USE OF SATELLITE REMOTE SENSING IN HYDROLOGICAL PREDICTIONS IN UNGAGED BASINS

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Abstract
Ungaged basins pose a challenge to hydrological studies as they lack both calibration and validation data for the use of land surface models. Therefore, one has to use the satellite data that is available which describes the aspects/attributes of the basin from a hydrological perspective. Soil moisture is routinely mapped by the Advanced Microwave Scanning Radiometer (AMSR). Vegetation is characterized by MODIS (Moderate Resolution Imaging Spectroradiometer) and surface temperature is estimated using AIRS (Advanced Infra-Red Sounder) as well as MODIS. Precipitation is measured (in the tropical regions) from the TRMM (Tropical Rainfall Measuring Mission) Microwave Imager (TMI) with the Global Precipitation Mission (GPM) due to be launched in a few years. The synergistic use of these data sets along with hydrological models would help us to (a) input precipitation and vegetation information into a hydrological model and calculate the soil moisture and surface temperature using the water and energy balance equations (b) the measured soil moisture and surface temperature can be used in two ways (i) to calibrate certain model parameters (ii) to verify the output of the model through validation. The overland runoff from the hydrological model would be routed in the stream channel network (obtained from the Digital Elevation Data) to obtain the streamflow at the catchment outlet. This would help in estimation of the water resources for the watershed. This paper will describe the state of the art knowledge in combining remote sensing, hydrological modeling and data assimilation.

1.0 Introduction

Land surface hydrology is an accounting of the water received (precipitation) and water lost (evaporation, runoff from land, streams to oceans) and the gain in water storage (rise in level of inland water bodies, increase in soil moisture, snow and, rise in water table). This accounting is based on a simple water balance principle, i.e. a conservation of mass. However, as evapo-transpiration (loss of water due to evaporation from the land surface and loss of water from the plant stomata due to transpiration) involves energy, the hydrological budget involves a coupled water and energy balance.

However, quantification of the hydrological budget is extremely difficult over large spatial domains and over large time periods through direct observations as in-situ observations are labor intensive as well as expensive. *This is specifically the case in un-gauged basins wherein stream flow data are absent or insufficient and little or no observations of spatially variable hydrological quantities are carried out. This makes it extremely difficult to carry out hydrological modeling for predictions of water resources.* Satellite remote sensing provides a methodology to overcome these issues with a broad spatial coverage and a repeat temporal coverage.

Of the hydrological variables derived using satellite data, precipitation (both by radar and satellites) is perhaps the one most extensively studied. Precipitation patterns are highly variable in space and time. Exclusive dependence on remotely sensed precipitation would not result in an adequate characterization of the state of the watershed in order to estimate stream flow as land areas exhibit heterogeneities in soils, topography, roughness and vegetation. *Therefore, a simple translation of rainfall into runoff is not possible so there is a need to utilize the readily available satellite images of other hydrological variables such as – soil moisture, surface temperature, vegetation, air temperature along with those of precipitation.*

In this paper, we describe the various satellite data sets that can be used to generate land surface hydrological variables followed future challenges and limitation to the use of satellite remote sensing in the context of PUB.

2.0 Satellite Data sets and their role in land surface hydrology.

This section of the paper describes the different data sets that are used in land surface hydrological research. References provide more complete documentation on satellite data products, their accuracy, spatial and temporal resolution and applicability. *In hydrology, soil moisture, precipitation, runoff, evaporation (through air temperature and surface humidity), transpiration (similar to evaporation, plus added vegetation content), surface temperature, incoming short and long wave radiation*

(using the atmospheric temperature and humidity profile, cloud fraction) can be observed/inferred directly or indirectly via remote sensing (also see Figure 1). We describe in detail some of these variables below.

Vegetation is characterized using the Normalized Difference Vegetation Index (NDVI), a ratio of the difference and the sum of the visible (0.55-0.68μm) and near-infrared (0.725-1.10μm) radiances measured by the Advanced Very High Resolution Radiometer (AVHRR) (Tucker, 1979, Goward et al. 1994). Currently, the vegetation index is measured by the MODIS - Moderate Resolution Imaging Spectroradiometer on the TERRA (1030am/pm overpass) and AQUA (130am/pm overpass). The NDVI can be converted into leaf area index (LAI) using a Beer's Law (for exponential decay) as in Baret and Guyot (1991). MODIS has many more channels and much higher spectral and spatial resolution than AVHRR (Justice et al, 2002). *Vegetation plays a role in the land surface hydrology, indirectly by (a) Providing a shadow effect on the ground for direct solar radiation (b) Interception of precipitation (c) Transpiration by canopy (d) Changes the roughness and aerodynamic resistance of the surface for latent and sensible heat fluxes*

Vegetation data is available at spatial resolutions of 100s of meters. This may be inadequate for small basin studies. Additional higher spatial resolution data sets may be available from commercial satellite sensors (such as SPOT, IKONOS and LANDSAT TM).

In the case of **soil moisture**, the microwave frequencies respond best to the variations in moisture content due to the polar nature of the water molecule. With the launch of the AQUA satellite (June 2002) and ADEOS II (December 2002), the data from the Advanced Microwave Scanning Radiometer (AMSR) is becoming available at two equatorial overpass times (130 am/pm - AQUA and 1030 am/pm – ADEOS II) (Njoku et al. 2003). The retrieval algorithms for AMSR soil moisture include Jackson (1993) and Njoku and Li (1999). The C-band of the AMSR (6.9 GHz) has a better sensitivity than the 19.4GHz channels of the SSM/I to retrieve soil moisture. In the past soil moisture has been measured from space using the Special Sensor Microwave Imager (SSM/I) with the 19, 37 and 85 GHz channels (Lakshmi et al. 1997a, b, c, Jackson, 1997). This sensitivity is the maximum at lower frequencies (L-band: 1.4 GHz and C-band: 6.9 GHz) and decreases as the frequency of observation increases due to increased contribution from the atmosphere and vegetation. *Soil moisture reflects the net land surface reaction to precipitation, infiltration, runoff and evapotranspiration.*

Spatial resolution of soil moisture (50km) is inadequate for basin scale studies. Future microwave soil moisture remote sensing missions improve the spatial resolution to around 10 km, even so, this is yet inadequate for basin scale studies. Therefore, soil moisture data derived from satellite remote sensing needs to be used as a qualitative reference in the region in and around the basin. Research for disaggregation/decomposition of large soil moisture pixel data to higher spatial resolution using other sensors (viz., vegetation data) is currently underway.

Surface temperature has been derived using the AVHRR (Price, 1984, Becker and Li, 1990); TOVS (TIROS Operational Vertical Sounder – Susskind et al. 1997); AIRS (Advanced Very High Resolution Radiometer - Susskind et al. 2003); MODIS (Moderate Resolution Imaging Spectroradiometer - Justice et al. 2002) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer **-** Gillepsie et al. 1998, Schmugge et al 1998). The energy emitted in the thermal channel that is observed by these sensors is directly related to the surface temperature. *Surface temperature is directly related to the energy balance and the water budget, viz., increased evapotranspiration lowers the surface temperature.* Surface temperature is currently observed at high spatial resolutions (90m) and can be readily used at the catchment scale to understand the thermal response of the catchment to radiation and evapotranspiration via the energy budget.

Surface air temperature can be derived from the TOVS (TIROS Operational Vertical Sounder – Susskind et al 1997) and AVHRR (Advanced Very High Resolution Radiometer - Prince et al 1998). More recent data are available from AIRS (Advanced Infra-Red Sounder - Susskind et al 2003) as a Level 2 core product. *The surface air temperature plays a dominant role in the determination of sensible heat flux by the difference through the difference in the land surface and the surface air temperature.*

Even though the air temperature is observed at coarse (50km) scales, the low spatial variability of air temperature over larger scales of 10s of km makes these measurements valid at the catchment scale.

Precipitation is measured in the microwave region by the SSM/I, AMSR and TMI (Tropical Rainfall Measuring Mission Microwave Imager). The microwave frequency responds to the falling hydrometeors and this response can be translated into a rainfall rate.

Variable	Sensor	Spatial Resolution	Temporal Resolution	Period of Record	Reference
Leaf Area Index	AVHRR	8 or 16 km	Bi-weekly	1980-Present	Goward
	MODIS	500m-1km	Bi-weekly	1999-present	Justice
Soil Moisture	SSM/I	50km	2/day	1987-present	Lakshmi,1997a
	AMSR	50km	2-4/day	2002-present	Njoku, 1999
Surface Temperature	ASTER	90m	On-request	2000-present	Gellipse
	MODIS	500m-1km	2-4/day	2000-present	Justice
	AVHRR	1-5 km	1-8 day	1980-present	Becker
	TOVS	1 °	2/day	1980-Present	Susskind, 1997
	AIRS	50km	2/day	2002-Present	Susskind, 2003
Surface Air Temperature	TOVS	1°	2/day	1980-present	Susskind, 1997
	AIRS	50km	2/day	2002-present	Susskind, 2003
Precipitation	TRMM	20km	Daily	1998-present	Kummerow, 2000
	SSM/I	50km	Daily	1987-present	Ferraro, 1997
	AMSR	50km	Daily	2002-present	Wilheit, 2003

Table 1. Remotely sensed data used in land surface hydrology

Precipitation is perhaps the most important variable in land surface hydrology. In the absence of, or inadequate number of stream gauges, the discharge at a watershed outlet is limited by the amount of precipitation on the watershed. Since precipitation is highly variable in space (scales of 1-2km), and time (scales of < 30minutes), accurate spatial and temporal measurements of rainfall are desired. Most ungauged (discharge) catchments suffer from a lack of or inadequate number of rain gauges. Therefore, remote sensing offers an alternative solution. However, satellite remote sensing yields products with low spatial (10-20km) resolution and temporal repeat (1-2 day revisit). However, weather radars have a much better spatial resolution (1-2km) and temporal revisit times (15-30 minutes). This would greatly enhance hydrological forecasting as well as decrease the prediction uncertainty of ungauged basins.

3.0   Future Challenges and applicability to PUB
We have a wealth of satellite data at various spatial scales, and different temporal resolutions that can be used in putting together a complete picture of the land surface hydrological cycle. Figure 1 represents both the wealth of data and the dilemma on its usage. It remains as a challenge to the scientific community to reconcile these issues and use this data in the most synergistic methodology possible to help in our endeavor to predict fluxes in ungauged basins.

The broad scientific objectives of PUB (as stated in the PUB Science Plan) which can be answered by satellite remote sensing are-

1. *Advance the ability of hydrologists worldwide to predict the fluxes of water and associated constituents from ungauged basins, along with estimates of the uncertainty of predictions;*

Prediction of fluxes of water by using vegetation, surface air temperatures as inputs to hydrological models and surface temperature and soil moisture as validation variables in the intermediate step to calculation of overland flow and stream flow.

2. *Advance the knowledge and understanding of climatic and landscape controls on hydrological processes to constrain the uncertainty in hydrologic predictions;*

Spatial mapping of land surface areas helps to identify regions of saturation/high vegetation content along with surface flow characteristics, viz., infiltration dominated and/or runoff dominated

3. *Demonstrate the value of data for hydrologic predictions, and provide a rational basis for future data requirements, by investigating links between data and predictive uncertainty;*

Key progress in the future will be accomplished by synergism of observational data and modeling. Specifically, altimetry-based systems that can observe surface water heights (Alsdorf et al., 2003) can be used along with stage-discharge curve to validate stream flow measurements in remote, ungauged areas and the difference between the two estimates (model versus satellite observations) can serve as a basis for data assimilation

4. *Advance the scientific foundations of hydrology, and provide a scientific basis for sustainable river basin management.*

Future estimation of water resources requires an accurate prediction of sources of surface and subsurface water, both of which can be mapped in space with the use of satellite remote sensing. Tracking fresh water estimates from space is a challenging problem that can be solved by a combination of satellite sensors (currently under research and development) and existing gauge

networks (Alsdorf and Lettenmaier, 2003). Indeed, prediction of ungauged water resources is fast becoming a well-defined and important problem in satellite hydrology.

Therefore it is apparent that the use of remotely sensed data is severely limited for most small-scale basins with areas less than a few km2. Most hill-slope scale processes, viz., 10-1000m^2 cannot benefit from the current generation of satellite or radar data due to coarse spatial resolution. However, medium sized basins, viz., 10-100km^2 can use most of the satellite and radar data sets (with the exception of the 50km soil moisture). Larger basins (100-10,000km^2) are perfect locations for use of satellite and radar data as they will have multiple pixel coverage. Since these basins are "large", remotely sensed data will help in "bridging" the existing (may be insufficient) observations on the ground. In the future, as technology improves, and satellite sensor resolutions become higher (<100m), smaller basins can also be observed from space.

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CLOSING THE TERRESTRIAL WATER BUDGET USING REMOTE SENSING

$$\Delta W/\Delta t = E + T - P - \text{div } Q$$

Atmospheric Water Balance

Rn Radiation
Shortwave GOES
Longwave AIRS/AMSU

H, G Surface Temperature
AIRS, AVHRR, MODIS

Clouds GOES
Water Vapor (LE)
AIRS/AMSU

The land surface
water and energy
budgets are linked
via evapotranspiration

AIRS/AMSU

P

T

q

T

E

ΔZ θ

Water table

R

Groundwater flux

θ Soil Moisture *Microwave*
AMSR, SMOS, HYDROS*

P Precipitation *Microwave*
TRMM/TMI, SSM/I, GPM

E Evaporation/Surface Humidity
Infrared/Microwave
AIRS/AMSU

T Transpiration/NDVI *Visible/NIR*
MODIS, AVHRR, GLI, VCL

R Runoff/River Level *Laser*
HYDRASAT*, TOPEX

* Planning Phase

Energy Balance

$$Rn + H + LE + G = 0$$

Water Balance
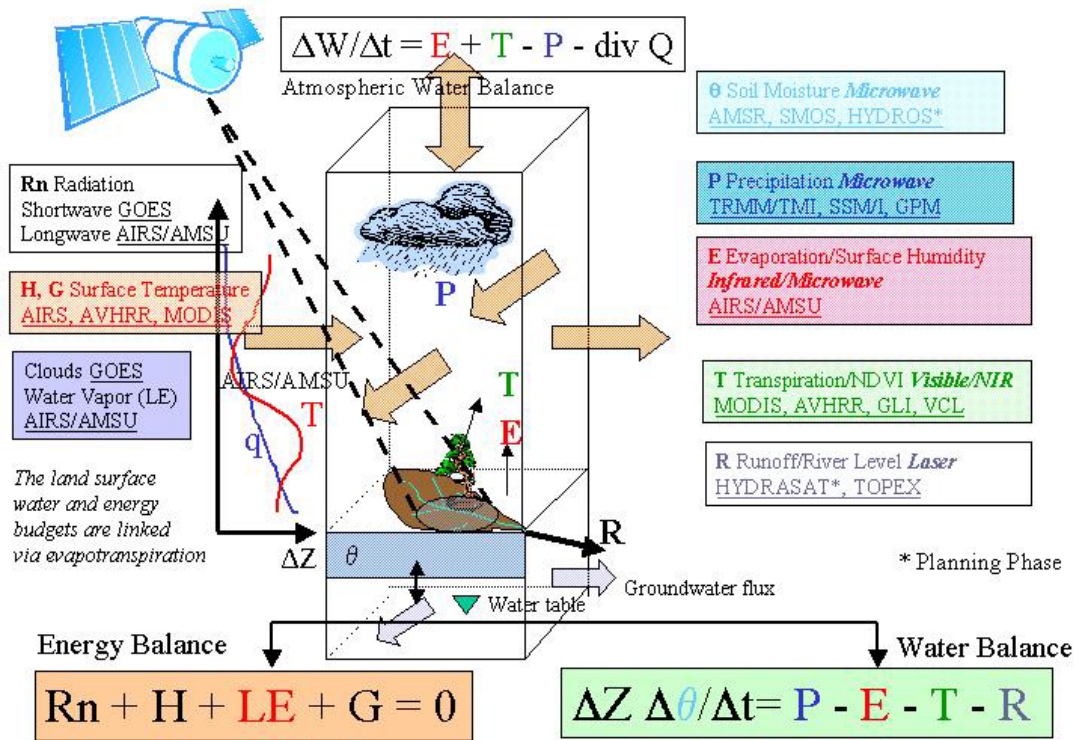
$$\Delta Z \, \Delta\theta/\Delta t = P - E - T - R$$

Figure 1 Satellite data in the land surface hydrological cycle

The land surface hydrological cycle responds to changes in the moisture stores and the fluxes. Specifically, the satellite sensors detect changes in the stored moisture, either in the atmosphere (In terms of atmospheric water vapor profile) or in the soil as in soil moisture or in lakes/ponds or rivers as changes in water level. These changes are modulated by vegetation changes that are observed by numerous satellite sensors.

The different variables of the hydrological cycle can be sensed using single or a combination of sensors on various satellite platforms. It should be the object of the Hydrologic Information Systems to combine information from various sources in a synergistic fashion, spanning across differing spatial resolutions and temporal repeats to piece together the entire, land-atmosphere hydrological cycle.

With the advent of numerous EOS-era sensors, we will have access to multiple sensors for the same variable. It will therefore be a challenge to catalog these data sets in a proper fashion for usage.

The model for use of satellite data would be the derived product rather than the raw radiances or brightness temperatures or backscatter values. This would overcome the problem for individual investigators to undertake retrieval algorithms and used standardized algorithms for the hydrologic community.

Satellite data represent a wealth of information. These bridge the gap between point measurements and computer based simulations. Properly utilized, the satellite data would be of great benefit to the hydrological community.