SMAP Utilization in Flood Forecasting, Crop Production, and Irrigation Management in the Indus River Basin

Summary. Pakistan, with its diverse geographical topography over a relatively small area, can serve as an excellent testing ground for post-launch data utilization activities for the SMAP mission. With only one major river basin to serve the water needs of a population of nearly 200 million people (over half that of the U.S), the region also has great potential for applications that can benefit from the SMAP data products, specifically, in sensor placement for river stage forecasting, irrigation system management, and crop yield forecasting. In turn, optimal sensor placement can eventually contribute to SMAP calibration and validation in a relatively poorly observed region of the world but with high average population density. This proposal details a plan for developing quantitative applications of SMAP data that can benefit the population within Pakistan's only river basin - the Indus – through three tasks: (i) by guiding the placement of in situ river and canal flow gauge sensors through studies of the relationship between such gauges and resulting soil moisture in irrigated cropland, (ii) developing statistical relationships between crop yield and soil moisture data observed over the growing season, and (iii) by using soil moisture data to help improve river stage and flood inundation forecasting. The project will involve collaboration between the CU Center for Environmental Technology, two universities in Pakistan: The Islamia University of Bahalwapur and the Syed Babar Ali School of Science and Engineering's Laboratory for Cyber Physical Networks & Systems (CYPHYNETS Laboratory), and the CU National Snow and Ice Data Center. The proposed applications will have significant potential to contribute to the infrastructure development and socioeconomic health of Pakistan, as we as in other watersheds that emerge from the Himalaya-Karakorum-Hindukush (HKH) region, long after the official three-year period of the mission is over.

1.0 Summary and Objectives. Pakistan, with its diverse geographical topography over a relatively small area, can serve as an excellent testing ground for post-launch data utilization activities for the SMAP mission. With only one major river basin to serve the water needs of a population of nearly 200 million people, the region also has great potential for applications that can benefit from the SMAP data products, specifically, in sensor placement for river stage forecasting, irrigation system management, and crop yield forecasting. In turn, optimal sensor placement can eventually contribute to SMAP calibration and validation in a relatively poorly observed region of the world but with high average population density. This proposal details a plan for developing quantitative applications of SMAP data that can benefit the population within Pakistan's only river basin - the Indus – through three tasks: (i) by guiding the placement of in situ river and canal flow gauge sensors through studies of the relationship between such gauges and resulting soil moisture in irrigated cropland, (ii) developing statistical relationships between crop yield and soil moisture data observed over the growing season, and (iii) by using soil moisture data to help improve river stage and flood inundation forecasting. The project will involve collaboration between the CU Center for Environmental Technology, two universities in Pakistan: The Islamia University of Bahalwapur and the Syed Babar Ali School of Science and Engineering's Laboratory for Cyber Physical Networks & Systems (CYPHYNETS Laboratory), and the CU National Snow and Ice Data Center. The proposed applications will have significant potential to contribute to the infrastructure development and socioeconomic health of Pakistan, as we as in other watersheds that emerge from the Himalaya-Karakorum-Hindukush (HKH) region, long after the official three-year period of the mission is over.

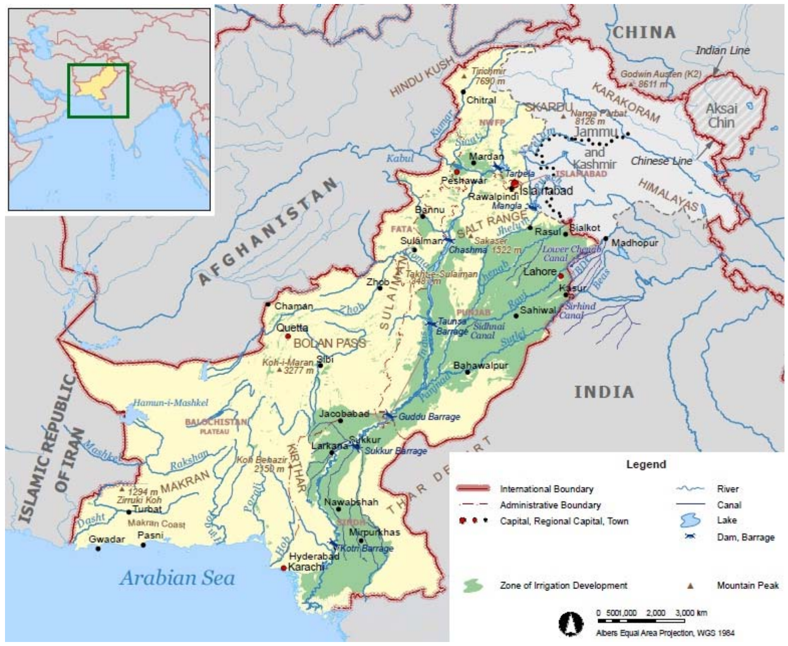

Figure 1. Topography, land use, and irrigation zones in Pakistan.

2.1 Hydrological Forecasting in Pakistan. Soil moisture is an important parameter that can significantly improve the prediction capabilities of regional hydrological and weather forecast models by improving the accuracy of run off and uptake, evapotranspiration, moisture and energy fluxes and related parameters that serve to initialize these models. While improved hydrological and weather forecasting is, in itself, a goal worth achieving, scientists working with the Himalayan region models stand to benefit more from the soil moisture data from SMAP than perhaps any other region of the globe due to several location-specific reasons: (i) the topography and climate of Pakistan is highly varied, and in locations such as the Himalaya-Karakorum-Hindukush (HKH) region the topography (and hence watershed complexity) is extreme, (ii) the high average density of population (~234/km^2 - exceeding that of Europe on average) and moderate intensity of land usage supports a critical and sensitive food-producing infrastructure, and (iii) relatively sparse surface-based geospatial information for modeling and prediction is available (Figure 1). Currently, the highest resolution weather and hydrological models for the region use remote sensing data with a spatial resolution of ~5 km. However, models with such fine-grained resolution, while appropriate for the regional topography, are too complex to warrant their use for near real-time analysis and hydrological prediction due to high computational costs. The increased temporal resolution of the SMAP geophysical data relative to many other hydrological data sources in Pakistan can result in simplification of the current models to create more physically-based and statistical hydrological models for use in near real-time analysis, forecast, and warning. More importantly, however, the SMAP soil moisture data can be used as a baseline to improve the basic design of these models and sensing infrastructure in profound and lasting ways.

To recognize these potential advantageous uses of SMAP data for Pakistan it is important to understand the geophysical and infrastructural characteristics of the Indus basin. In the northeast, the Himalayan region is unique in that there are extreme changes in topography occurring over small geographic areas. This variability causes current hydrological models based upon modeling parameters developed for other midlatitude regions with less extreme topography to not be fine-grained enough to predict and model the hydrology of the HKH region. Statistically based climate, weather, and hydrological models that are used for this region run increasingly fine-grained resolutions to iteratively achieve better prediction and analysis capability. These statistically based fine-grained models, consequently, are complex enough not to warrant their use for near real-time analysis and prediction of water availability, precipitation, river flow, and other climatic variables. Research suggests that simpler, physically-based basin models such as such as the Indus Basin Model Revised (IBMR) have a higher potential for use in real-time monitoring and prediction of hydro-climatological parameters [1,10]. However, it is not possible to have realistic physically-based models as the HKH region suffers from a lack of in-situ observations. Only very sparse spatio-temporal data is available for topographic changes in the terrain as well as the geophysical parameters. The extreme topography and lack of accessibility to most parts of the region limits the possibility of more dense in-situ observations.

A study on the decadal change in the glaciers of Nepal [2] shows how meteorological equipment placed at high altitudes, working in a semi-automatic fashion, often malfunctions due to logistical reasons. As a result it has only been possible to use daily maximum and minimum temperature values to provide averages for the study. The study further highlights how these averages are often not realistic mean values and emphasizes the need for long term hourly temperature data to ensure that more representative values of the daily mean temperature can be found. Similarly, soil moisture data would provide an important measure of run off potential, but can only practically be obtained using a high resolution sensor such as SMAP.

In an earlier project [1], we proposed that a wireless sensor network with sensors placed at dense spatial resolutions with an ability to provide temporally dense near real-time observations of geophysical parameters should be developed to improve the local climatic models. This dense spatio-temporal data would also open the way to devise physically-based models for more realistic and reliable prediction of water availability, snow pack water equivalent, and precipitation patterns. Placement of probes for measurement of (e.g.) rainfall must be done strategically to obtain representative measurements for the catchment level analysis of the rainfall patterns. With an extremely high rainfall variability in the Indus Basin this data also has to be temporally dense to provide useful insights into interactions between monsoon and other weather systems that interact to produce unexpected precipitation events in the Himalayas. Dense sampling requires an increase in the number and types of sensors as well as an optimal placement of these sensors to ensure representative data can be obtained with least cost. Such a sensor network could form the backbone of a proposed infrastructure system for the Indus Basin, regulating the inputs and outputs into the system.

However, owing to the large area (~1.16×10^6 km^2) of this basin the placement of probes, which are necessarily limited in number, must be judiciously determined. The proposed system required that the sensor network would be iteratively improved and guided by incorporating the feedback from earlier placement of sensors and available routing information. This strategy would permit the placement of sensors to become strategically optimal as the sensor network evolved. It was noted, however, that the low number of in-situ observations and the lack of reliable remote sensing data on rainfall and run off potential would limit the optimal placement of the first sensor nodes in the network, and optimization may require years of expensive relocation and maintenance.

To resolve this problem of in situ sensor placement we propose in one of our tasks to use the SMAP 9-km soil moisture product to help iteratively guide optimal or near-optimal placement of flow sensors on canals located in the Indus valley used for irrigation, resulting in evolution of a reliable and optimal network in much less time than by use of the available sensors themselves. The SMAP mission has the potential to provide this key surface data with relevant temporal and spatial resolution resulting in a possibility of a cyber-physical system that will improve water management by allowing optimized flows to be adjusted to achieve prescribed soil moisture conditions. The sensors are being deployed as part of a project conducted by collaborator Prof. Abubakr Muhammad of SBA School of Management Science, Lahore University of Management Science (LUMS) in Lahore, and will be funded under a separate proposal to the Pakistani government. The site to be instrumented is located in the Lahore area, although a second site that is already instrumented and located in Punjab (Bahawalnagar) will also be used. The Punjab Irrigation Department has already received government support and collaboration with projects from LUMS where irrigation networks are being automated using sensor networks and data assimilation.

This specific application has two-fold benefits since these same sensors would be also able to be used in the future to further study run off potential derived from SMAP data. The SMAP mission requires such in-situ networks for calibration and validation activities. Optimal daployment of the proposed sensor network in the lower Indus within irrigated cropland will provide an additional sparse flow network that can be expected to benefit SMAP validation efforts in the future. It is expected that the mission will acquire and provide data for three years after its launch which is sufficient period of time to evolve the design of the wireless sensor network (WSN) into its most optimal placement. This means that the infrastructure system that gained its inputs and data from SMAP mission can continue to work using the wireless sensor network even after this SMAP projects reaches completion.

The above discussion of sensor placement tacitly assumes a relation between soil moisture and tributary or feeder channel flow the results from pure run off. However, we note that precipitation is a major component of this relationship, and cannot be neglected in quantitative studies. Weather radar imagery form the Pakistani National Weather Forecasting Centre, along with regular precipitation data from the NASA GPM mission (GMI and Rain Radar) is available and will be used within this project to help close the water budget for all quantitative studies relating flow measurements to soil moisture. In addition, final closure will calculated using evapotranspiration estimates based on normalized differential vegetation index (NDVI) estimates from MODIS. We note that improvement of estimates of precipitation and evapotranspiration based on NDVI are not primary objectives in this project. Instead, data on these important variables will be taken at face value from NASA data bases to provide water budget closure that relates soil moisture (and hence run off potential) to flows.

2.2 Drought and Crop Forecasting. An estimated 45,000 square km of Pakistan is a desert with a population of more than a million people. These areas are at the lowest development index across Pakistan, facing droughts of varying degrees every year. Hundreds of infants and adults die due to hunger in these regions annually. However, the desert in Pakistan is fertile and has been a hub of cultural and social activity for the local populations for centuries. The people in these regions have evolved remarkable means to weather droughts and water scarcity using time tested mechanisms to harvest and preserve water more intelligently than most modern dwellers. Still, the increase in population and the increased frequency and extent of drought due to what appears increasingly to be global warming has put increased stress on this extremely water stressed region, bringing it to its limits. More recently, even the arid and semi-arid areas of the country have seen more frequent and more severe agricultural droughts creating food security concerns as agricultural productivity decreases.

Overall, Pakistan depends upon agriculture for a significant 24% of its GDP. Against this backdrop, it is critical that the available water resources of Pakistan are managed optimally for agriculture. To this end, 45% of Pakistan's total labor force depends upon agriculture for their living and a staggering 60% of Pakistani population lives below the poverty line, earning less than $2 a day. This means that improving agricultural productivity is an imperative for economic development and growth and stability [11,14]. In this regard, monitoring of drought as well as agricultural yield play a pivotal role in revolutionizing Pakistan's agricultural sector and therefore improving the per capita income of its people.

SMAP near-surface soil moisture data and indirectly derived root zone moisture data can be most useful for predicting and optimizing agricultural yields. Even today, Pakistani farmers use traditionally thirsty crops with huge water footprints such as cotton and rice to earn their livelihoods. Additionally, there are no agricultural prediction models available for farmers to improve the productivity of their land or to predict soil moisture and water availability for improved agricultural practices. Realistic and temporally dense soil moisture values can be used to improve agricultural prediction models. It is believed that the availability of SMAP data for agricultural yield prediction could lead to participatory and community-based projects to improve agricultural productivity in the basin as well as encouraging farmers to use less thirsty varieties/crops. Since the mission looks to disseminate this data to public and government organizations in user-friendly formats, there is a huge market in Pakistan's agriculture based economy that stands to gain from the availability of this data to improve socioeconomic conditions and livelihoods of people here. The soil moisture and root zone moisture values, along with historical crop yield versus soil moisture data, could be made available online in a user-friendly way for use by the agriculture community as a beginning.

The complex network of canals and irrigation channels across the country still makes it impossible to estimate the rate of evapotranspiration, seepage and leakage losses across the aquifer, causing loss of precious resource in an already water stressed region. [7] A project is already underway that deploys electronic gauges in canals to detect river flows and assimilate this data from several sites to derive the losses in the channel through derived parameters. Extension and optimization of such networks could be guided by SMAP data. While the soil moisture data could itself be instrumental in finding the losses and leakages from channels, deployment of a wireless flow sensor network guided by SMAP data (as discussed) could result in continued availability of crop yield predictions long after the SMAP data becomes unavailable.

2.3 Flash Floods and Glacial Lake Outburst Flows (GLOFs). An increase in the frequency of extreme weather events such as floods and droughts, presumably precipitated by global climate change, has also resulted in more frequent Glacial Lake Outburst Flow (GLOF) events and flash floods in the Indus basin [4,15]. The northern areas of Pakistan are affected by flash floods every year, with at least eight flash flood warnings between 2010-2011 [5]. A potential disaster resulting from a landslide dam at Attabad was averted by emergency services during January, 2010. Reports from remote sensing and in-situ observations in the larger Himalayan region including Nepal, Bhutan, Pakistan and India suggest that an increased number of glacial lakes have formed in the HKH region during the last decade. While it has been possible earlier to identify such glacial lakes, when they reach a certain size, through remote sensing, it has not been possible to predict a GLOF event reliably.

SMAP data products have the potential to contribute to prediction, loss aversion, and recovery of this unique type of disaster in the Himalayas. SMAP data can be used to identify transient water bodies, even in darkness and under heavy cloud cover. While this potential has been discussed as an important capability of the SMAP data to locate inundation patterns on land, more refined data products will be required to reduce error in finding the transient water bodies (lakes) in the snow/ice covered regions. Refinements would also require combining the flagged data from SMAP with data from other satellites to detect water bodies reliably. It can be anticipated that the state of freeze/thaw parameters at the edges of these water bodies can be instrumental in anticipating when a boundary of the water body is about to give way, causing a flash flood or GLOF event. Such a detection method could revolutionize the emergency response mechanisms in the northern areas of Pakistan where there is currently no reliable means of warning for flash floods, causing loss of life and infrastructure several times every year. In the face of global warming and increased frequency of such events, it is imperative that the already existing data products can be used to delineate transient water bodies within the snow/ permanent ice region and the freeze/thaw state at the boundaries of these water bodies can be analyzed.

2.4 Flood Forecasting and Inundation Patterns. Due to the close proximity with the Himalayan Mountains, the Indus Basin has always had a high variability in rainfall patterns and relatively frequent droughts in some areas. However, the global climate change in the recent times has made it more prone to disasters by increasing the already high precipitation variability and longer, hotter drought seasons [6]. This has also resulted in an increased frequency of extreme weather events like floods and droughts.

The July-August 2010 flood in Pakistan was one of the largest of global disasters in recent history. It was termed as a “slow-motion tsunami” by Ban-Ki Moon, and devastated the infrastructure of a staggering 20 million people (~10%) of the country, inundating some of the lowlands for more than a year. Since then, Pakistan has faced floods of considerable intensity every year including 2014. Besides these extreme events, Pakistan is a largely arid and semi-arid area with per capita water availability of 1038 cubic meters per year as measured in 2010. In spite of the frequency of such inundation - being already water stressed with a declining per capita water availability - Pakistan is projected to be the most water scarce country in South Asia beyond 2035 [6].

With this extreme variability in water availability between alternate droughts and floods, it is imperative to devise mechanisms that ensure better inundation prediction during floods and better water management during droughts. It is also important to devise better inundation patterns for flood water, directing it away from high value infrastructure and agricultural lands and into the driest desert regions where droughts are usual. In this manner, the flood water could be used to increase the soil moisture of the areas facing droughts instead of running off to the ocean.

Pakistan has one of the largest irrigation networks in the world comprising a large enough infrastructure for control and release of flood water, meaning that flood water can be directed to a number of channels if prediction can be done early enough. In recent times, some of these channels are being equipped with sensor nodes to find data like the flow of water, seepage, leakage and waste of water. However, the soil moisture readings from the SMAP mission could be instrumental in finding out the channel and sub-basin with lowest soil moisture so that water could be directed to a region with least run off and most absorption into the aquifer. This alone could ensure better utilization of flood water as millions of cusecs are absorbed as soil moisture instead of being drained off to the ocean.

Soil moisture is a key variable in identifying run off potential leading to a flood risk. SMAP data, along with simple hydrological flow models such as IBMR, can be used in flood forecast models to better predict the inundation patterns. Identifying recurring patterns using SMAP data may also warrant building of water control infrastructure by the government to ensure that water can be suitable directed to various parts of the Indus basin. This is increasingly important in the lower Indus Delta where coastline retreat into the delta has caused intrusion of saline sea water, turning hundreds of acres of once fertile farmland into mere water-logged swamp. This water logging can also be identified by SMAP data and irrigation network and water channels can be built to avoid water logging and to discourage encroachment of the sea.

Finally, some of the lowlands in the country may remain inundated for months before the water dries out causing increased disease vectors and health issues long after the immediate threat of flood has passed. Early forecast of floods and modeling and simulation of flooding/inundation patterns can help improve emergency response and evacuation as well as preparedness for disease in the areas likely to be inundated for long.

2.5 Glacial Melt in the Himalyas. In addition to the aforementioned three primary application of SMAP data, there are a number of ancillary areas that will be studied in this project. For an example, the SMAP mission can delineate permanent ice and snow from subsurface or surface liquid water, however, the data is marked with flags indicating a high error in the detection (Figure 2). It has been suggested to the users of SMAP to conduct further research to correct the error and achieve better parameter estimation in such regions. In this regard, it may be possible to combine this SMAP data product with IceSat-2 data (in future years) and MODIS IGBP and IMS-NOAA data products to achieve more accurate detection of various kinds of snow and ice cover on land and in water bodies. This detection will result in better insight into the increase or decrease of glacial ice and snow cover in the Himalayas, thus either substantiating or invalidating glacial retreat and its extent by monitoring seasonal changes over the year [13,16].

Similarly, the freeze/thaw data could help predict the onset of snow melt and its addition in the river flows. There could be insights gained into the relationship between the seasonal changes in geophysical parameters and freeze/thaw state (and consequently, snow pack water equivalent) enabling better prediction of water availability. In addition, the soil moisture data from SMAP could be used in conjunction with the contribution of snowmelt (obtained through freeze/thaw state) within surface models to improve the prediction of water availability downstream.

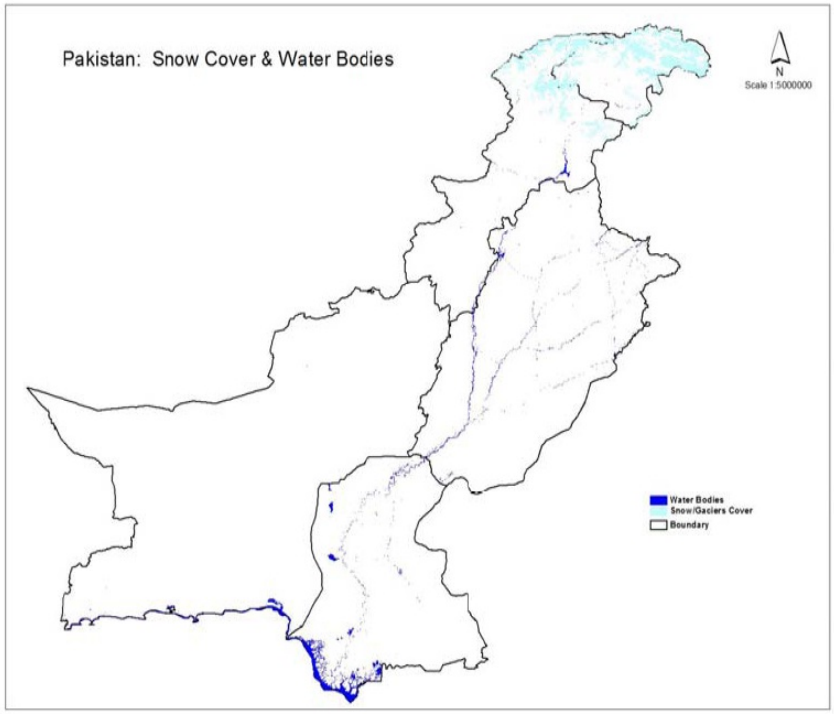

Figure 2. Glaciers, snow cover and water bodies associate with the Indus basin.

The detection of permanent ice cover and the extent of glacial retreat are also important in understanding the long term climate of the region. For an example, measurement of the contribution of glacial ice to the river flow could help determine the longer time availability of water in the next few decades. Similarly, detection of lakes and water bodies in the snow-covered regions could result in better understanding of the temperature variations between different parts of the HKH region. Such a study may also provide a very important link between carbon and water cycles in determining whether melting glaciers release large relevant amounts of CO_2 or methane into the atmosphere [3], and thus exacerbate melting by radiative feedback.

2.6 National Security and Conflict Management. SMAP data is expected to provide critical data for trafficability and mobility on ground and in air by providing information about fog and dust generation. However, the national security takes a new dimension for water management in Pakistan. The aspect of water management that is important for various countries of the South Asian region is equitable and reliable distribution of river flows between different riparian zones in the delta. India and Pakistan, who have been traditional rivals and have the issue of water distribution at the core of the constant tension in the region, have agreed to install a telemetry system to monitor distribution of irrigation water between the two countries. This system, however, is also not relied upon by both the countries and requires the presence of a neutral observer to verify temporal flows between the countries to achieve its goals as a confidence building measure. [8] Similarly, a telemetry based observation system has been set up for distribution of water between different provinces of Pakistan. However, it suffers from a similar lack of trust by the riparian zones sharing the water resources. Consequently, the efficacy of telemetry installations has only been of limited value for water resource monitoring and conflict management.

SMAP data can be used to help manage this conflict by guiding the sensor node placement that can automate the monitoring of flows for all channels of water for the two riparian zones. Secondly and more importantly, however, the soil moisture values can help cut off the root of the conflict by calculating the amount of water that will become available for use for the lower riparian zone. Research points out that drought and low soil moisture content may cause up to 100% of precipitation getting absorbed into the ground with no contribution to run off. The lack of consideration of soil moisture gives unrealistic results for expected flows in the river for lower riparian. Having a value for soil moisture can give more realistic results about how much water will be absorbed during run off while upper riparian uses it and how much can be available for use at the lower riparian.

One of the most important instruments of water-related conflict management in the region is the Indus Treaty. The treaty allocates shares of water in percentage of water that must be released for all six tributaries of the Indus from the upper riparian. The treaty suggested that three of the tributaries of the Indus will contribute a 70% of their share in the upper riparian while the other three tributaries will only contribute a 30% of their flows in India. This has resulted in significant change in the characteristics of the deltas of the former three tributaries, leading to the fact that most of the farmland in Pakistan that used their flows has turned barren as the flows coming to Pakistan are not sufficient even to contribute to the soil moisture in the region, leave alone any irrigation. Similarly, the three tributaries that are to contribute to Pakistan's water share are often claimed to have higher run offs at times of flood, causing increased devastation in the lowlands whereas the usual flows are claimed to have been cut down by use in India.

The lack of trust and inequitable sharing of these rivers has meant that the region is home to a constant conflict, not only between India and Pakistan, but also causing constant occupation and dispute over a piece of land called Kashmir where most of the tributaries of the Indus emerge. In a suggested updated version of the Indus Treaty, the water of all the tributaries could be divided on the basis of percentage of water flows instead of entire rivers, resulting in better distribution of water without disturbing the overall soil moisture balance of the basin. This could be possible after evidence of significant change in the soil moisture values of the region, and associated loss in soil moisture balance and change in climatic conditions, could be established. SMAP data applied (for example) in the context of this proposal, can play a part in establishing these values during its life time, resulting in better resolution of this conflict in the region.

2.7 Water Management and Energy Security. Pakistan has been suffering an extreme energy crisis in recent years which is also rooted in water management issues. The country uses hydropower to meet between 40% to 50% of its energy needs. There are two large and one small dams that have been the major source of water storage in the country for drought and flood management as well as for energy generation. In recent times, the increased floods and droughts have rendered the two large dams insufficient to meet the storage needs of the country during drought seasons. Also, increased flash flooding and frequent alternation between drought and flood periods means that millions of cusecs of precious water runs off to the ocean without much time to increase absorption in soil and any increase in the overall water reservoirs of the basin as absorbed soil moisture. The two dams are insufficient to store enough flood water to be used during the following drought periods or to meet the ever-increasing energy needs of the country.

SMAP mission data could help in better water management and planning by allowing realistic estimates of the overall yearly water availability and storage capacity in the aquifer, not only by way of absorption into the lower layers of earth, but also as soil moisture and likely precipitation. Since SMAP is capable of identifying precipitation, soil moisture, transient water bodies as well as onset of thaw predicting river run off times, it can help estimate the availability of water resources in the aquifer in the short term as well as in the longer term by predicting likelihood of absorption, evaporation and surface temperature values. Therefore, SMAP can be used to realize the infrastructure system that has been proposed earlier by making it possible to monitor, evaluate and predict water resources in near real-time as well as providing enough data to policy-makers and communities so that better infrastructure can be developed based upon the monitoring and evaluation parameters. The available data can be used for optimization of the existing sensing infrastructure, as well.

Governments in developing countries like Pakistan are less likely to adopt water management infrastructure and information systems and to use agricultural models at the institutional level due to a lack of political will. The availability of this data to public institutions and communities is more likely to induce change, not only because communities are more receptive to the use of these approaches but also because they can drive the political will so that decision-makers are forced to take the right steps under public scrutiny and participation. Additionally, agricultural and urban use of water is more likely to be changed and evolved by participation of the community instead of infrastructure systems that enforce it. Therefore, the community is the major stake holder in this regard and its involvement can reap benefits like none of the government institutions can enforce. Pakistani government and institutions are becoming more receptive to technological solutions as they use advanced information technology such as satellite data to manage resources, find and control disease vectors, and serve the complaints of general public in so far as such data is applicable. It is expected that these departments will support efforts for automation of water infrastructure and building of an intelligent water grid using SMAP data during and after the course of this proposed project.

2.8 Future SMAP Calibration/Validation Site Development. The SMAP data requires input values for the kind of vegetative cover to correctly predict the soil moisture in the farmland areas or areas with forestation. Pakistan can serve as a useful testing ground for such vegetative cover values and related validation as areas have been used traditionally for years rotating only a certain set of crops for each of the two crop seasons. Such validation efforts can take place as we identify a set of SMAP validation sites in Pakistan. The SMAP sites that have already been formally established by NASA are diverse and are located at various geographical areas across the world. Pakistan, in spite of its relatively small geographical area can contribute to such sites being set up in all different topographical conditions. For an example, a site to imitate the arid or desert-like topography of Texas has been identified by us in the Cholistan and Southern Punjab part of Pakistan. Setting up an site in the Himalayas has unique calibration/validation inputs as well as applications that are unprecedented for the rest of the world while having the potential to serve $1/5^{th}$ of the world's population that depends for its water needs on the rivers originating from HKH region. Similarly, Pakistan has lost an estimated 24% of its farmland to waterlogging, encroachment from sea and salinization [9]. While this makes the region an ideal validation site for water-logged soils and their characteristics, Pakistan stands to gain a great deal from soil moisture data to manage this problem better. Once water logged or saline, significant time and financial investment is required to clear a water logged area for agricultural use again. SMAP can help predict water logging at the onset and action could be taken to avoid it without wasting much of fertile land. We note that the identification of such sites would be a natural product of this project, but their development would require additional proposal effort to and support on the part of the Pakistani government. Nonetheless, their identification is a critical first step.

3.0 Workplan, Timetable, and Deliverables. As discussed, the proposed project will consist of three primary activities intended to further the use of SMAP data in the Indus basin. These activities are in the application areas of: (1) irrigation channel flow analysis, (2) crop yield assessment and soil moisture correlation, and (3) inundation and flood stage forecasting. The specific activities to be performed, personnel to be involved, and deliverables are outlined below. Additional related study activities to further the other aforementioned potential uses of SMAP data are also likely, but will be performed on a time- and resource-available basis.

1. SMAP Irrigation Channel Flow Analysis. In collaboration with Prof. Abubakr Muhammad of the SBA School of Science & Engineering in Lahore, CU researchers will analyze the correlation of feeder canal flow measurements obtained within irrigated and cultivated areas with soil moisture from SMAP, satellite precipitation data from GPM, and rain gauge, rain radar, and NDVI (proxy evapotranspiration estimate) data. The goal of this study is to determine the impact of controlled canal flow on cropland soil moisture, accounting for precipitation and evapotranspiration, over two small instrumented areas of cropland. The sites (Figure 3) identified include a region of size ~15 km covered by ~3 SMAP pixels at Bedian near Lahore (31°18′47″N, 74°30′12"E), and a slightly larger region (~50 km, covered by ~30 SMAP pixels) in southern Punjab at Haroonabad near Bahawalpur (29.61°N, 73.12°E). Each of these areas has distinct crops, precipitation patterns, and urbanization levels. There are two growing seasons in both of these areas. In the fall season starting from September/October to April the typical crop is wheat while the spring season starting from April/May until October is used for growing cotton in Southern Punjab (Bahawalpur) and rice in Upper Punjab (Lahore).

   The first project year will consist of collecting feeder canal flow data and ascertaining proper calibration of the sensors network. Visits to the Lahore and Bahawalpur sites will be necessary to map site feeder topology, assess sensor accuracy, and facilitate remote data set access. The second project year will involve collection of satellite (SMAP and GPM) data along with precipitation gauge and rain radar data. The third year will consist of data set correlation analysis including evapotranspiration estimate analyses to close the water budget and identify the impact of canal feeder operation on SMAP soil moisture. Correction for vegetation type and canopy density will be studied in this third year, and applied as the available data permit. The third year will also consist of publication of the results from the correlation study.

   Pending results, we expect that SMAP measurements along with precipitation measurements will be able to point to means to improve irrigation practices to achieve required soil moisture levels using feeder canals, and thus enhance water conservation while maximizing crop yield.

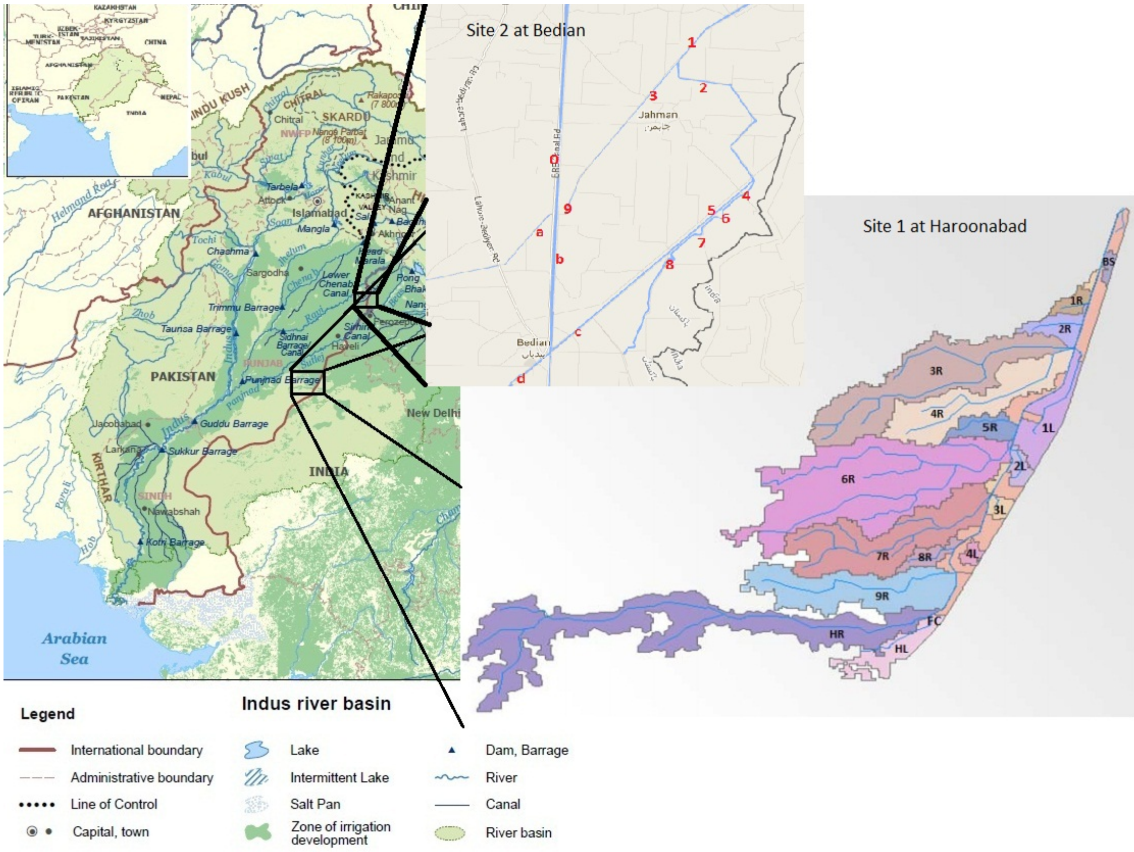

Figure 3. Details of channel flow gauge placement at Lahore and Bahalwapur sites.

2. <u>SMAP Crop Yield Correlation.</u> As a means of understanding how SMAP can be used to predict crop yields across Pakistan the soil moisture data for the Indus basin will be integrated across up to three growing seasons and correlated with crop yields. To this end, crop data will be obtained from government ministerial services, for example, the Punjab crop reporting service (http://www.crs.agripunjab.gov.pk/), from the IBMR basin hydrological and agricultural model, and other areas where such data is available, including crop reporting service website such as http://crs.pitb.gov.pk/reports and crops report maps from http://crs.pitb.gov.pk/maps. These sites also provide remotely sensed maps of the two geographical areas supporting the flow sensor measurements.

   The first year of effort will be in acquiring crop yield estimate data for key regions within the Indus basin. Visits to key ministry offices in Pakistan are anticipated to collect this data, as well as operation of the IBMR. The second year will consist of correlating this data with SMAP soil moisture estimates and comparing them to IBMR estimates using only conventional data sources. The third year will consist of refining and publishing these results, with potential suggestions for inclusion of soil moisture data into IBMR in future versions.

3. <u>SMAP Inundation and Flood Stage Forecasting.</u> The IBMR is also a flood stage forecast model that integrates rainfall and river flow data across the Indus basin to predict downstream flows. This model was developed under the support of the World Bank, is run by the Pakistan Water and Power Development Authority (WAPDA), has been upgraded by the National Engineering Services Pakistan (NESPAK) in collaboration with

WAPDA, and is available for our use in studying the impact of SMAP soil moisture data on run off potential. It has been in use for many applications in different sectors ever since the early 1980s (Figure 4). The model permits a range of inputs and provides key outputs needed for this study. The first year of effort on this task will focus on acquiring the model and running it at CU using existing data while identifying the means for integration of SMAP soil saturation data. The second year of effort will involve assessing model runs during years 1 and 2 using modified run off coefficients based on SMAP soil saturation, and quantitatively estimating impact on flood stage prediction accuracy. The third year will focus on refining the model and data assimilation method, and publishing results.

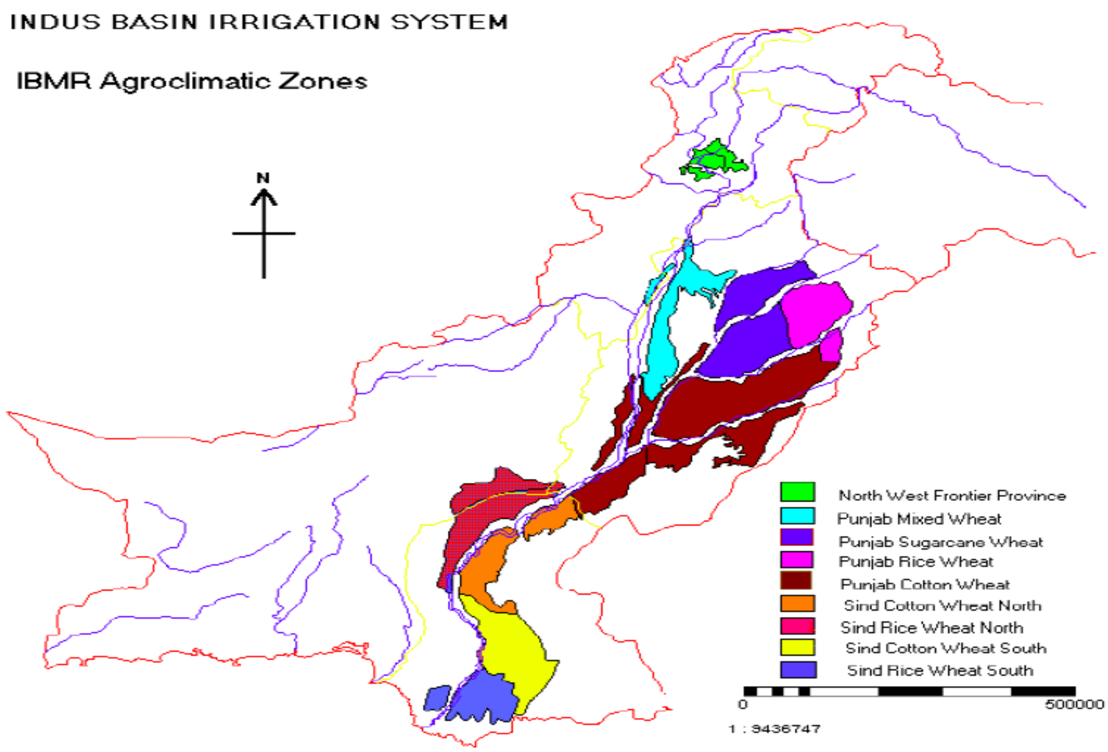

Figure 4. IBMR model of the Indus basin irrigation system, illustrating crop types and watershed boundaries.

Ongoing in Pakistan are related projects in flood forecasting and modeling (e.g. http://www.sgs-suparco.gov.pk/floodhazard/default.aspx). These projects are attempting to do what we propose, but using soil moisture data from sources other than SMAP or any other L-band sensor (e.g., see http://www.sgs-suparco.gov.pk/floodhazard/outline.aspx). However, these efforts provide excellent examples of the type of output that will be generated under this task (e.g., http://www.sgs-suparco.gov.pk/floodhazard/features.aspx) and the general data processing scheme to be implemented, but with SMAP data as an additional data driver. To minimize duplication, coordination with the operators of these models is being organized by our Pakistani colleagues involved with this project (graduate student Farah Akhtar and Prof. Abubakr Muhammad).

Deliverables for this project include peer-reviewed publications in journals such as the IEEE Transactions on Geoscience and Remote Sensing on each of the three tasks, presentations as

NASA and international scientific meetings such as IGARSS, and model code and data sets made public through CU NSIDC archives.

4.0 Personnel. Personnel on this project include Prof. Albin J. Gasiewski (PI), who has been a consistent contributor in microwave radiative transfer models, microwave retrieval and assimilation algorithms, and airborne and spaceborne instrumentation (especially in the area of passive microwave hydrology) for three decades. He currently heads the NOAA-CU Center for Environmental Technology (CET) at the University of Colorado, with a group of eight graduate students engaged in passive microwave instrument and algorithm design and development. He is the principal developer of the Polarimetric Scanning Radiometer (PSR) suite of airborne microwave instruments that have been used for NASA AMSR-E calibration and validation, and a drone-based L-band soil moisture radiometer that will be sued for very high resolution (~15 m spatial scale) SMAP validation. Previously, he has worked at the NOAA Environmental Technology Laboratory, and currently works in collaboration with the NASA, NOAA, and DoD on several meteorological and hydrological remote sensing projects.

Assisting Prof. Gasiewski in all aspects of computer programming, model development, and (especially) interfacing with Pakistani scientists and government personnal will be graduate student Farah Akhtar, who will be making this project work central to her Ph.D. thesis. Previous to entering the graduate program at CU Ms. Akhtar has had several years' experience as an instructor at the Islamia University of Bahalwapur working in the area of hydrological management and measurement in Pakistan using distributed wireless sensor arrays. Ms. Akhtar will begin her Ph.D. work at CU in the fall of 2015 under the guidance of Prof. Gasiewski in the CU CET.

Assisting in the identification of SMAP, GPM, and other data sets and the archival and dissemination of output data sets will be Dr. David Gallaher of the CU National Snow and Ice Data Center (NSIDC). Dr. Gallaher is a recognized expert in data management, environmental data systems, and satellite data science. Within NSIDC he brings an extensive set of capabilities for data management to this project.

Also collaborating will be Dr. Abubakr Muhammad, Ph.D., Associate Professor of Electrical Engineering and Director of the Laboratory for Cyber Physical Networks & Systems (CYPHYNETS Lab) at the SBA School of Science & Engineering, LUMS, Lahore, Pakistan. Dr. Muhammad is an expert in hydrological measurement and water management in Pakistan, and developer of sensors used for river flow measurement on feeder canals in Pakistan. He will be a non-funded collaborator interested in furthering the development of water management techniques in Pakistan.

The project will be managed by Prof. Gasiewski, who will be Ms. Akhtar's Ph.D. thesis advisor beginning in fall 2015. Management will proceed with regular weekly meetings, along with ~bi-weekly telecon meetings with Drs. Muhammad and Gallaher. Regular project status updates will be made available by presentations at the annual IGARSS and NASA SMAP science team meetings, as well as regular visits to Pakistan by Ms. Akhtar to develop collaborative activities involving hydrological and crop yield data sets and prediction models.

5.0 Facilities and Resources. The CU Center for Environmental Technology provides laboratory space and basic computing and intellectual resources for this project, including global secure VPN access to servers within the CET lab. CET also provides examples of radiometric imaging and sensing hardware that can be used as examples of equipment relevant to the sensing mechanisms associated with this project. CET is located on the CU main campus in the CU Engineering Center.

The National Snow and Ice Data Center (NSIDC) is housed in an administrative/research complex on the East Campus of the University of Colorado. Conventional and wireless network services provide connectivity to internal services and to the internet. NSIDC houses two major Information Technology environments, the NSIDC/CU system and the NASA ESDIS Core System (ECS). The Computer center is an award winning "Green" data center that cut cooling energy more than 90% and total energy 70%. The NSIDC/CU infrastructure provides archive, production, and distribution services to a wide range of data sources: DMSP SSM/I, NOAA AVHRR, TOVS, and the NSF Advanced Cooperative Arctic Data and Information Service (ACADIS) as well as, value-added data sets generated by a variety of cryospheric researchers. Principal components of the University of Colorado NSIDC infrastructure include:

- 10/1-Gigabit LAN residing in the University of Colorado address space
- Fully virtualized server environment totaling over 80 servers
- A 1600 sq ft datacenter with advanced cooling & solar power system (~0 CO_2 footprint)
- Linux servers for core IT functions and MS Windows server for internal admin functions
- Network attached storage array with solid state cache 200 TB capacity
- Redundant array of inexpensive disks (RAID) of 280 TB capacity
- Off-site back up servers on a RAID array with 70 TB capacity
- Quantum tape backup systems
- Sungrid engine for parallel processing
- Full development, test and production environments
- Linked to the CU MRI (Janus) supercomputer with 10,000 cores and 1PB of disk storage
- MySQL, PostgreSQL, database servers
- Apache, Glassfish web servers along with Drupal content management systems
- Conversant collaboration tools and Jira tracking tools
- Catalog metadata database and publishing system
- Search and discovery data access systems (Polaris/Sage)
- Environment supporting Java, Ruby on Rails, and Jenkins, Subversion/GIT
- Datarods Database server with 24 GB memory and 60 TB storage
- Google Mini appliance, high speed film scanners, plotters
- Unix, Windows and Mac user platforms
- 2.5 hours of UPS backup
- 50,000 watts of solar power with solar power backup for the cooling system

The NASA EOSDIS Core System (ECS) provides archive and distribution services to data obtained from MODIS, AQUA/AMSR-E, and ICESat/GLAS. Principal components of the ECS include:

- 1-Gigabit LAN residing in NASA address space
- Quantum tape backup with capacity of over 500 TB
- StorNext for tape and disk file system management, respectively
- 700 TB disk array providing for on-line data access
- Linux Redhat server and IBM blade server environments
- Sybase Enterprise Server relational database management system
- File-level subsetting services (HEW Subsetting Appliance) developed at UAH
- Search and order interfaces to the NASA EOS Data Gateway client and the NASA EOS Clearinghouse (ECHO/ Reverb)

The Computer systems Engineering group and NSIDC are connected together and to the outside world by the University of Colorado LAN and the NSIDC ECS LAN, which are connected to the University of Colorado Campus 10-Gigabit backbone, providing routes to and from NCAR, the Front Range GigaPop, and the Abilene (I2) national backbone.

Sensor and data resources available through Prof. Abubakr Muhammad include access to a sensor network in Lahore / Kasur districts (Punjab), planned for deployment in 2015 to measure canal flows and sharing of experience of a similar deployment in Bahawalnagar in 2012-14. Importantly, Prof. Abubakr Muhammad will help to connect University of Colorado researchers to local research and government agencies in Pakistan for calibrating/validating model and in gathering statistical data. Prof. Muhammad's group will also be willing to host project members, especially Ph.D. student Ms. Farah Akhtar during her visits to Pakistan for any project related activity.

6.0 Related Work. Related to this project but not funded in support of it are two activities. First, the CU CET is developing a small Unmanned Aerial System (sUAS) hosting a compact L-band soil moisture radiometer for SMAP validation and precision agricultural water management. This project is being conducted with Black Swift Tehcnologies, LLC, in Boulder, CO, under NASA Phase II support. Second, CU NSIDC is supporting a project entitled "Contribution to High Asia Runoff from Ice and Snow (CHARIS [12])," under USAID funding (http://nsidc.org/charis). The project is complementary to this proposed work in having the objective to develop a thorough and systematic assessment of the individual contribution of seasonal snow melt and glacier ice melt to the water resources. The amount, timing and spatial patterns of snow and ice melt play key roles in providing water for downstream irrigation, hydropower generation, and general consumption. NSIDC involvement with this project will complement proposed SMAP utilization studies in Indus basin.

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Albin J. Gasiewski (PI)

Education:

Ph.D.	1988	Massachusetts Institute of Technology	Electrical Engineering
M.S.	1983	Case Western Reserve University	Electrical Engineering
B.S.	1983	Case Western Reserve University	Electrical Engineering
B.S.	1983	Case Western Reserve University	Mathematics

Appointments:

Professor/Tenure	Department of Electrical and Computer Engineering, University of Colorado at Boulder	1/06-present
Chief	NOAA Environmental Technology Laboratory, Division of Microwave Systems Development, Boulder, CO	10/01-1/06
Electronics Engineer	NOAA Environmental Technology Laboratory, Boulder, CO Laboratory, Boulder, CO	7/97-9/01
Associate Professor/Tenure	School of Electrical and Computer Engineering, Georgia Institute of Technology	7/95-6/97
Assistant Professor	School of Electrical and Computer Engineering, Georgia Institute of Technology	1/89-6/95

Research Interests: Passive and active remote sensing of atmospheric and oceanographic processes, radiative transfer and electromagnetic theory, signal detection, estimation, and data assimilation, microwave instrumentation, calibration and metrology, development of surface-based, airborne, and spaceborne sensing systems for meteorology, hydrology, and climatology. Related interests include continuum electrodynamics and statistical and quantum physics.

Synergistic activities: Director, NOAA-CU Center for Environmental Technology (CET), 1/06-present. Past-President (2006-2008) of the Geoscience and Remote Sensing Society (GRS-S) of the Institute of Electrical and Electronic Engineers (IEEE), and co-founding member of the Executive Committee of the IEEE Committee on Earth Observations (ICEO). Member of the IEEE GRSS Seniors Council, and immediate Past Chair of USNC/URSI Commission F. Principal faculty member in CU/ECEE Remote Sensing Group, and developer of the three-course core graduate sequence in remote sensing at CU.

Relevant publications:

Tian, M., and A.J. Gasiewski, "A Unified Microwave Radiative Transfer Model for General Planar Stratified Media: Slab Formulation," IEEE Trans. Geosci. Remote Sensing, vol. 51, no. 7, pp. 4103-4118, July 2013.

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Farah Akhtar (Graduate Student)

Farah Akhtar received her M.S in Computer Engineering with specialization in Networks in Distributed Systems in 2010. Previously, she received her B.E. in Computer Engineering from College of Electrical and Mechanical Engineering at National University of Sciences and Technology in 2006. She worked as Software Design Engineer with a technology company rendering solutions in diversified fields including Energy Metering and Fleet Management Services. She has been with the Department of Computer Systems Engineering since 2010 working as an Assistant Professor. In this capacity, she has developed and taught courses in Operating Systems Design, Parallel and Distributed Computer, Digital Signal Processing and Digital System Design.

Her earlier research work at graduate and undergraduate levels has two underlying themes. One set of projects focuses on enabling low-cost technologies for developing world for better e-learning and e-health services. These projects explore the idea of sensor design and use of available technologies for cost effective solutions for the developing world. The second set of projects focuses on networks and robotic design with the idea of using sensors, networks and robots for disaster mitigation, rescue, surveillance and intelligent self-localization. These projects motivate her current interest sensor design and wireless networks. Her current research focuses on monitoring and analysis of the hydrology of the Indus Basin due to its integral value as the only major river basin in Pakistan and its importance in understanding of the Himalayan weather.

For the last two years, she has worked to find answers to questions that haunt the policy and infrastructure for water resource management in Pakistan. She has co-authored a paper that looks at the policy implications of global climate change for water management in South Asian politics. In another proposal submitted to United States Education Foundation in Pakistan for her Fulbright application, she propose a system-level solution using wireless sensor networks to provide affordable real-time monitoring of the hydrologic processes in the Upper Indus Basin for better estimation of available water resources. These measurements will augment the remote sensing data for better interpretation of earlier studies and to improve the effectiveness of the regional climatic models for the Himalayas.

All her past work is inspired by the power of technology to improve human lives and livelihoods. These projects try to help decrease inequality between developed and underprivileged communities, enabling development through community engagement and participation. Ultimately, her vision is to use her research to help discourage economic and political disparity and encourage participation and engagement in access to the most essential commodity of life, that is, water.

David W. Gallaher (Co-I)

David Gallaher is a Senior Associate Scientist, Manager, Information Technology Services, National Snow and Ice Data Center (NSIDC), Cooperative Institute for Environmental Sciences (CIRES), University of Colorado, Boulder, CO. He has more than 30 years experience in Geosciences, IT technology and remote sensing. He has been with the National Snow and Ice Data Center in Boulder, Colorado since 2007 as the Technical Services Manager and Project Scientist Principle Investigator. He has served in a variety of remote sensing roles with NASA, DOE, DOD, NSF, state, local government and the private sector.

Professional Preparation:

B.S., Geology, University of Illinois, 1979
M.S., Geology, Northern Arizona University, 1984

Appointments:

PI/IT Manager, National Snow and Ice Data Center, Boulder, CO, 2007-present
IT Director, City of Boulder, Boulder, CO, 2005-2007
IT Development Manager, Jefferson County, Golden, CO, 1995-2005
Manager GIS, Advanced Sciences Incorporated, San Diego, CA, 1992-1995
Manager GIS, Petroleum Information Corporation, Littleton, CO, 1988-1992
Systems Analyst, Exxon USA, Denver, 1984-1988

Selected Publications and Presentations:

1. Gallaher D., G. Campbell, W. Meier, J. Moses, D. Wingo, 2015: The Process of Bringing Dark Data to Light: The Rescue of the Early Nimbus Satellite Data. *GeoResJ*. doi:10.1016/j.grj.2015.02013
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6. Meier, W.N., D. Gallaher, and G.G. Campbell, 2013: New estimates of Arctic and Antarctic sea ice extent during September 1964 from recovered Nimbus I satellite imagery. *Cryosphere* No.: tc-2012-187
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SMAP Utilization in Flood Forecasting, Crop Production, and Irrigation Management in the Indus River Basin

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Research Interests

◦ **Disciplines:** applied mathematics; systems & control;
◦ **Focus Areas:** water systems analysis; agricultural robotics;

Education

◦ PhD in Electrical Engineering, Georgia Institute of Technology, USA, 2005
◦ MS in Mathematics, Georgia Institute of Technology, USA, 2005
◦ MS in Electrical & Computer Engineering, Georgia Institute of Tech. 2002
◦ BSc in Electrical Engineering, UET, Lahore, Pakistan, 2000

Academic appointments

◦ **Assistant Professor of Electrical Engineering** *Nov 2008–present*
LUMS School of Science & Engineering, Pakistan
◦ **Acting Chair of Electrical Engineering Department** *April 2009–Feb 2010*
LUMS School of Science & Engineering, Pakistan *Sept 2014–Dec 2014*
◦ **Postdoctoral Research Fellow** *Nov 2007–Nov 2008*
Quantum Information Processing Group *and*
Center for Intelligent Machines (CIM), McGill University, Canada
◦ **Postdoctoral Researcher** *Jan 2006–June 2007*
General Robotics, Sensing & Perception Lab,
(GRASP), University of Pennsylvania,

Recent Selected Publications (Related to Water & Sustainability)

1. Ch.Ammad Rehmat, Abubakr Muhammad, Naveed ul Hassan, ”A Model Driven Frame- work for Risk Mitigation in Irrigation Networks”. Climate Change in Pakistan, IDRC-CRDI Working Paper Series #2, 2014.
2. Zahoor Ahmad and Abubakr Muhammad, ”Low Power Hydrometry for Open Channel Flows”, 40th Annual Conference of the IEEE Industrial Electronics Society (IECON), Dallas, USA, 2014.
3. Zahoor Ahmad, Ehsan U. Asad, Abubakr Muhammad, Waqas Ahmad and Arif Anwar, ”Development of a Low-Power Smart Water Meter for Discharges in Indus Basin Irrigation Network”, Wireless Sensor Networks for Developing Countries, Springer Communications in Computer and Information Science (CCIS), Volume 366, 2013.
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