | No Comparison | N/A |
| 11-Hydropower Model | Reconnaissance Report (United Nations 1969) | 21% |
| | | |
| 12-Flood Attenuation Model | Engineering Project | 11% |
| 13-Water Surface Elevation Model / Population Inundation Tool | Computer Program HEC-RAS (WSEL Model) | 0.1 to 1.9 foot difference (WSEL Model) |

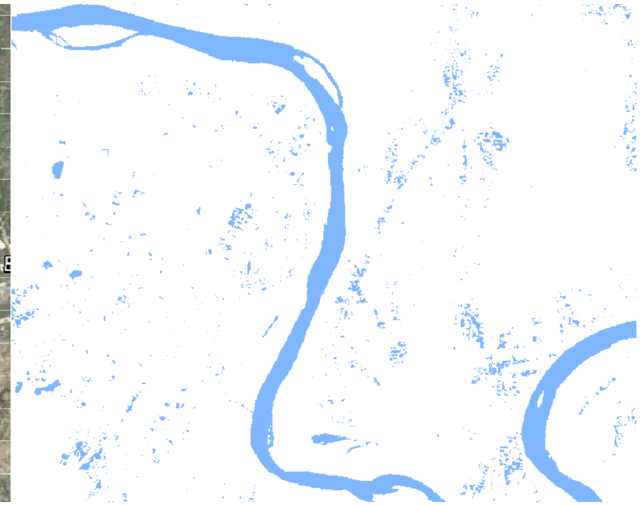
**TABLE 6.4.1** – Comparison of Results Summary Table

The results of utilization of the Perennial Stream Mapping Data Processing Tool were compared to two reaches of the Mekong River in the Lower Mekong Basin. The first reach compared runs through Vientiane, Laos. Results of this comparison are shown in Figure 6.4.2, below. Frame 3 shows the overlay of a georeferenced Google Earth image (discussed in Chapter 3) with resulting water mapping created by the MMI Data Processing Tool. As can be seen in this figure, the water mapping overlays quite well with the georeferenced satellite image. Very minimal differences are observed with the horizontal alignment of the river meander. Sand bars at river bends also align compare well.

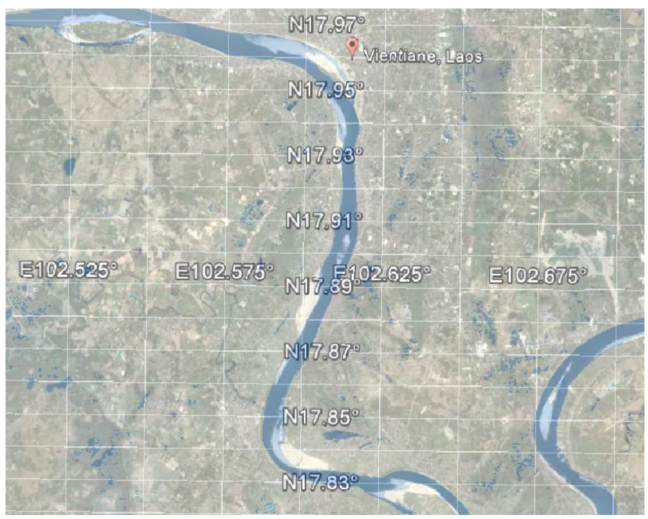
The second reach compared runs through Phnom Penh, Cambodia. Results of this comparison are shown in Figure 6.4.3. Again, Frame 3 of this figure displays the overlay of a georeferenced Google Earth image with the resulting water mapping from the MMI Data Processing Tool. As with the first comparison, the water mapping from the MMI Data Processing Tool overlays well with the georeferenced satellite image.




FRAME 1



FRAME 2

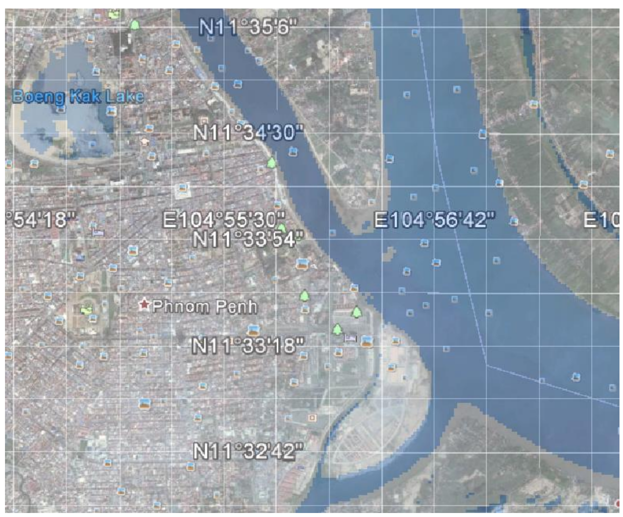



FRAME 3

**FIGURE 6.4.2** – Comparison of results for Vientiane, Laos. Frame 1 displays georeferenced Google Earth image. Frame 2 displays the Data Product resulting from the utilization of the “MMI Data Processing Tool”. Frame 3 displays the overlay of Frames 1 and 2, comparing how well the water mapping created lines up with the georeferenced satellite image.


**FRAME 1**

**FRAME 2**




**FRAME 3**

**FIGURE 6.4.3** – Comparison of results for Phnom Penh, Cambodia. Frame 1 displays georeferenced Google Earth image. Frame 2 displays the Data Product resulting from the utilization of the "MMI Data Processing Tool". Frame 3 displays the overlay of Frames 1 and 2, comparing how well the water mapping created lines up with the georeferenced satellite image.

The Stage-Storage Tool was compared to an engineering project done by the author in professional practice. A stormwater detention reservoir located in Loveland, Colorado that was designed by the author and analyzed with traditional topographic contour methods, was compared with the new Stage-Storage Tool created with this research. The following tables summarize the results of this comparison.

| STAGE | Storage (Using Contour Method) | Storage (Using New Stage-Storage Tool) |
|---|---|---|
| 0 | 0 | 0 |
| 4 | 0.386780794 | 0.224690083 |
| 8 | 2.073885712 | 1.94760101 |
| 12 | 5.609983664 | 5.828455005 |
| 16 | 11.93351924 | 12.35967631 |
| 20 | 21.86149055 | 22.41190312 |
| 24 | 36.09828188 | 36.94530533 |
| 28 | 56.46433492 | 57.46068641 |
| 32 | 85.26594876 | 85.27519513 |
| 36 | 119.6727828 | 120.8293159 |
| 38 | 142.5322678 | 141.5360996 |

| | Total Capacity Analyzed with Contour Method | Total Capacity Analyzed with New Stage-Storage Tool | % Difference |
|---|---|---|---|
| Detention Reservoir Capacity | 142.5 acre-feet | 141.5 acre -feet | 1% |

**TABLE 6.4.4** – Comparison of results for detention reservoir at Centerra, Loveland, Colorado.

The Annual Yield Model was compared to a potential reservoir site evaluated in the report “Survey of Four Tributaries in the Lower Mekong Basin” (United Nations, 1969). Annual yield at the potential “Banan” reservoir site (located in eastern Cambodia) estimated in this report was compared with the Annual Yield Model created with this research. The following table summarizes the results of this comparison.

| | Estimate from UN, 1969 | Estimate from New Annual Yield Model | % Difference |
|---|---|---|---|
| Contributory Watershed Area | 2840 km^2 | 2910 km^2 | 2% |
| Mean Annual Inflow | 2.28 km^3 | 3.36 km^3 | 33% |

**TABLE 6.4.5** – Comparison of annual yield estimates for potential “Banan” reservoir site located in eastern Cambodia.

The Hydropower Model was compared to a potential reservoir site evaluated in the report “Survey of Four Tributaries in the Lower Mekong Basin” (United Nations, 1969). Estimated Hydropower at the potential “Nam Ngum” reservoir site (located in northern Laos) evaluated this report was compared with the Hydropower Model created with this research. The following table summarizes the results of this comparison.

| | Estimate from UN, 1969 | Estimate from New Hydropower Model | % Difference |
|---|---|---|---|
| Contributory Watershed Area | 8460 km^2 | 8316 km^2 | 2% |
| Hydropower Potential | 20,000 KW | 25,343 KW | 21% |

**TABLE 6.4.6** – Comparison of results for "Nam Ngum" reservoir site located in northern Laos.

The Flood Discharge Model was compared at six major gage stations located throughout Laos, Thailand, and Cambodia. Gage data was obtained from the Mekong River Commission (2007), and Ewart & Brutsaert (1972) The following table summarizes the results of this comparison.

| Gage Location | Gage Listed Watershed Area (km^2) | Watershed Area from Data Product (km^2) | % Difference |
|---|---|---|---|
| Vientiane, Laos* | 299000 | 288357 | 3.6% |
| Thakhek, Laos** | 371000 | 359713 | 3.0% |
| Mukdahan, Thailand** | 391000 | 368646 | 5.7% |
| Pakse, Laos** | 545000 | 527280 | 3.3% |
| Stung-Treng, Cambodia** | 635000 | 538300 | 15.2% |
| Kratie, Cambodia* | 646000 | 610346 | 5.5% |

*Data from Mekong River Commission, 2007
**Data from Ewart and Brutsaert, 1972

**TABLE 6.4.7** – Comparison of results of resulting watershed areas from the Data Product "High Resolution Flow Accumululation Grid for Lower Mekong Basin".

| Gage Location | Mean Annual Flood Discharge from MRC, 2007; Ewart & Brutasaert, 1972 (m^3/s) | Mean Annual Flood Discharge from New Flood Discharage Model (m^3/s) | % Difference |
|---|---|---|---|
| Vientiane, Laos* | 16700 | 20772 | 24.4% |
| Thakhek, Laos** | 25260 | 25161 | 0.4% |
| Mukdahan, Thailand** | 27530 | 25702 | 6.6% |
| Pakse, Laos** | 36070 | 35051 | 2.8% |
| Stung-Treng, Cambodia** | 46610 | 35685 | 23.4% |
| Kratie, Cambodia* | 51500 | 39791 | 22.7% |

*Data from Mekong River Commission, 2007
**Data from Ewart and Brutsaert, 1972

**TABLE 6.4.8** – Comparison of mean annual estimates for gage sites in Laos, Thailand, and Cambodia.

The Flood Attenuation Model was compared to flood reservoir evaluated by the author for a project that he had done as a professional consultant, the “Law Basin” located just north of Windsor, Colorado. The John Law Reservoir was, at the time of the authors professional work on this project, recognized by FEMA as having a flood control component to the reservoir with a flood storage volume of 125 acre-feet. With this flood attenuation volume, the flood hydrology computer model EPA-SWMM was utilized to compute the attenuated peak flood discharge (100-year recurrence interval). This reservoir was used in the research as a means of comparison for the newly created Flood Attenuation Model. The following table summarizes the results of this comparison.

| | Data from Law Basin Study | Data from New Flood Attenution Model | % Difference |
|---|---|---|---|
| Peak Inflow | 2136 cfs | 2136 cfs | N/A |
| Attenuation Volume | 130 acre-feet | 130 acre-feet | N/A |
| Attenuated Flood Outflow | 1073 cfs | 953 cfs | 11% |

**TABLE 6.4.9** – Comparison of results for John Law Reservoir site located in northern Colorado.

The Water Surface Elevation Model was compared to results from the river hydraulics computer model HEC-RAS for two of the river reaches investigated in this research and discussed in Chapter 3. A reach of the Cucharas River near La Veta, Colorado (discussed in Chapter 3) was the subject of comparison for the newly created Water Surface Elevation Model which is shown in Table 6.4.10, below. Additionally a reach of the Cache La Poudre River near Greeley, Colorado (discussed in Chapter 3) was utilized for comparison, which is shown in Table 6.4.11, below.

| | Water Surface Elevation from HEC-RAS | Water Surface Elevation New WSEL Model | Difference (Feet) |
|---|---|---|---|
| Cross-Section 1 | 7082.3 | 7082.6 | 0.30 |
| Cross-Section 2 | 7111.43 | 7109.5 | -1.93 |
| Cross-Section 3 | 7120.5 | 7120.4 | -0.10 |

**TABLE 6.4.10** – Comparison of results for reach of Cucharas River located near La Veta, Colorado.

| | Water Surface Elevation from HEC-RAS | Water Surface Elevation New WSEL Model | Difference (Feet) |
|---|---|---|---|
| Cross-Section 1 | 4714.3 | 4714.3 | 0.00 |
| Cross-Section 2 | 4723.1 | 4722.7 | -0.40 |
| Cross-Section 3 | 4729.9 | 4728.9 | -1.00 |

**TABLE 6.4.11** – Comparison of results for reach of Cache La Poudre River located near Greeley, Colorado.

It is noted that the three tools that were not compared: Irrigable Area Tool, Serviceable Population Tool, and Population Inundation Tool are unique and no means to provide comparison was found. The reliability of these Tools and Models is based on the data sources themselves. Discussion of the reliability of the data sources is provided in Chapter 3 of this research.

## 6.5 Conclusions

The focus of this research has been on the newly available geospatial data, and how to use the data to generate information not previously available for the purpose of reservoir planning and decision support in developing nations. This study is foundational for further work that could be done to formulate a Decision Support System which could include a Multi-Criteria Decision Analysis tool. This study sets the stage and provides the basis for such a tool in that it lays out methodologies for the creation of a database, and the tools and models that would be utilized for the extraction of pertinent information from the database.

The case studies conducted in Chapter 6 demonstrate the use of the data products, tools, and models that have been created in this research. It is seen in the case studies that the data products provide a complete database. The tools and models provide efficient means to extract the information necessary from this database, allowing a user to address fundamental reservoir planning questions.

The cost comparisons provided in this chapter show significant savings in terms of time, manpower, and money that can be realized with the data products, tools, and models created in this research. Additionally, the reliability of the information generated has been compared to traditional methods and studies in this chapter. These comparisons show good reliability of the information generated for regional scale decision making purposes. This study has shown results that are within a reasonable tolerance for regional scale planning.

# 7.0 – A METHODOLOGY FOR GIS-BASED EVALUATION OF IMPACTS VERSUS BENEFITS

## 7.1 Introduction

The tools and models discussed previously are now combined in this chapter with a methodology for the consideration of potential adverse impacts alongside the potential benefits of proposed reservoir alternatives. GIS is proposed as the platform to facilitate a visual decision support method and with this proposed methodology, stakeholders would be able to visualize the impacts versus the benefits within a spatial framework.

One of the themes of this research discussed in the first chapter was the creation of more transparency in the decision making process for reservoir planning in developing nations. This chapter outlines a methodology which is intended to create transparency, and to lay out a framework/architecture for a visual decision support system. A visual decision support system would go beyond the traditional decision matrix composed of rows and columns of numbers as the final output. It is the aspiration of the research to create a visual representation of the decision matrix that a larger audience can relate to.

The proposed methodology includes communication of positive and negative aspects of proposed alternatives as well as showing the prioritization that has been given to the various evaluation criteria. Showing the prioritization of evaluation criteria could enable the evaluation of a pre-disposed leaning towards the benefits or the costs/impacts. This could both enhance the decision makers' understanding of the potential benefits and impacts, as well as facilitate public forums, presentations, information campaigns, etc.

The proposed methodology facilitates input from experts with multi-disciplinary backgrounds (biologists, sociologist, economists, etc.) who would be included in the decision making process. This research does not attempt to fill in all the information that truly could only result from consultation such a multi-disciplinary panel of experts. Many impacts as well as benefits are very difficult to assess and the data may be lacking. This section of the research proposes an architecture for a communication tool that could facilitate the communication of multi-disciplinary points of view.

It is well recognized that the planning process for a new reservoir must take into consideration potential adverse impacts alongside the perceived benefits of a planned reservoir. History gives us many examples of reservoirs which have been planned with only the benefits being considered, resulting in devastating human and environmental costs. Cross-border impacts also have not in many cases been considered in the planning process, and examples are here as well of significant turmoil ensuing, both environmental and social (Baird and Wyatt, 2007),

To use the Lower Mekong Basin as a historic example of the traditional approach to reservoir planning, in the early 1960's this basin was a focal point for many U.S. studies as we had development interests in the region. Schaaf and Fifield (1963) in their book, "The Lower Mekong: Challenge to cooperation in southeast Asia" state:

*"The most striking aspect of the Lower Mekong, however, is not the size and length of the river, nor its potentialities, but the extent to which these resources have been left untapped."*

Schaaf and Fifield discuss the studies that had been undertaken at that time by the U.S. Bureau of Reclamation. In particular, reference to a U.S.B.R. study that was completed of the Lower Mekong in 1956 is noted to have considered multiple factors related to benefits of tapping into the resources that the river offered. The study gathered a large amount of data which was entirely focused on means to harvest potential benefits from the Lower Mekong. No efforts were undertaken, to assess potential environmental and cultural adverse impacts.

This could be considered the "traditional" approach to reservoir planning, with assessment of first the physical feasibility, then evaluating benefits of potential reservoir sites, and finally selecting sites based on this information alone. History has taught that this decision paradigm is often unfair for the people groups involved who often suffer displacement and loss of livelihood. This approach is also detrimental to the environment upon which people groups in developing nations often highly depend upon. Grumbine, et.al. (2012) discusses the Xiaburi Dam, the first of the proposed projects for the Lower Mekong River mainstem. This is to be the first of a series of dams along the Lower Mekong River mainstem that will, as Grumbine notes, "exacerbate changes to natural flow patterns that already occur as a result of dam building in China." Grumbine goes on to warn of substantial disruption to fisheries, as well as negative implications for millions of people who depend on the Mekong River for their livelihoods. Additionally the dam is anticipated to alter the migratory patterns of several fish species such as the Julians Barb, important to the surrounding populations for both food supply and livelihood.

The tools and models that were discussed in the previous chapter have been created to address some of the key reservoir planning questions relating to both potential benefits that could be realized from the development of a reservoir, as well as the potential adverse impacts resulting from a planned reservoir. The tools and models created in this research can be summarized in the following four categories.

**Tools/models that provide general site assessment:**

- Available storage tool (Stage-Storage tool)
- Annual yield model
- Flood discharge model

**Tools/models that provide adverse impact assessment:**

- Population displacement tool
- Farmland loss tool (land inundated by reservoir)
- Average annual flow reduction model

**Tools/models that provide benefit assessment:**

- Irrigable area tool
- Serviceable population tool
- Hydropower yield model

**Flood Evaluation Tools/Models**

- Flood attenuation model
- Population Inundation tool

## 7.2 Methodology Concept

Figure 7.1, below illustrates the proposed concept of a visual representation of potential benefits versus potential adverse impacts. The intent of such a visual tool is to assist in bridging the communication gap between decision makers, stakeholders and other parties involved in such projects in developing nations. GIS has been utilized as a platform for creating a visual representation of the multi-criteria decision.

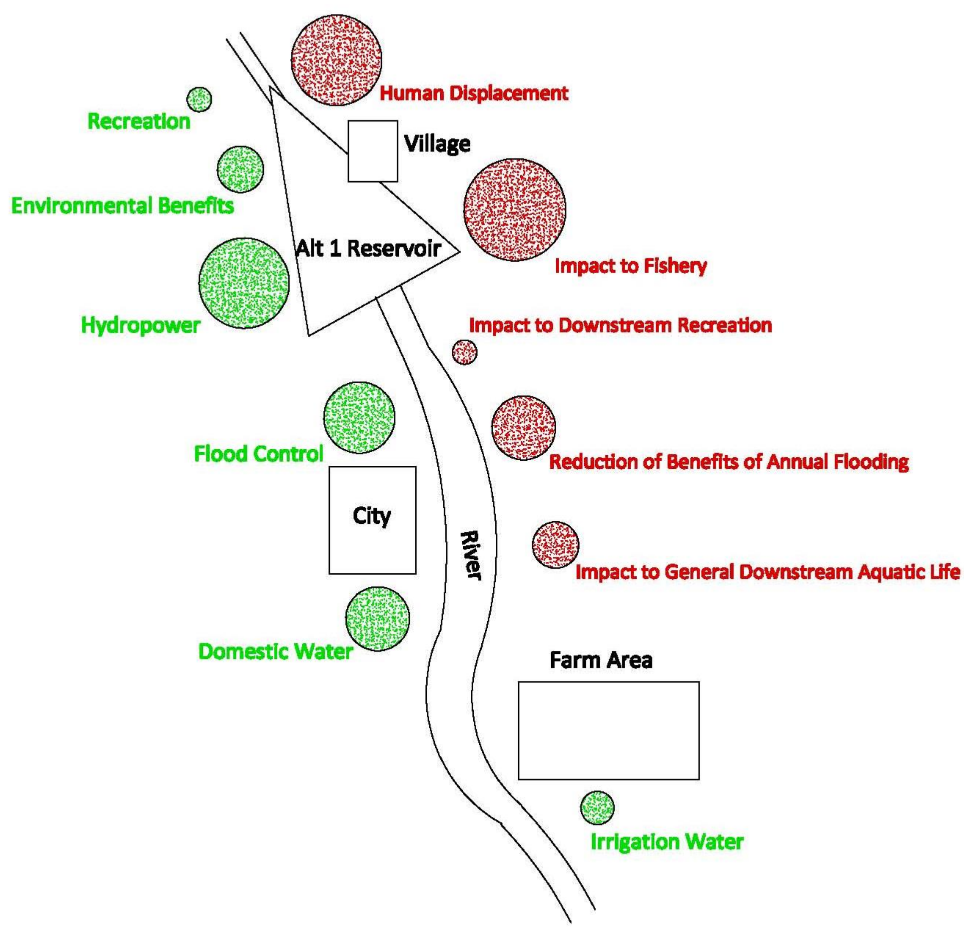


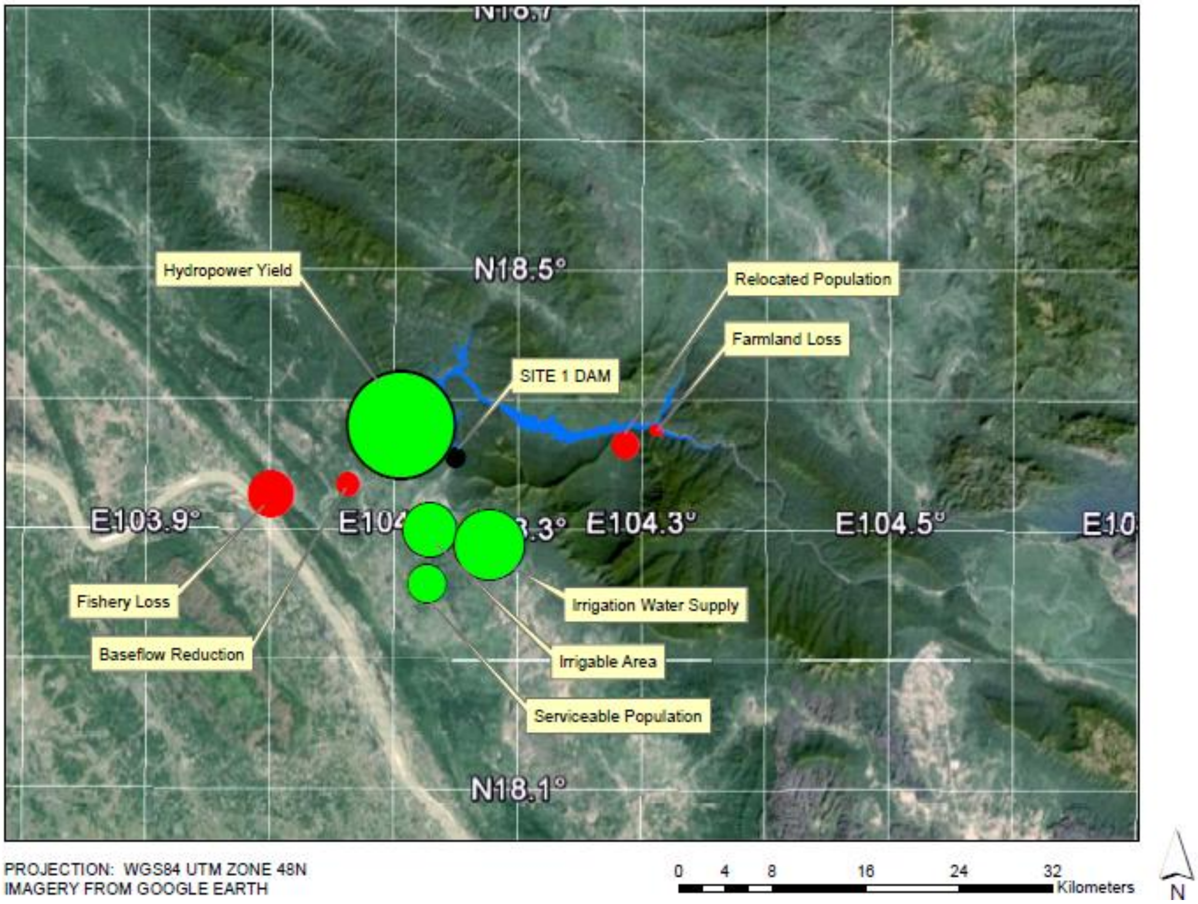

**FIGURE 7.2.1** – Concept diagram illustrating visual representation of benefits versus adverse impacts

The concept is to utilize the spatially oriented nature of GIS to create a visual platform for the representation of the decision matrix. This would facilitate the communication of the factors involved in the reservoir planning process, both potential benefits and potential adverse impacts, to a much broader audience. It would allow the visualization of, in essence, the decision matrix. Rather than a decision matrix formatted as rows and columns of numbers, the decision matrix could take on a more tangible sense. This could both enhance the decision makers' understanding and appreciation of the positives and negatives of reservoir alternatives, as well as facilitate public forums, presentations, and information campaigns.

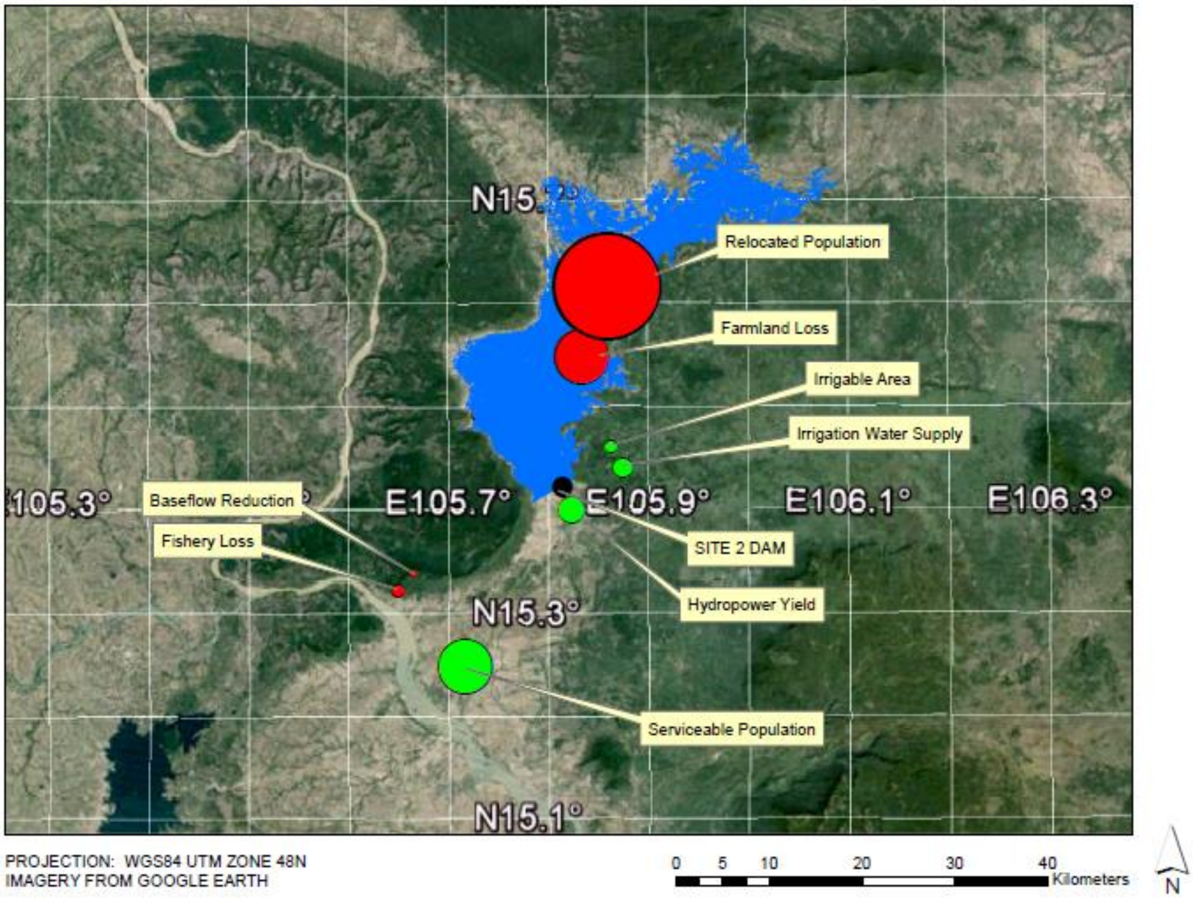
## 7.3 Visual Representation of the Decision Matrix

The three sites evaluated in Chapter 6 have been utilized to demonstrate the propose methodology. As shown in the following GIS-based maps, decision makers and stakeholders can quickly obtain a visual sense of impacts versus benefits for Site 1, 2, and 3; hence, a visual representation of the decision matrix is achieved. Red circles represent potential adverse impacts, while green circles represent potential benefits for each reservoir site. The size of each circle is scaled according to the GIS Visual Scaling worksheet (Worksheet 7, discussed in the following section). Thus, the size of each circle is proportionate with respect to the other decision evaluation criteria, giving a visually accurate sense of the potential impact or benefit.

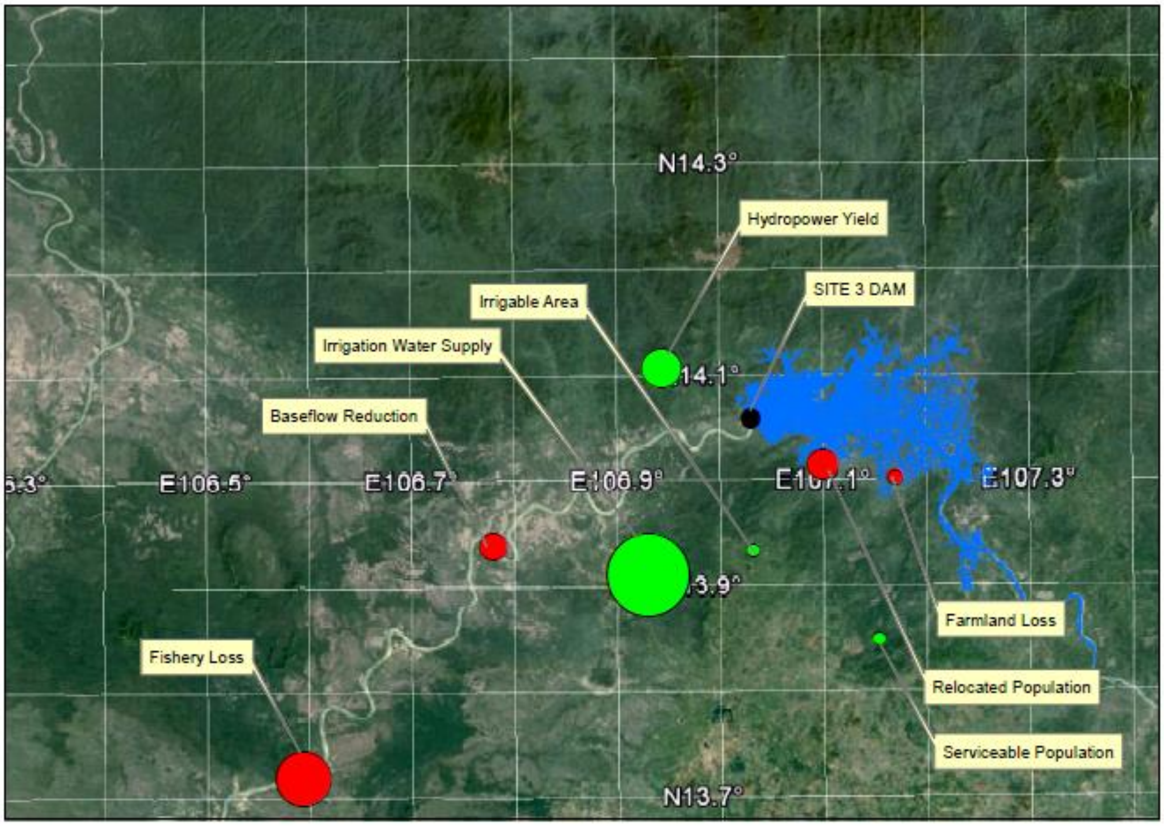
## SITE 1


Hydropower Yield
N18.5°
Relocated Population
Farmland Loss
SITE 1 DAM
E103.9°
E104.3°
E104.5°
Fishery Loss
Baseflow Reduction
Irrigation Water Supply
Irrigable Area
Serviceable Population
N18.1°
PROJECTION: WGS84 UTM ZONE 48N
IMAGERY FROM GOOGLE EARTH
0 4 8 16 24 32
Kilometers
N

**SITE 2**


N15.5°
Relocated Population
Farmland Loss
Irrigable Area
Irrigation Water Supply
E105.7°
E105.9°
E106.1°
E106.3°
Baseflow Reduction
Fishery Loss
SITE 2 DAM
Hydropower Yield
N15.3°
Serviceable Population
N15.1°
PROJECTION: WGS84 UTM ZONE 48N
IMAGERY FROM GOOGLE EARTH
0 5 10 20 30 40
Kilometers
N

**SITE 3**




PROJECTION: WGS84 UTM ZONE 48N
IMAGERY FROM GOOGLE EARTH

0 5 10 20 30 40 Kilometers

N

The representative circles are scaled, and are also placed in vicinity to the potential benefit or impact area, to give the user a spatially based understanding of the consequences of a proposed alternative.  Google Earth imagery has been placed in the background for spatial reference, and has been georeferenced according to the methodology outlined in Chapter 4.

### 7.4 Visual Representation of Benefit to Impact Ratios

Sites 1, 2, and 3 are shown in the following GIS –Based Overview map.  Based on the information obtained from the Tools and Models for these sites as discussed in Chapter 6, the sites are now visually ranked on a scale ranging from -3 to +3.  In the example, ranking of three alternative sites was as follows:  Site 1->Site 3->Site 2.  This ranking is based on Site 1 having the highest positive Benefit:Impact Ratio (+0.95), and Site 2 having the lowest Benefit:Impact Ratio (-1.55).  Shades of green and red represent the degree of positive or negative Benefit:Impact Ratio, according to the scale chart shown below.

| **GIS Color Coding:** | | | | | | |
|---|---|---|---|---|---|---|
| ADVERSE IMPACTS OUTWEIGH BENEFITS | | | | BENEFITS OUTWEIGH ADVERSE IMPACTS | | |
| Most | Somewhat More | More | Neutral | More | Somewhat More | Most |
| -3 | -2 | -1 | 0 | 1 | 2 | 3 |
| | | | | | | |

**OVERVIEW MAP**
**BENEFIT:IMPACT RATIO**


PROJECTION: WGS84 UTM ZONE 48N
IMAGERY FROM GOOGLE EARTH

### 7.5 Proposed Methodology

The proposed methodology is broken into eight steps, which, in this research have been formatted in a Microsoft Excel workbook. The Excel spreadsheet has been broken into 8 worksheets, with each of the worksheets representing one of the steps in the methodology. The worksheets have been placed in the sequential order of the methodology, and are described below. A workflow diagram is provided first in order to summarize the eight step methodology.

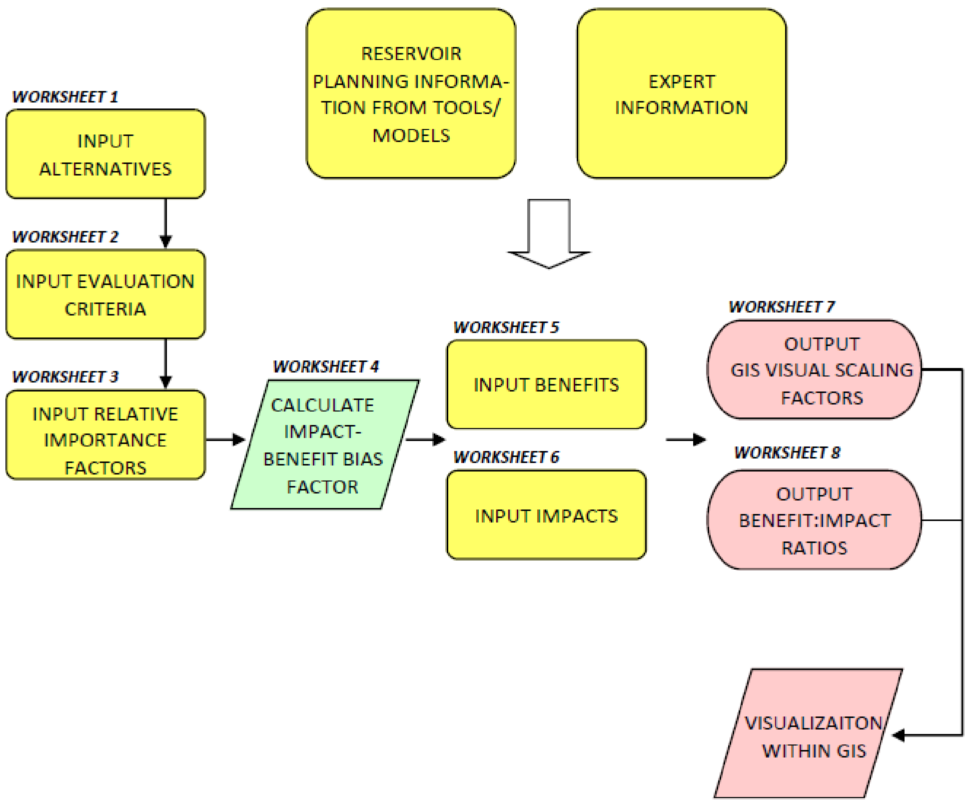



**FIGURE 7.5.1** - Workflow diagram illustrating the proposed methodology for a visual representation of potential benefits versus potential adverse impacts.

**Worksheet 1** – The user inputs reservoir sites being considered along with location and dam height. In this example, three potential reservoir sites are evaluated. The user has room to add potential sites, and can input as many alternative sites as desired.

| | A | B |
|---|---|---|
| 1 | **Sheet 1 (User Input) - Definition of Alternatives** | |
| 2 | | |
| 3 | **ALTERNATIVE** | **LOCATION, DAM HEIGHT** |
| 4 | Site 1 | Latitude: 18d 21.325m, Longitude: 104d 8.881m; 100 m dam height |
| 5 | Site 2 | Latitude: 15d 25.431m; Longitude: 105d 48.698m; 20 m dam height |
| 6 | Site 3 | Latitude: 14d 3.586m; Longitude: 107d 1.812m; 20 m dam height |
| 7 | | |
| 8 | | |
| 9 | | |
| 10 | | |

**Worksheet 2** – The user inputs evaluation criteria. In this example, four potential benefit and four potential adverse impact evaluation criteria for the reservoir sites are evaluated. The user has room to input additional evaluation criteria.

| | A | B | C | D |
|---|---|---|---|---|
| 1 | **Sheet 2 (User Input) - Evaluation Criteria** | | | |
| 2 | | | | |
| 3 | **Potential Benefits** | **Units** | **Potential Adverse Impacts** | **Units** |
| 4 | **Irrigation Water Supply** Irrigation water that could potentially be yielded at a site. | Km^3 | **Downstream Reduction in Baseflow** Reduction in downstream baseflow due to extraction of irrigation water. | Km^3/sec |
| 5 | **Water Supply Serviceable Population** Population that could be serviced via gravity system water supply. | Number of Persons | **Relocated Population** Population relocated due to area flooding by creation of reservoir. | Number of Persons |
| 6 | **Irrigable Area** Irrigable area that could be serviced via gravity system. | Km^2 | **Loss of Local Agricultural Area** Agricultural area lost due to area flooding by creation of reservoir. | Km^2 |
| 7 | **Hydropower Yield** Potential hydropower generation at a site. | MW | **Fishery Impacts** Impacts to fishery both upstream and downstream of reservoir. | Tons |

**Worksheet 3** – The user inputs relative importance factors for each evaluation criteria. In this example, what is considered the highest priority potential benefit is hydropower yield. The potential adverse impact that is considered the highest priority to consider is relocated population.

| | A | B | C | D |
|---|---|---|---|---|
| 1 | **Sheet 3 (User Input) - Relative Importance Factors** | | | |
| 2 | **Potential Benefits** | **Relative Importance Factor** | **Potential Adverse Impacts** | **Relative Importance Factor** |
| 3 | Irrigation Water Supply | 3 | Reduction in Baseflow | 1 |
| 4 | Water Supply Serviceable Population | 2 | Relocated Population | 4 |
| 5 | Irrigable Area | 2 | Loss of Local Agriculture Area | 2 |
| 6 | Hydropower Yield | 4 | Fishery Impacts | 2 |
| 7 | | | | |

**Worksheet 4** – The Benefit:Impact Bias Factor is calculated. This can be a useful indicator, giving the user an indication of whether there is a predetermination of bias towards the costs or the benefits. A positive Benefit:Impact Bias Factor indicates a predetermination of bias towards benefits. A negative Benefit:Impact Bias Factor indicates a predetermination of bias towards costs. In this example the Benefit:Impact Bias Factor is a positive value of 0.22, which indicates a slight bias towards the potential benefits.

| | A | B | C | D |
|---|---|---|---|---|
| 1 | **Sheet 4 (Calculations) - Benefit : Impact Bias Factor** | | | |
| 2 | **Potential Benefits** | **Relative Importance Factor** | **Potential Adverse Impacts** | **Relative Importance Factor** |
| 3 | Irrigation Water Supply | 3 | Reduction in Baseflow | 1 |
| 4 | Water Supply Serviceable Population | 2 | Relocated Population | 4 |
| 5 | Irrigable Area | 2 | Loss of Local Agriculture Area | 2 |
| 6 | Hydropower Yield | 4 | Fishery Impacts | 2 |
| 7 | | | | |
| 8 | | | | |
| 9 | **sum:** | **11** | **sum:** | **9** |
| 10 | | | **Benefit to Impact Bias Factor:** | 0.22 |

**Worksheet 5** – The user inputs benefit values. Values are based on reservoir planning information from tools and models. Expert information related to economic considerations can also be input in this worksheet, in order to add a financial dimension to the decision making process. Scoring of the alternative sites are based on highest and lowest values for each evaluation criteria, and interpolation of intermediate values.

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | **Sheet 5 (User Input) - Benefit Value Input** | | | | | |
| 2 | | | | | | |
| 3 | **Benefits:** | | **Units** | **Site 1** | **Site 2** | **Site 3** |
| 4 | | **Irrigation Water Supply** | Km^3 | 6.55 | 2.53 | 7.36 |
| 5 | | Expert Input - Monetary Benefit (Annual) | | $130,910 | $50,538 | $147,147 |
| 6 | | | max | 7.36 | | |
| 7 | | | min | 2.53 | | |
| 8 | | | *1/m* | 1.61 | | |
| 9 | | | | | | |
| 10 | | | **score (1 to 4 scale):** | **3.50** | **1.00** | **4.00** |
| 11 | | | | | | |
| 12 | | | | | | |
| 13 | | | **Units** | **Site 1** | **Site 2** | **Site 3** |
| 14 | | **Water Supply Serviceable Population** | Number of Persons | 49,125 | 66,919 | 21,017 |
| 15 | | Expert Input - Monetary Benefit (Annual) | | $98,250 | $133,837 | $42,035 |
| 16 | | | max | 66918.61 | | |
| 17 | | | min | 21017.32 | | |
| 18 | | | *1/m* | 15300.43 | | |
| 19 | | | | | | |
| 20 | | | **score (1 to 4 scale):** | **2.84** | **4.00** | **1.00** |
| 21 | | | | | | |
| 22 | | | | | | |
| 23 | | | **Units** | **Site 1** | **Site 2** | **Site 3** |
| 24 | | **Irrigable Area** | Km^2 | 1803.62 | 16.30 | 4.43 |
| 25 | | Expert Input - Monetary Benefit (Annual) | | $360,725 | $3,259 | $886 |
| 26 | | | max | 1803.62 | | |
| 27 | | | min | 4.43 | | |
| 28 | | | *1/m* | 599.73 | | |
| 29 | | | | | | |
| 30 | | | **score (1 to 4 scale):** | **4.00** | **1.02** | **1.00** |
| 31 | | | | | | |
| 32 | | | | | | |
| 33 | | | **Units** | **Site 1** | **Site 2** | **Site 3** |
| 34 | | **Hydropower Yield** | MW | 390.68 | 30.16 | 87.83 |
| 35 | | Expert Input - Monetary Benefit (Annual) | | $781,357 | $60,329 | $175,654 |
| 36 | | | max | 390.68 | | |
| 37 | | | min | 30.16 | | |
| 38 | | | *1/m* | 120.17 | | |
| 39 | | | | | | |
| 40 | | | **score (1 to 4 scale):** | **4.00** | **1.00** | **1.48** |

**Worksheet 6** – User inputs benefit values. Values are based on reservoir planning information from tools and models. Expert information related to economic considerations can also be input in this worksheet, in order to add a financial dimension to the decision making process. Scoring of the alternative sites are based on highest and lowest values for each evaluation criteria, and interpolation of intermediate values.

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | **Sheet 6 (User Input) - Adverse Impact Value Input** | | | | | |
| 2 | **Adverse** | | | | | |
| 3 | **Impacts:** | | **Units** | **Site 1** | **Site 2** | **Site 3** |
| 4 | | **Reduction in Baseflow** | Km^3/sec | 230.47 | 88.97 | 259.05 |
| 5 | | Expert Input - Monetary Loss (Annual) | | $921,864 | $355,887 | $1,036,202 |
| 6 | | | max | 259.05 | | |
| 7 | | | min | 88.97 | | |
| 8 | | | *1/m* | 56.69 | | |
| 9 | | | | | | |
| 10 | | | **score (1 to 4 scale):** | **3.50** | **1.00** | **4.00** |
| 11 | | | | | | |
| 12 | | | | | | |
| 13 | | | **Units** | **Site 1** | **Site 2** | **Site 3** |
| 14 | | **Relocated Population** | Number of Persons | 7 | 57,628 | 2,292 |
| 15 | | Expert Input - Monetary Loss (Annual) | | $2,900 | $23,051,200 | $916,873 |
| 16 | | | max | 57628.00 | | |
| 17 | | | min | 7.25 | | |
| 18 | | | *1/m* | 19206.92 | | |
| 19 | | | | | | |
| 20 | | | **score (1 to 4 scale):** | **1.00** | **4.00** | **1.12** |
| 21 | | | | | | |
| 22 | | | | | | |
| 23 | | | **Units** | **Site 1** | **Site 2** | **Site 3** |
| 24 | | **Loss of Local Agriculture Area** | Km^2 | 0.14 | 233.32 | 8.04 |
| 25 | | Expert Input - Monetary Loss (Annual) | | $5,671 | $9,332,889 | $321,605 |
| 26 | | | max | 233.32 | | |
| 27 | | | min | 0.14 | | |
| 28 | | | *1/m* | 77.73 | | |
| 29 | | | | | | |
| 30 | | | **score (1 to 4 scale):** | **1.00** | **4.00** | **1.10** |
| 31 | | | | | | |
| 32 | | | | | | |
| 33 | | | **Units** | **Site 1** | **Site 2** | **Site 3** |
| 34 | | **Fishery Impacts** | Tons | 13828 | 5338 | 15543 |
| 35 | | Expert Input - Monetary Loss (Annual) | | $5,531,186 | $2,135,324 | $6,217,209 |
| 36 | | | max | 15543.02 | | |
| 37 | | | min | 5338.31 | | |
| 38 | | | *1/m* | 3401.57 | | |
| 39 | | | | | | |
| 40 | | | **score (1 to 4 scale):** | **3.50** | **1.00** | **4.00** |

**Worksheet 7** – GIS visual scaling factors are calculated. These factors are used to create circles of appropriate diameter in GIS. Weighted scores are taken and multiplied by a factor which allows better visibility of each benefit and cost for a given alternative.

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 1 | **Sheet 7 (Calculations)- GIS Values and Visual Scaling** | | | | | | |
| 2 | | | | **Score** | **Relative Importance** | **Weighted** | **GIS Visual** |
| 3 | **Benefits:** | **Evaluation Criteria** | | **(1 to 4 Scale)** | **Factor/Weight** | **Score** | **Scaling** |
| 4 | | **Irrigation Water Supply** | | | | | |
| 5 | | Site 1 | | 3.50 | 3 | 10.49 | 21.0 |
| 6 | | Site 2 | | 1.00 | 3 | 3.00 | 6.0 |
| 7 | | Site 3 | | 4.00 | 3 | 12.00 | 24.0 |
| 8 | | | | | | | |
| 9 | | | | | | | |
| 10 | | | | **Score** | **Relative Importance** | **Weighted** | **GIS Visual** |
| 11 | | **Evaluation Criteria** | | **(1 to 4 Scale)** | **Factor/Weight** | **Score** | **Scaling** |
| 12 | | **Water Supply Serviceable Population** | | | | | |
| 13 | | Site 1 | | 2.84 | 2 | 5.67 | 11.3 |
| 14 | | Site 2 | | 4.00 | 2 | 8.00 | 16.0 |
| 15 | | Site 3 | | 1.00 | 2 | 2.00 | 4.0 |
| 16 | | | | | | | |
| | | | | | | | |
| | | | | **Score** | **Relative Factor** | **Weighted** | **GIS Visual** |
| 19 | | **Evaluation Criteria** | | **(1 to 4 Scale)** | **Factor/Weight** | **Score** | **Scaling** |
| 20 | | **Irrigable Area** | | | | | |
| 21 | | Site 1 | | 4.00 | 2 | 8.00 | 16.0 |
| 22 | | Site 2 | | 1.02 | 2 | 2.04 | 4.1 |
| 23 | | Site 3 | | 1.00 | 2 | 2.00 | 4.0 |
| 24 | | | | | | | |
| 25 | | | | | | | |
| 26 | | | | **Score** | **Relative Factor** | **Weighted** | **GIS Visual** |
| 27 | | **Evaluation Criteria** | | **(1 to 4 Scale)** | **Factor/Weight** | **Score** | **Scaling** |
| 28 | | **Hydropower Yield** | | | | | |
| 29 | | Site 1 | | 4.00 | 4 | 16.00 | 32.0 |
| 30 | | Site 2 | | 1.00 | 4 | 4.00 | 8.0 |
| 31 | | Site 3 | | 1.48 | 4 | 5.92 | 11.8 |
| 32 | | | | | | | |
| 33 | | | | | | | |
| 34 | | | | | | | |
| 35 | | | | **Score** | **Relative Importance** | **Weighted** | **GIS Visual** |
| 36 | **Adverse Impacts:** | **Evaluation Criteria** | | **(1 to 4 Scale)** | **Factor/Weight** | **Score** | **Scaling** |
| 37 | | **Reduction in Baseflow** | | | | | |
| 38 | | Site 1 | | 3.50 | 1 | 3.50 | 7.0 |
| 39 | | Site 2 | | 1.00 | 1 | 1.00 | 2.0 |

**Worksheet 8** – Benefit:Impact Ratios are calculated. A positive Benefit:Impact Ratio indicates that benefits outweigh adverse impacts. A negative Benefit:Impact Ratio indicates that adverse impacts outweigh benefits. A Benefit:Impact Ratio of 0 indicates that benefits equal adverse impacts. A seven tone color coding is assigned in GIS in order to give the user a visual indication of Benefit:Impact ratios. Scores greater than zero to three are indicated by three shades of green. Scores less than zero to negative three are indicated by three shades of red.

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | **Sheet 8 (Calculations)- Benefit : Impact Ratio Calculation** | | | | |
| 2 | | | **Site 1** | **Site 2** | **Site 3** |
| 3 | | **Evaluation Criteria** | **Weighted Score** | **Weighted Score** | **Weighted Score** |
| 4 | **Benefits:** | Irrigation Water Supply | 10.49 | 3.00 | 12.00 |
| 5 | | Water Supply Serviceable Population | 5.67 | 8.00 | 2.00 |
| 6 | | Irrigable Area | 8.00 | 2.04 | 2.00 |
| 7 | | Hydropower Yield | 16.00 | 4.00 | 5.92 |
| 8 | | **Total benefits score:** | **24.16** | **13.04** | **16.00** |
| 9 | | | | | |
| 10 | | | | | |
| 11 | | | | | |
| 12 | | | | | |
| 13 | **Adverse Impacts:** | Reduction in Baseflow | 3.50 | 1.00 | 4.00 |
| 14 | | Relocated Population | 4.00 | 16.00 | 4.48 |
| 15 | | Loss of Local Agriculture Area | 2.00 | 8.00 | 2.20 |
| 16 | | Fishery Impacts | 6.99 | 2.00 | 8.00 |
| 17 | | **Total impacts score:** | **16.49** | **27.00** | **18.68** |
| 18 | | | | | |
| 19 | | **Benefit:Impact Ratio:** | 0.32 | -0.52 | -0.14 |
| 20 | | **Scaled Benefit:Impact Ratio:** | 0.95 | -1.55 | -0.43 |
| 21 | | | | | |

**GIS Color Coding:**

| ADVERSE IMPACTS OUTWEIGH BENEFITS | | | | BENEFITS OUTWEIGH ADVERSE IMPACTS | | |
|---|---|---|---|---|---|---|
| Most | Somewhat More | More | Neutral | More | Somewhat More | Most |
| -3 | -2 | -1 | 0 | 1 | 2 | 3 |
| | | | | | | |

The Benefit:Impact Ratio (BIR) is calculated as:

For B>I, BIR = 3 *( I / B )

For B<I, BIR = -3 * ( B / I )

For B=I, BIR = 0

Where BIR = Benefit:Impact Ratio

B = Benefit Value

I = Impact Value

In this example, Site 1 has obtained a positive Benefit:Impact ratio of 0.95, while Sites 2 and 3 have obtained negative Benefit:Impact ratios of -1.55 and -0.43, respectively. Based on this information, Site 1 would be the preferred alternative.

## 7.6 Conclusions

The proposed methodology set forth in this chapter has been intended to provide a possible means of representing the decision matrix in a visual context. Many times the decision matrix is represented as a series of columns and rows with numbers only, and the end user is given little sense of scale or spatial context. The proposed methodology would provide a sense of place as well as a sense of scale. Evaluation criteria are represented in a map environment with potential adverse impacts and benefits shown to scale. The user can quickly get a visual sense of the consequences of an alternative, and can see how the impacts may outweigh the benefits or vice-versa. The understanding gained from such a visual methodology for decision making would seem greatly enhanced over the traditional comparison of numbers alone.

# 8.0 – CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

## 8.1 Conclusions

The research that was explained in the previous chapters demonstrates a model planning process that takes advantage of the expanded availability of data to change traditional planning processes and improve transparency. The methodology involves the utilization of the newly available global geospatial data and contemporary geographic information systems to conduct reservoir planning tasks on a regional scale. The study probes the use of the new geospatial information technologies to enable decision makers to explore more alternatives, achieve better decisions, and identify the impacts of planning decisions. It addresses two facets of the data revolution as it applies to water resources planning. First, it is apparent that the vastly expanded accessibility of geospatial data via the Internet creates new possibilities to use the data for planning purposes. The study identifies the types of data and main new channels for data availability to analyze how manageable it is in contemporary geographic information systems for planning purposes. The second part of the study explores how the expanded availability of data can change traditional planning processes, and improve transparency in the planning process for reservoirs in developing nations.

To identify the types of data and channels for data availability, the study proposes methodologies for transforming the newly available global geospatial data into packaged "Data Products" for reservoir planning. The data were transformed by creating tools and models to address key reservoir planning questions, such as how much annual yield could be expected at a potential reservoir site, how much hydropower could be harvested at a potential site, what irrigable area could be serviced, etc.  These tools and models allow the decision maker to manipulate the geospatial data as well as extract geospatial data from a geographic information system.  Several of the tools and models have been created to process the data for export into a spreadsheet user interface.

The literature review focused on current GIS data sources and capabilities and the use of GIS in water resource planning.  In short, it was found that a wealth of information is now available to resource managers around the globe.  The flood of geospatial data now available via the world wide web has created a world that is much more understandable and manageable.  With such a great deal of information now available, it seems that wise resource planning and management should be much more of a possibility for those areas of the globe that have in the past had very limited data to work with.  There is a growing trend to utilize GIS in water resource applications.  The advantages of a spatially oriented water resource decision support systems model are numerous.  GIS allows for improved database organization and storage.  Water resource studies often require the gathering of multiple base maps and extracting data such as land cover, terrain slope, drainage channels and networks.  Creation of this data can be time consuming and laborious with paper maps and aerial photographs, especially when base mapping can be from different sources and at different scales.  With the use of GIS, the creation of this data is much more easily done and is much less time consuming to manage.

Many data sources were researched by the author over a period of several years in order to find those data sets and data sources of value for the purposes of this study.  It was found that there are a multitude of data with potential uses.  However most data are of a lower resolution than what would be required to fulfill the purposes of this study. MODIS data for example, provides data, at best, on a 250 meter grid. This spatial resolution is not adequate for utilization within the tools and models created in this research.

Several tools and models have been created in this study with the purpose of answering fundamental reservoir planning questions on a regional scale. These tools and models rely on terrain data, land cover data, population data, and satellite imagery. Out of the multiple data sources researched, four data sources were found to stand out as the currently best available sources. All of the data sets researched are global in nature; hence, the methodologies created in this research could be applied to any developing nation or data limited area of the globe.

The data research component of the study included a very thorough exploration of the Shuttle Radar Topography Mission (SRTM). This data set provides geospatial terrain data for the majority of the globe. The means for obtaining the data was discussed initially, and following this discussion, background for the SRTM data was expounded. Finally, comparison of the SRTM data set to several other sources of data including the National Elevation Dataset (NED), local data sets (aerial topographic data), and the ASTER data sets was provided. Some of these comparative data sets provide global coverage, and some provide coverage only for the United States. Point datasets within the Lower Mekong Basin was also compared to the SRTM dataset. The SRTM data set was an integral part of the ten tools and models that have been created in this research, as terrain data is a vital component of many of these tools and models.

Following this, the Landsat and Landscan datasets were researched. The Landsat data set provides land cover scenes for nearly the entire globe, and is available typically on a 30 meter grid. Scenes are available on a temporal resolution typically of 1 month; thus, studies such as vegetation change over time can be conducted on a month by month basis. The Landsat data is very efficiently managed and manipulated in contemporary geographic information systems (GIS), as the data is provided in a grid raster format. LandScan is a global population data set that is readily imported into a geographic information system as a grid raster. The LandScan raster is provided on a 1 kilometer grid, with each grid cell listing population within that 1 kilometer square. Both the Landscan and Landsat data sets were incorporated in the tools and models created in this research for reservoir planning and decision support in developing nations.

The data research component of the study moved into research of high resolution satellite imagery which is now available for most of the planet. Several commercial providers currently offer satellite imagery products that have up to 0.5m pixel resolution. At this level of resolution, natural and man-made features can be clearly identified. Google Earth is, in a sense, a repository of this aerial imagery. The imagery Google Earth offers is taken from commercial sources, and is free of charge. Methodologies for georeferencing and utilizing this the imagery that is freely available through Google Earth have been presented.

The application research component of the study began with explanation of the proposed data product concept with this research, which is to utilize the more advanced capabilities of ArcMap by Esri to create data products that could then be utilized in open source GIS software. Once data products have been created, the end user could be free obtain an open source GIS program of their own choice and utilize the data products within that GIS software package. Several data products have been created in this research as georeferenced TIFF Raster files, and have been created utilizing global data sets obtained freely via the world wide web. The open source computer software "Quantum GIS" was downloaded at no cost and the data products were utilized in this program in order to test their useability in an open source GIS software package.

The data products created were utilized as the base data source for a set of tools and models created in the study. Several tools and models have been created, which utilize the geospatial data provided by the data products for the purposes of generating information pertinent to reservoir planning and decision support. Further, the study has demonstrated utilization of the data to create a database for the Lower Mekong Basin. All data utilized is available over the world wide web and is global in nature. Thus, the type of database set up in this research, using the Lower Mekong Basin as a case study, could be re-created for any data limited area or developing nation in the world.

Application research moved into the creation of the aforementioned tools and models. The tools and models have been created to offer a decision maker the ability to manipulate and model the database represented by the data products created. They allow efficient means to create new information from the existing data, and provide the decision maker with the ability to conduct high level assessments on a regional scale and answer fundamental questions revolving around the reservoir planning process.

The research demonstrated the use of the data products, tools, and models created with two case studies. The first case study shows how the data products, tools, and models can be used to screen potential reservoir sites on tributary rivers in the Lower Mekong Basin. The second case study demonstrates the use of the data products, tools, and models to evaluate flood control benefits of a hypothetical reservoir placed just upstream of the City of Vientiane, located on the Lower Mekong River in northern Laos. This case study shows how maps of estimated inundation areas, and the estimated number of persons affected by flooding can be created with great efficiency using the data products, tools, and models.

What is new and innovative in this research? On a broad level, in the field of water resources planning the data sets that have been researched have not been combined and utilized as proposed in this research. One can find many applications for using say, the SRTM data set singly; however, there is no work that that combines the four data sets identified in this research to create the planning and decision support information as proposed for developing nations and data limited areas. As seen in the literature review, the focus for utilization of the available geospatial data and abilities of contemporary GIS has been, and continues to be more focused on single data sets. Research focused on assisting developing nations with the utilization of combinations of multiple data sets and in the synthesis of data sets is lacking.

This research concludes that the capabilities of contemporary GIS, and the geospatial data that are now available have considerable potential to allow an overall perspective to be visualized more clearly in developing nations and data limited areas. This is what is needed in water resource planning for such areas: the ability to provide a more inclusive planning vision, and to see beyond what is in the forefront. In resource planning it is often found that hindsight is clear. Projects often progress such that this clarity occurs mid-way through a project, since a broad perspective was not adequately considered in the planning stage. A broad level planning and decision support tool, which this research provides a basis for, is proposed as an innovative solution to this planning problem in data limited areas. In a sense, this research proposes an innovative paradigm shift in the planning and decision making process for water resources in developing nations. This research demonstrates the potential of GIS and geospatial with the two case studies conducted.

### 8.2 Recommendations for Future Research

It is expected that new data availability will assist decision makers in the planning process, but what are the broader implications? The new technologies can transform how the process of integration takes place. More alternatives can be explored to achieve better decisions. For example, it might be possible to explore low impact approaches such as tributary river development rather than the predominant choice of main-stem dams, assuming that institutional problems could be solved. Decision makers will be better able to identify the impacts of planning decisions and will be better equipped to avoid natural disasters. Additionally, a new paradigm of transparency with citizens can result by sharing the results of the planning decisions more widely. More research could be completed in this area, exploring how the data products, tools, and models could be placed within a web-based user interface, allowing public access to the data as well as access to simplified versions of the tools and models.

The prime focus of this research has been on the newly available geospatial data, and how to use the data to generate information not previously available for the purpose of reservoir planning and decision support in developing nations. This study is foundational for further work that could be done to formulate a decision support system which could include a multi-criteria decision analysis tool. This study sets the stage and provides the basis for such a tool in that it lays out methodologies for the creation of a database, and the tools and models that would be utilized for the extraction of pertinent information from the database. The case studies that have been conducted demonstrate the use of the data products, tools, and models that have been created in this research. It is seen in the case studies that the data products provide a complete database. The tools and models provide efficient means to extract the information necessary from this database, allowing a user to address fundamental reservoir planning questions.

The tools and models outlined in Chapter 5 have focused on single reservoir sites and localized areas around these proposed sites. Further research could be done and is recommended on the issue of “teleconnectivity”. This can be explained, in the context of reservoir planning, as the affects that a reservoir or series of reservoirs may create to areas both downstream and upstream. It is well documented that any change introduced to a natural system can and often does have an associated impact to the system in both the area immediate to the change as well as areas sometimes significantly removed from the immediate area experiencing the change. Specific to reservoirs and reservoir systems, a newly introduced dam site or sites, can affect reaches of connected waterways significantly upstream or downstream.

The proposed visual decision support methodology outlined in Chapter 7 relies on a version of weighted average method for its Multi-Criteria Decision Analysis (MCDA) method. This simplistic approach to MCDA displays it weaknesses in consideration of the user specified weights given to the decision criteria utilized for the decision analysis. In essence the decision analysis can be highly driven by the user specified weights and as such the outcome of the analysis can in many cases be completely driven these weights. Possibly, Compromise

Programming could be integrated into the methodology, which would provide much less of a predetermined outcome.

Finally, the tools and models section of this research (Chapter 5) could be further expanded to include more research in the area of sensitivity analysis. Several of the models that have been developed in Chapter 5, particularly the “Annual Yield Model” and the “Peak Discharge Model, could benefit from further research in sensitivity analysis. Examples of sensitivity analysis are adjusting watershed area parameters (area, slope, impervious area, etc.) while monitoring the resulting model output, say, peak discharge. The models that have been generated in Chapter 5 have been constructed for the purpose of demonstrating the overall methodology being outlined in this research, as well as for showing the utility of the data that has been researched. Because of this, research efforts were not spent on sensitivity analysis.

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