Hydrology With Unmanned Aerial Vehicles (UAVs)

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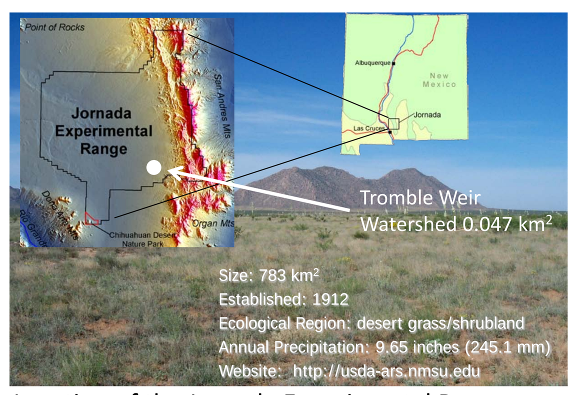
Introduction

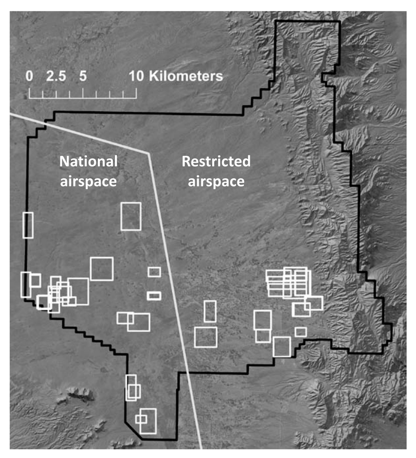
Hydrological remote sensing often relies on operational satellite products that require expensive and infrequent aircraft observations as well as ground-based measurements for validation. As data from new, hydrologically-relevant satellite missions, such as, the Soil Moisture Active-Passive (SMAP) mission (launch date 11/2014) and the Landsat Data Continuity Mission (LDCM) (launch date 12/2012) become available, there is a pressing need for more frequent and less expensive techniques for validating satellite retrievals that can also be integrated with ground sensor networks. In the case of LDCM, the major advantage is that this coverage can be linked to an enormous Landsat database extending back to 1972. UAVs can provide such information at intermediate to high resolution data, collect detailed and versatile spatial coverage, and fill gaps between the ground sensors and satellite coverage at considerably less expense than manned aircraft.

Location of Test Sites

The primary test site is at the USDA-ARS-Jornada Experimental Range north of Las Cruces, NM. The advantages of this test site include that it is virtually unsettled, has little air traffic, possesses a long period of record (approx. 100 years), has over 6,000 aerial photos from 1936-present and numerous satellite images, such as, Landsat and ASTER, due to persistent clear skies. We are able to fly our UAVs there in the FAA National Airspace system thanks to our MOU with New Mexico State's Physical Science Lab Flight Test Center and in Restricted Military Airspace of the White Sands Missile Range. Because the two types of airspace are present at Jornada, we have become adept at flying in both the National Airspace and Restricted Airspace. We have also flown at test sites in Idaho and Arizona. The Jornada has also worked closely with the USDA-NRCS to install a Soil Climate Analysis Network (SCAN) site. Soil moisture is measured at 5 depths in 3 separate soil types. The Jornada also has a NOAA Climate and Reference Network (CRN) station and at least 3 other remotely telemetered soil moisture sites.



Location of the Jornada Experimental Range



Airspace at the Jornada Experimental Range, 783 km²

- Operated 2 BAT-3 UAVs since 2006
- Acquired >25,000 images, 75 image mosaics
- 5-6 cm pixel resolution
- Very little manned aircraft traffic is encountered in this remote area
- UAV flights in the National Airspace require FAA approval, and in Restricted Airspace the approval of White Sands Missile Range


USDA-NRCS soil and climate analysis network (SCAN) station at Jornada Experimental Range

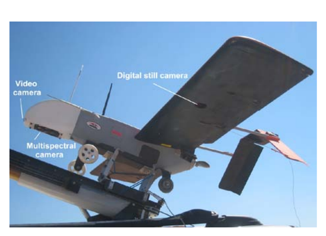
Characteristics of the Jornada UAVs

BAT 3 UAV (2 separate airframes)
- 1.8 m wingspan, 10 kg weight, 1.4 kg payload
- Flight duration: 2-5 hours
- Cost $48,000

Sensors
- Canon SD900 10 mp
- Tetracam MiniMCA, 6 narrow bands, blue to near infrared
- Daylight video

Image acquisition
- 215 m AGL
- 75% forward overlap, 40% sidelap for stereo analysis
- Data file: X,Y,Z, roll, pitch, heading


True color imagery


Multispectral + true color imagery

Then, what are the steps necessary to fly in FAA-NAS?

Steps in order to fly UAVs in the National Airspace System Under FAA Regulations

1. **Qualifications, Exams, Training** (Examples)
   - FAA Ground School (for external and internal pilots)
   - Second class or higher FAA airman's medical certificate
   - FAA Private Pilot's License (Pilot-in-Command)
2. **Application for Certificate of Authorization (COA)** (Examples)
   - Ownership of UAV by public government entity
   - Submit COA application with a 3-4 month waiting period
3. **Flying the UAV** (Examples)
   - Receive COA and fly according to all specifications in COA
   - Pre-flight planning to
     - establish home location coordinates for use after launch and in case of loss of link to UAV
     - establish flight pattern for travel to and from test site and for photography over test site with desired forward and sidelap; always maintain line-of-sight contact
   - Flight Mission
     - issue Notice to Airman (NOTAM) 48 hours before flight
     - conduct flight crew briefing before flight and de-briefing after flight
     - conduct airplane and control center checklists
4. **Documentation** (Example)
   - Update log books and keep complete records

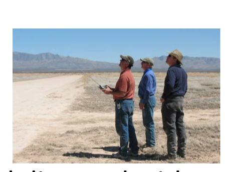
Catapult launch and radio control landing



Observers placed on perimeter of flight pattern looking for oncoming traffic and in contact with external pilot by radio


External pilot takes over manually on final approach because it results in a smoother landing


Sequence of Jornada Bat-3 smooth landing



What other things must be done?
- Grade a short runway which can only be 50 m and can just be a slightly improved dirt road without fencing on either side
- Line-of-sight must be maintained by the external pilot at all times, so if distance exceeds 1.1 km, we must move the external pilot. This is because we do not have sense-and-avoid capabilities

Outcome

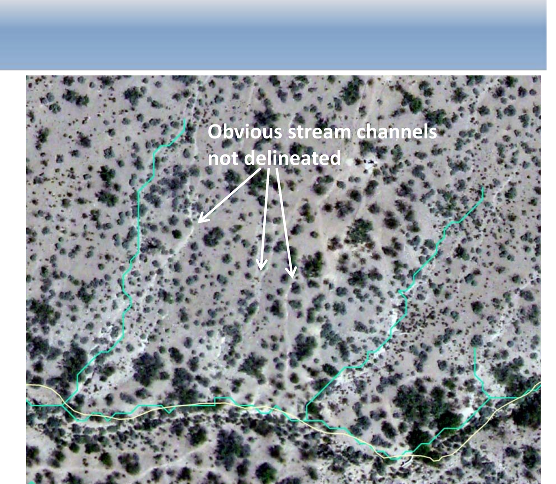
1. This method is legal but somewhat slow. It takes at least 4 times as long to get the data and much more time planning the missions, BUT, we get the data we need.
2. We now have a highly trained UAV flight crew who potentially can fly anywhere in the United States. Two of the crew have their FAA private pilot's licenses. The flight team has allowed us to be recognized as working on the cutting edge of civil UAV applications.
3. We are integrating different remote sensing approaches into the National Airspace System.
4. We have an operational system that can acquire UAV data over rangelands which make up 50-70% of the Earth's land cover.

Future plans involve the use of a larger UAV (Bat 4) with the following characteristics:
- Wingspan 4 m vs 1.8 m (more stable flight)
- Weight 45 kg vs 10 kg
- Payload 14 kg vs 1.4 kg
- Takeoff on wheels vs from catapult
- Significant room for additional instrumentation vs currently no additional space for new instruments

Products Available From UAV Data

- Ground survey drainage area = 56,988 m² (yellow)
- UAV DEM drainage area = 46,734 m² (blue)
- 22% difference
- Ground survey drainage density = 0.0128 (yellow)
- UAV drainage density = 0.032 (blue)

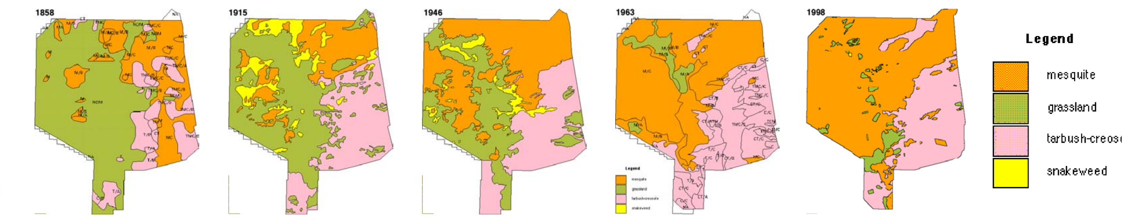
The products derived from UAV flights depend upon the sensors that can be flown. In most cases, video coverage is only useful for military or security applications. But, broadband camera coverage and multispectral camera coverage are very useful for hydrological, ecological, agricultural, and other civilian applications. Small UAVs can generally accommodate these types of cameras. The following products can result: mosaics covering entire watersheds; DEMs at 1m resolution; vegetation and land cover classification; and changes over time of environmental variables. Because UAVs can be programmed to re-fly the same locations at an optimum revisit interval, change detection at very high resolution can be accomplished. Ground surveys of the basin boundary and drainage network of the Tromble Weir watershed are shown in yellow, whereas the same properties are shown in blue as derived from UAV data. The UAV approach making use of overlapping stereo photography provides a much more detailed drainage basin and network.



Comparison of individual stream channels delineated by ground survey vs that determined by use of UAV DEM data show much more network detail with UAV data, but, even so, not all channels are located

Long Term Vegetation Record at Jornada

150 years of record documenting vegetation change is available at Jornada. Because early data were collected either from General Land Office records or field ground surveys, resolution is variable until most recently when aerial photography was employed (1998). With the addition of the UAV aerial photos, very high resolution is possible and repetitive flights can be made at any time. The Jornada is a NSF Long-Term Ecological Research site, a NSF NEON site, and an ARS Long-Term Agro-Ecosystem Research Network site.

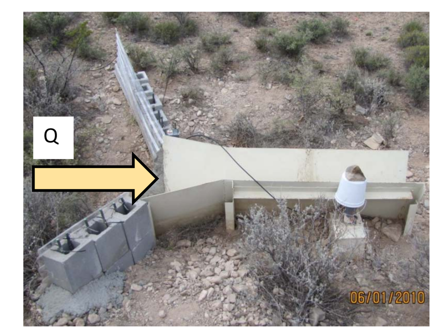


Broad-scale shift of dominant vegetation over 150 years at Jornada

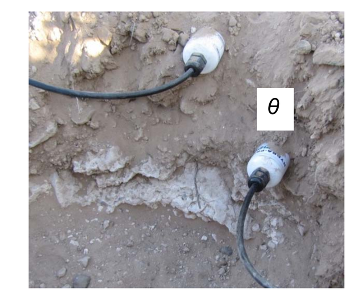
Possible Causes:
- climate change
- severe drought
- excessive grazing
- fire suppression

Ground-based Measurements and Vegetation Mapping

Rain gauges were installed for measuring basin input. A Santa Rita flume was used to measure basin output and three mini flumes were used to measure sub basin outputs. Soil moisture probes were used throughout the watershed to measure moisture variability with depth. An eddy covariance tower was used to measure flux variability. Classification of the vegetation was done using the UAV data as part of a regional classification using an object-oriented approach.
34% of the basin was covered by vegetation and 66% was bare soil. These values are very indicative of this part of the Chihuahuan Desert. It was noted that the vegetation types were not spread uniformly across the watershed. The most common shrub was mariola followed by mesquite and creosote. Combining the UAV DEM and vegetation classification capabilities allows more detailed information needed for input to hydrologic models such as tRIBS.
When comparing the UAV vegetation classification with the best field measurements employing the line-point intercept (LPI) approach, we have determined that the UAV vegetation classification is 78 to 98% accurate. When this approach was further compared to the LPI method in Idaho flights, it was concluded that the UAV approach was cost effective after only eight plots were measured. After those eight plots, the UAV saves money and effort in additional measurements in the region of interest.

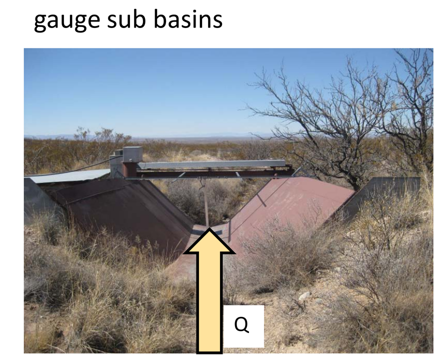


One of 3 installed miniflumes to gauge sub basins



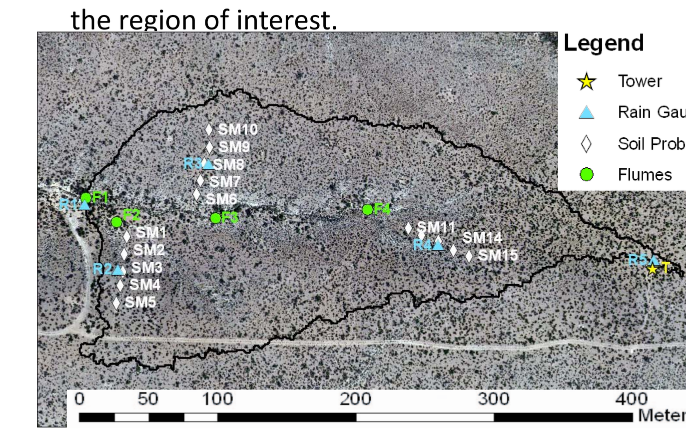
5- & 15-cm depth Hydra Probes with underlying caliche layer to measure soil moisture

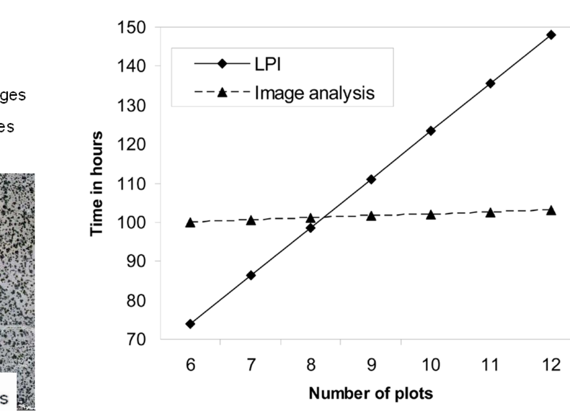
Eddy Covariance Tower to measure fluxes



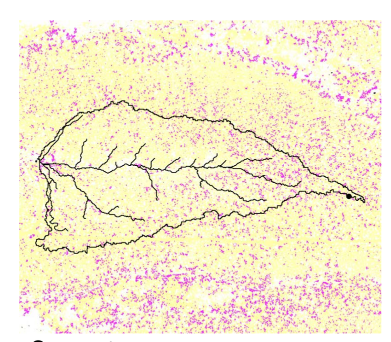
Outlet Flume at the Tromble Weir watershed

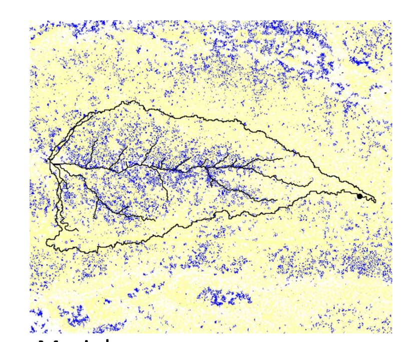
Tipping Bucket Rain Gauge

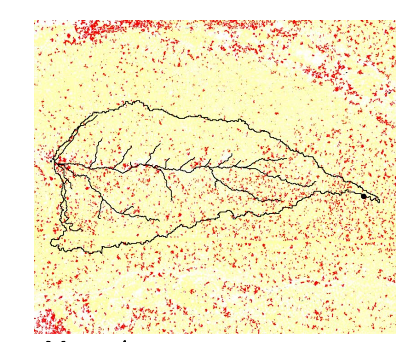




- 3 soil moisture/temperature transects with 5 sites per transect at 5, 15, and 30 cm
- 4 flumes, 5 rain gauges, and 1 eddy covariance tower

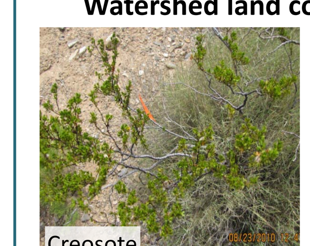

Creosote


Mariola


Mesquite

High resolution, UAV data classification shows that individual mesquite and creosote shrubs tend to prefer the flatter, deeper soil areas of the Tromble Weir basin, whereas the mariola shrubs prefer the steeper hillslope areas with more shallow soils.

Watershed land cover over the Tromble Weir watershed


Creosote


Mariola

- Historically a grassland, the watershed is now shrub dominated
- ~34% of the watershed is covered by vegetation
- Large shrubs (e.g. mariola, creosote, mesquite, and tarbush) account for ~80% of vegetation cover


Tarbush

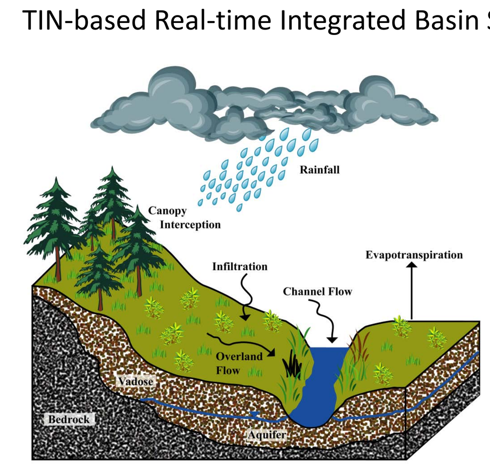

Mesquite

UAV Object-Oriented Classification

Vegetation	Type	% Cover
Tobosa Grass/Dropseed	Grass	1.40
Bush Muhley	Grass	2.89
Mesquite	Shrub	6.47
Tarbush	Shrub	2.48
Creosote	Shrub	5.82
Mariola	Shrub	11.9
Snakeweed	Shrub	1.82
Sumac	Shrub	1.15
Intercanopy	Bare soil	66.0

Hydrologic Measurements and Modeling are Ongoing as Work Continues 2012-2013

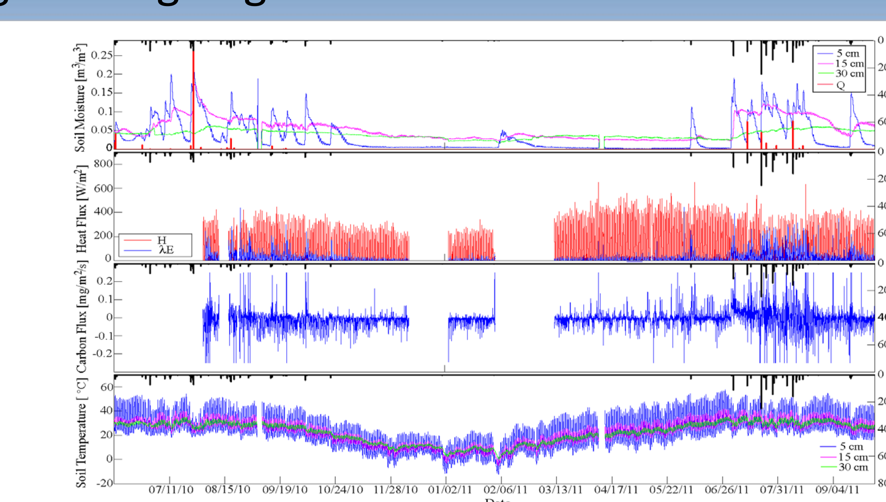
TIN-based Real-time Integrated Basin Simulator (tRIBS)



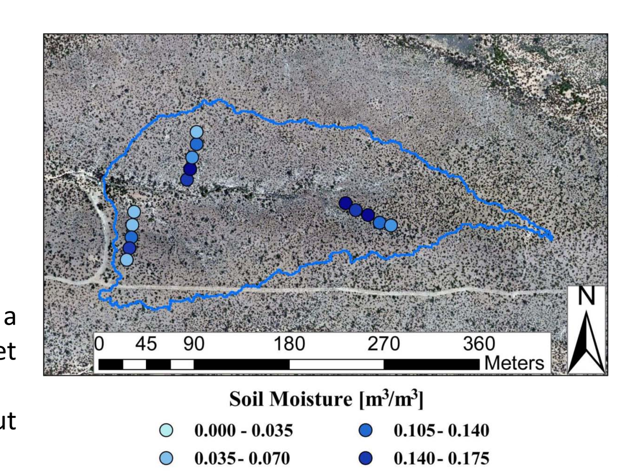
We are interested in merging high resolution UAV products into the TIN-based Real-time Integrated Basin Simulator (tRIBS), a fully-distributed watershed model. The goal is to incorporate into the simulation of the Tromble Weir basin the best-available information on topography and vegetation cover that has been derived from the UAV. Initially, the vegetation characteristics will be static in time, but as the model application continues, we plan on using multi-temporal images from the UAV.

tRIBS has the following characteristics that allow it to be applied for the Tromble Weir basin:
- Coupled water, energy and radiation fluxes
- Lateral soil moisture redistribution and runoff generation
- Detailed hillslope and channel representations
- Partitioning of ET from soil evaporation and plant transpiration

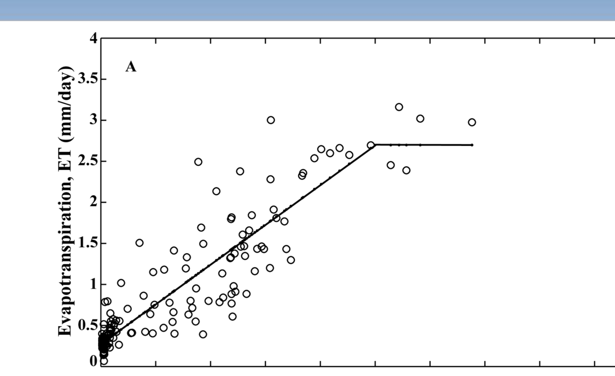
The application of the model will utilize the ground-based measurements for testing the soil moisture/temperature in a distributed fashion, the runoff at internal sites and the outlet flume, and the surface fluxes at the eddy covariance tower. UAV products can also be helpful in testing the model output if multispectral or thermal imagery could be utilized as proxies for soil temperature or moisture.

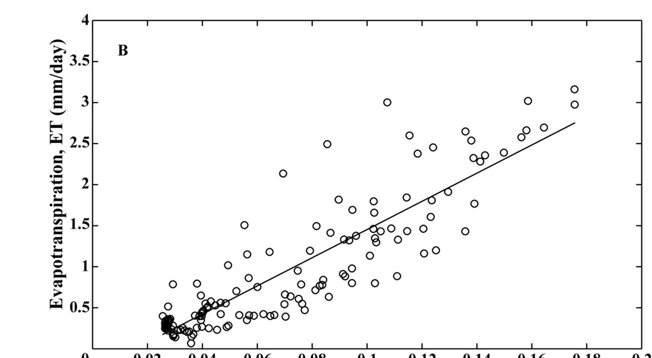


Ground-based measurements 2010-2011, 6/6/10-9/31/11 - The top image shows the spatially averaged 5, 15, and 30 cm soil moisture for the watershed; the 2nd image down shows the latent and sensible heat fluxes; the 3rd image down shows the carbon flux; and the 4th image shows the temporal dynamics of watershed averaged soil temperature for 5, 15, and 30 cm depths. Gaps indicate periods of equipment failure. The measurements will continue for 2012-2013.



We show the soil moisture distribution in the basin obtained as an average of the periods during four storm events in the summer of 2011 and at 5 cm depth. In the eastern most transect the spatial variations of soil moisture follow position along the hill slope. The tRIBS model outputs can be tested against the observed spatial patterns in soil moisture for storm events to generate confidence in the simulations. During storms, there are spatial variations in soil moisture as well as different meteorological forcings, and both can be used to test the model spatial predictions.





Here we are comparing all of the daily-averaged soil moisture at 5 cm depth from either: a) is a spatial average from all sensor locations (based on a weighting that uses elevation and aspect) and b) is the tower observation alone. Having said this, we expect an ET-soil moisture relationship that has a ramp shape (as this is typically used in modeling studies and from other empirical data). Observing the ramp shape in A suggests that the use of the spatial average is more appropriate than the use of the tower data alone. Again, the important point here is that we can test the model operating over the basin to see if it depicts the observed ET-soil moisture relation (as obtained in A).

Conclusions

UAVs provide a way to obtain frequent and affordable aerial coverage of study areas and to provide high-resolution data to fill in gaps in ground observation networks and between satellite coverage dates.
UAVs are well suited to providing detailed vegetation classifications, detailed DEMs, mosaics of entire watersheds, and inputs to both hydrological and rangeland health models.
By providing a detailed understanding of watershed states and changes with time, UAVs can be employed to validate upcoming products from satellite missions.

Acknowledgements: We appreciate the dedication of the Jornada Experimental Range field personnel and the UAV operations team and ASU graduate students Ryan Templeton and Cody Anderson.