Final Report

Project Title: Implementing the Hydroclimatic Index in Short- and Long-Term Drought Forecasting within the Colorado River Basin

Project Period: 6/4/2007 through 8/31/2010

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Complimentary Project: National Oceanic and Atmospheric Administration's (NOAA) Transition of Research Applications to Climate Services (TRACS) project no. NA07OAR4310455: Instituting Multi-scale Hydroclimatic Indices in Drought Monitoring and Mitigation in Arizona

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Project Overview

The project aimed to enhance the drought monitoring/forecasting tools available to decision-makers in Arizona and the Southwest United States by transitioning a new, effective, and easily understood drought index (now called the "Moisture Balance Drought Index" (MBDI)) into an operational form. The index contrasts precipitation with climatic demand for water across any geographic domain and it was to be used to specify the time periods most appropriate for monitoring different forms of drought in Arizona and across the Southwest to fill a knowledge gap identified by stakeholders. The index was to be generated on a fine-scale spatial resolution for the Colorado River Basin to yield a data base of historical data and a stream of operational data.

Current Status

During August 2010 we made the MBDI fully operational with a systematic monthly update procedure and implementation of an MBDI website, and we made further progress on validating the index. Since operational, we have been fine-tuning aspects of the website based on user feedback generated by a group of stakeholders organized by the Phoenix Area Office of the BOR and based on review by the project team. We are working on revisions to one research paper (water-related MBDI validation), and are in the process of drafting two other research papers (ecosystem-related MBDI validation; interactions with stakeholders). The Climate Assessment for the Southwest (CLIMAS) featured the MBDI in the August 2010 Southwest Climate Outlook (http://www.climas.arizona.edu/feature-articles/august-2010) or http://www.climas.arizona.edu/files/climas/pdfs/periodicals/SWClimateOutlook_Aug10.pdf).

Overview of Accomplishments

The project consisted of two phases, (1) data refinement and testing, and (2) transition to operations and extension. In the first phase, we generated MBDI data at fine spatial resolution (4 km), extended it to the entire Colorado River Basin, and validated the MBDI using water-related metrics (e.g., groundwater and reservoir levels, streamflow) and ecosystem metrics (e.g., acres burned by fire, and NDVI). In the second phase, we convened seven groups of resource managers and other potential MBDI users, and (a) briefed them on MBDI calculation, caveats and validation, and (b) garnered feedback on potential pitfalls and opportunities. We also developed a website and guidebook during the second phase, and from this we garnered feedback from the operational home of the MBDI, Arizona's State Climate Office, and from a group of Arizona water-users that was organized by the Phoenix Area Office of the BOR. We have published a peer-reviewed paper on the MBDI, we have submitted a second, and we are preparing a third, and possibly a fourth depending on the logic of combining two validation exercises. We have also given seven presentations about the MBDI at professional meetings, academic institutions, or stakeholder meetings.

Specific Accomplishments

Extension of the high resolution drought index to the Colorado River Basin. This task was completed using the Parameter-elevation Regressions on Independent Slope Model (PRISM), monthly, 4-km resolution data base from Oregon State University's Spatial Climate Analysis Service. The data are downloaded to a UNIX server at Arizona State University where the data are clipped to the area of the Colorado River Basin and manipulated to produce the MBDI and all of the various representations of drought based on the index for stakeholder benefit. A paper from this work was published in the *International Journal of Climatology* (Ellis et al., 2009 DOI: 10.1002/joc.1882).

Validation of Drought Index Efficacy. Water supply is the greatest drought impact variable of interest in Arizona and the Southwest, so the bulk of our validation effort has been focused on surface and ground water resources across the region. We used the popular precipitation-only Standardized Precipitation Index (SPI) and the MBDI, which balances precipitation with potential evapotranspiration, to assess the benefit of representing climatic demand within drought indices when considering hydrologic drought in the region. We evaluated time series of watershed runoff, reservoir storage, and groundwater level against time series of the drought indices, which were calculated for various timeframes to represent short-, intermediate-, and long-term conditions. For our comparative analyses we identified the timeframe for which each drought index explains the greatest amount of variability in each water resource variable.

We found that the SPI generally explains a greater percentage of the variance in runoff for the full historical record, but when focusing only on the dry one-half of the record the MBDI explains more of the variance for many of the basins that we studied. For reservoir storage, we found that the SPI best explains the historical variability for the larger capacity system of the two studied, especially during the cool season, but for the smaller capacity system the MBDI generally performs better, especially during the warm season. The MBDI explains a greater percentage of the variance in groundwater than the SPI at most of the well sites that we studied, although the two indices proved to be comparable in relating to groundwater. The results have led us to conclude that there is benefit to representing moisture balance in drought monitoring tools by including the temperature-driven climatic demand for water, especially given the recent and projected warming in Arizona and the Southwest. A manuscript that describes this work has been submitted to the peer-reviewed journal *Water Resources Research* and is currently under revision.

To validate the MBDI using shorter-term hydroclimatic impacts, we have completed evaluation of vegetation status data (Normalized Drought Vegetation Index (NDVI)) from collaborator Michael Crimmins (University of Arizona Cooperative Extension) and wildland fire data (acres burned and fire frequency data) from Tony Westerling, (University of California-Merced and California Applications Project). However, we have not yet completed writing up the results from these analyses. Our plan is to skip white-paper style reporting, and write up these results as a manuscript for peer review.

Transition of the MBDI for Operational Use. We established the beta-version of the MBDI website (http://azclimate.asu.edu/mbdi/) on the web page of the State Climatologist for Arizona (http://azclimate.asu.edu/) at the urging of State Climatologist Dr. Nancy J. Selover. Dr. Selover also serves as co-chair of the Arizona Drought Monitoring Technical Committee. The website contains comprehensive information about the MBDI, all of the validation results generated thus far, and interfaces that allow the user to select custom time frames and regions for displaying drought status and data (Figures 1-5). We continue to refine the website, and envision working with the State Climatologist to incorporate user suggestions for improvements to MBDI display, data, and website content.

Education, Outreach, and Feedback. In conjunction with the complimentary NOAA project, we conducted seven workshops during the course of the project, in order to introduce the MBDI to stakeholders, report back on MBDI validation, and to garner feedback on additional validation data, useful case studies, and potential use of the MBDI. We learned that the MBDI is less useful to urban water management professionals in Arizona, because their interests focus specifically on well-defined triggers associated with water supplies. They are not interested in drought *per se* and they rely on monitoring management trigger thresholds for reservoir and well levels. In contrast, ecosystem management stakeholders found the MBDI to be potentially valuable for monitoring drought conditions. Ecosystem managers expressed particular interest in connections between MBDI and: lightning occurrence, fire, NDVI, and wildlife habitat change. Several groups also expressed an interest in use of the MBDI for drought prediction, and for assessment of observed climate changes. During the last four months, we have received inquiries from The Nature Conservancy and Tohono O'odham Nation (Native American nation in southern Arizona) regarding potential operational use of the MBDI in monitoring and assessment. Recently, we received feedback from a group of Arizona water-users that was organized by the Phoenix Area Office of the United States Bureau of Reclamation and we have implemented changes to the web pages based on the feedback.

Plans for Further Work

We plan to make additional changes to the website, specifically to: upload the PDF version of the MBDI guidebook, improve graphic displays, update validation results, and update ancillary information (such as publications and presentations). We will continue to give presentations on the MBDI, and will work with the ADMC to incorporate MBDI as an indicator in considerations of weekly drought status reporting to the U.S. Drought Monitor. We will also complete manuscripts in progress and submit them for publication and two presentations are scheduled for the January 2011 meeting of the American Meteorological Society.

Outreach, Publications, and Presentations

<u>Workshops</u>

- Pima County Local Drought Impact Group, Tucson, AZ, December 10, 2008.
- East Valley Water Forum, Tempe, AZ, December 12, 2008.
- Society of American Foresters (Southern Arizona Chapter), Oro Valley, AZ, February 12, 2009.
- Natural Resource Working Group, Eagar, AZ, September 9, 2009.
- AGFD, Carefree, AZ, September 30, 2009.
- US Fish & Wildlife Service, Phoenix, AZ, October 6, 2009.
- East Valley Water Forum, Mesa, AZ, October 20, 2009.

<u>Presentations</u>

- A Hydroclimatic Index for Drought Monitoring. Arizona Drought Monitoring Technical Committee. July 2008.
- A Multi-Scale Hydroclimatic Index for Monitoring Drought in the Semiarid West. NOAA Climate Prediction and Applications Science Workshop. March 2009.
- Drought Index Verification in the Colorado River Basin, USA. Annual Meeting of the Association of American Geographers. March 2009.
- The Moisture Balance Drought Index and Efforts to Improve Drought Indicator Reporting. U.S. Drought Monitor Forum. October 2009.
- How Dry Is It? Satisfying the Growing Thirst for Drought Information. Department of Geography Seminar Series. Texas A&M University, College Station, Texas. October 2009.

• A Moisture Balance Drought Index for the Semiarid West. MTCLIM 2010 Biannual Conference, Consortium for Integrated Climate Research on Western Mountains. Blue River, Oregon. June 2010.
• How to Monitor Drought. Colloquium Series. School of Geographical Sciences and Urban Planning, Arizona State University. October 2010.
• Moisture Balance Drought Index For Monitoring Drought in the Colorado River Basin, Webinar, U.S. Bureau of Reclamation. November 2010.

Publications

• Ellis AW, Goodrich GB, Garfin GM. 2009. A Hydroclimatic Index for Examining Patterns of Drought in the Colorado River Basin. International Journal of Climatology. DOI: 10.1002/joc.1882.
• Ellis AW, Hawkins TW, Lenart M, Murphy KW, Garfin GM, Haws M. 2010. An Evaluation of Representing Climatic Demand in Drought Indices: Hydrologic Drought in the Southwest United States. Water Resources Research. In Revision.
• Garfin GM, Ellis AW, Lenart M. 2010. Working with stakeholders to evaluate a new index for drought monitoring and prediction. NOAA-NWS Science and Technology Infusion Climate Bulletin. (Manuscript in progress).
• Lenart M, Ellis AW, Crimmins M, Luo H, Garfin GM. 2010. Validation of the Moisture Balance Drought Index: Ecosystem Parameters. International Journal of Climatology. (Manuscript in progress).
• Lenart M, Ellis AW. 2010. Introducing the Moisture Balance Drought Index. Southwest Climate Outlook (August 2010). http://www.climas.arizona.edu/files/climas/pdfs/feature-articles/2010_aug_moisturebalance.pdf

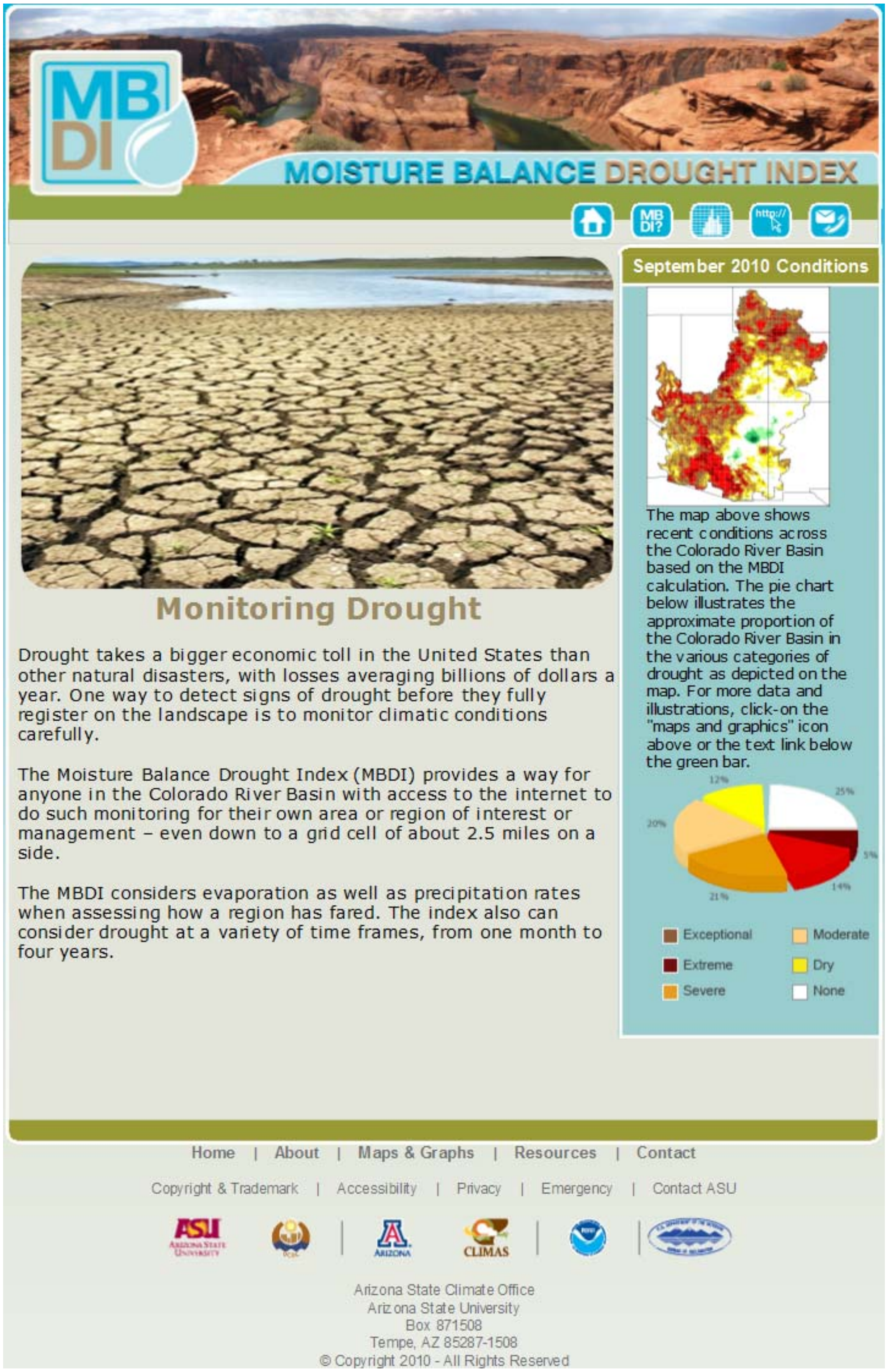
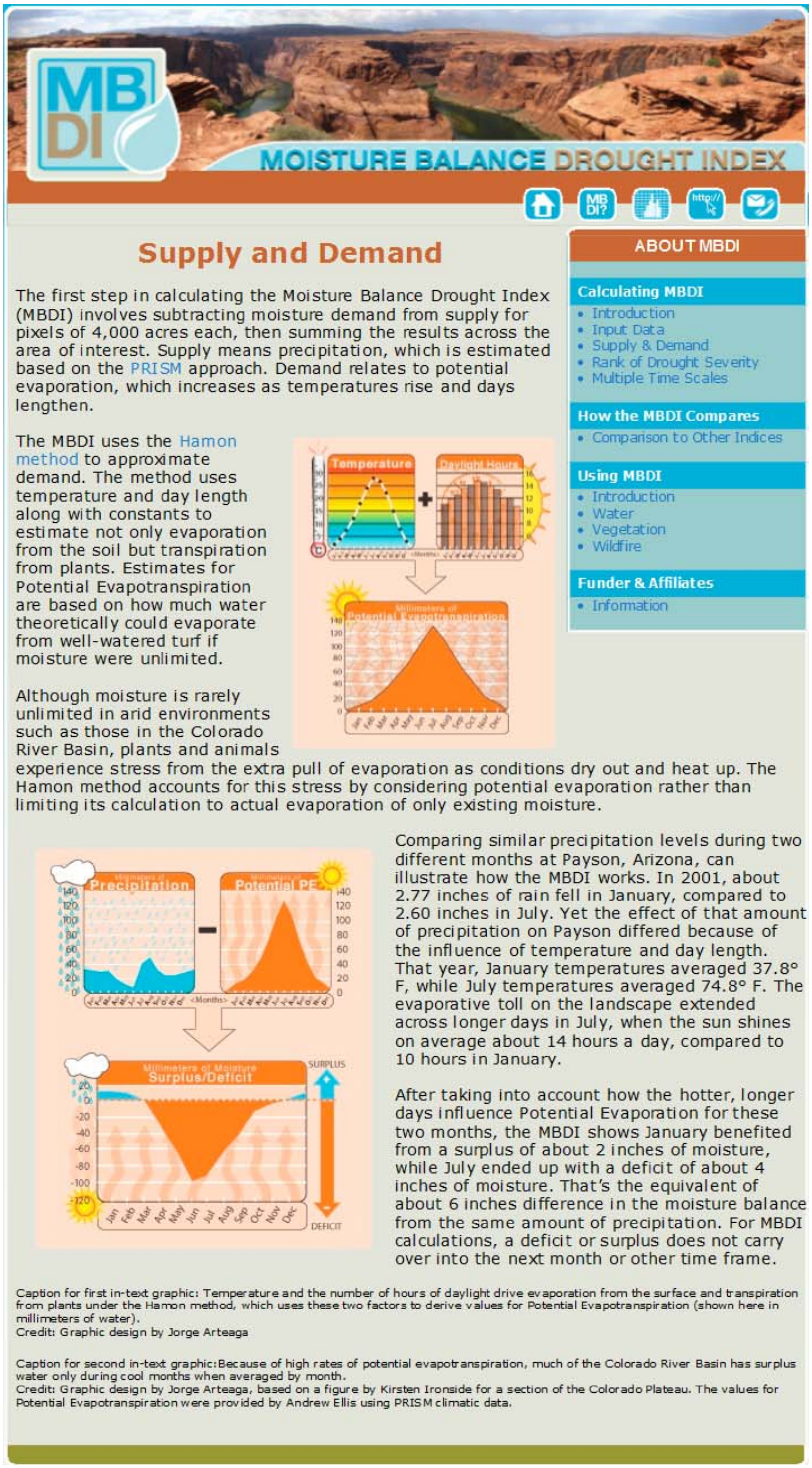


Figure 1. MBDI website home page. The website displays maps of current MBDI drought status, time series of recent MBDI values for the Colorado River Basin and sub-basins across Arizona, and percentages of the Colorado River Basin and Arizona sub-basins in U.S. Drought Monitor categories as determined by the MBDI. http://azclimate.asu.edu/mbdi/


MOISTURE BALANCE DROUGHT INDEX

Supply and Demand

The first step in calculating the Moisture Balance Drought Index (MBDI) involves subtracting moisture demand from supply for pixels of 4,000 acres each, then summing the results across the area of interest. Supply means precipitation, which is estimated based on the PRISM approach. Demand relates to potential evaporation, which increases as temperatures rise and days lengthen.

The MBDI uses the Hamon method to approximate demand. The method uses temperature and day length along with constants to estimate not only evaporation from the soil but transpiration from plants. Estimates for Potential Evapotranspiration are based on how much water theoretically could evaporate from well-watered turf if moisture were unlimited.

Although moisture is rarely unlimited in arid environments such as those in the Colorado River Basin, plants and animals experience stress from the extra pull of evaporation as conditions dry out and heat up. The Hamon method accounts for this stress by considering potential evaporation rather than limiting its calculation to actual evaporation of only existing moisture.

Comparing similar precipitation levels during two different months at Payson, Arizona, can illustrate how the MBDI works. In 2001, about 2.77 inches of rain fell in January, compared to 2.60 inches in July. Yet the effect of that amount of precipitation on Payson differed because of the influence of temperature and day length. That year, January temperatures averaged 37.8° F, while July temperatures averaged 74.8° F. The evaporative toll on the landscape extended across longer days in July, when the sun shines on average about 14 hours a day, compared to 10 hours in January.

After taking into account how the hotter, longer days influence Potential Evaporation for these two months, the MBDI shows January benefited from a surplus of about 2 inches of moisture, while July ended up with a deficit of about 4 inches of moisture. That's the equivalent of about 6 inches difference in the moisture balance from the same amount of precipitation. For MBDI calculations, a deficit or surplus does not carry over into the next month or other time frame.

Caption for first in-text graphic: Temperature and the number of hours of daylight drive evaporation from the surface and transpiration from plants under the Hamon method, which uses these two factors to derive values for Potential Evapotranspiration (shown here in millimeters of water).
Credit: Graphic design by Jorge Arteaga

Caption for second in-text graphic: Because of high rates of potential evapotranspiration, much of the Colorado River Basin has surplus water only during cool months when averaged by month.
Credit: Graphic design by Jorge Arteaga, based on a figure by Kirsten Ironside for a section of the Colorado Plateau. The values for Potential Evapotranspiration were provided by Andrew Ellis using PRISM climatic data.

ABOUT MBDI

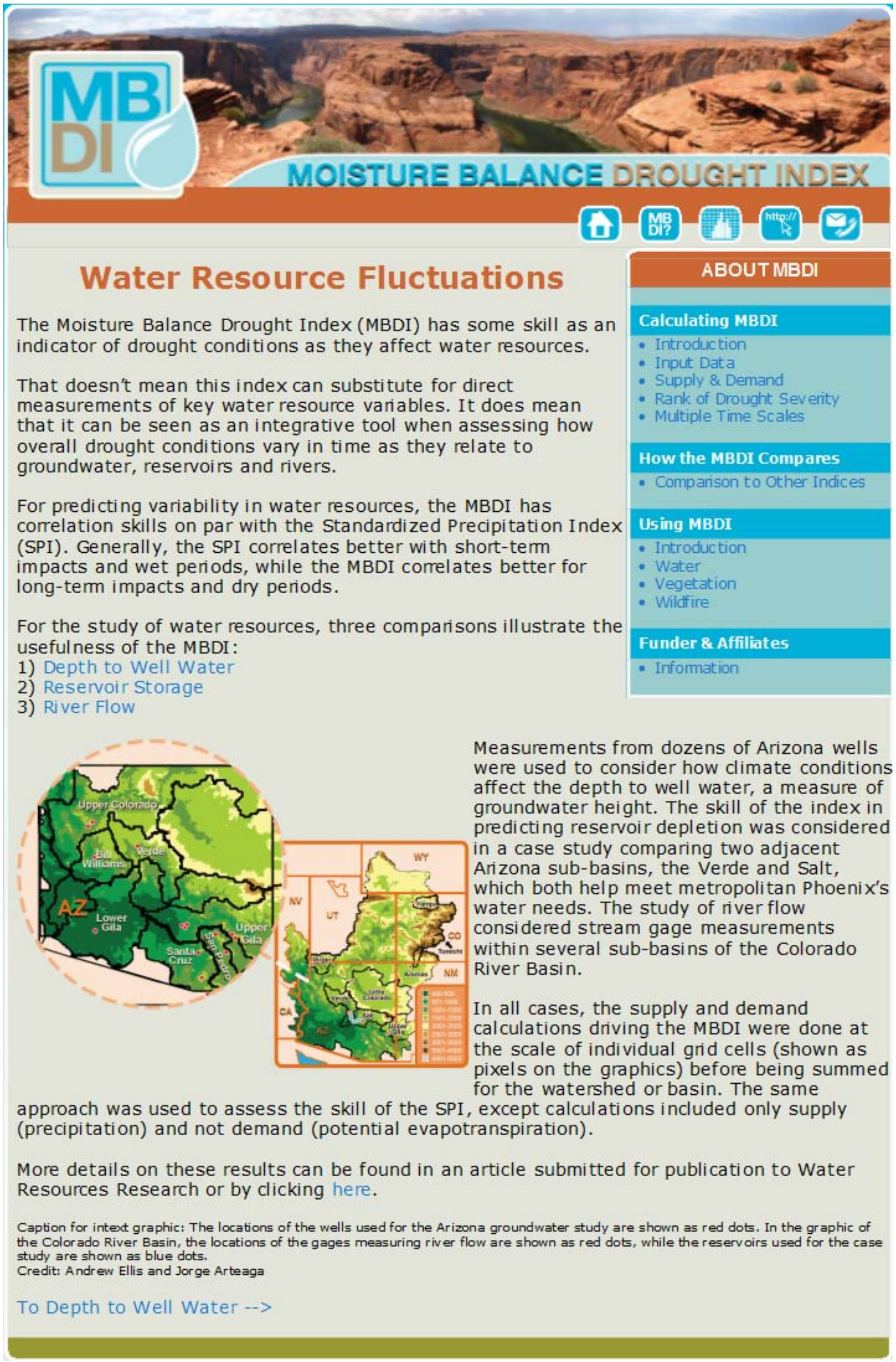
Calculating MBDI
- Introduction
- Input Data
- Supply & Demand
- Rank of Drought Severity
- Multiple Time Scales

How the MBDI Compares
- Comparison to Other Indices

Using MBDI
- Introduction
- Water
- Vegetation
- Wildfire

Funder & Affiliates
- Information

Figure 2. MBDI website Supply and Demand page. Other pages explain various aspects of MBDI calculation, in terms that can be comprehended by an interested layperson.



MOISTURE BALANCE DROUGHT INDEX

Water Resource Fluctuations

The Moisture Balance Drought Index (MBDI) has some skill as an indicator of drought conditions as they affect water resources.

That doesn't mean this index can substitute for direct measurements of key water resource variables. It does mean that it can be seen as an integrative tool when assessing how overall drought conditions vary in time as they relate to groundwater, reservoirs and rivers.

For predicting variability in water resources, the MBDI has correlation skills on par with the Standardized Precipitation Index (SPI). Generally, the SPI correlates better with short-term impacts and wet periods, while the MBDI correlates better for long-term impacts and dry periods.

For the study of water resources, three comparisons illustrate the usefulness of the MBDI:
1) Depth to Well Water
2) Reservoir Storage
3) River Flow

Measurements from dozens of Arizona wells were used to consider how climate conditions affect the depth to well water, a measure of groundwater height. The skill of the index in predicting reservoir depletion was considered in a case study comparing two adjacent Arizona sub-basins, the Verde and Salt, which both help meet metropolitan Phoenix's water needs. The study of river flow considered stream gage measurements within several sub-basins of the Colorado River Basin.

In all cases, the supply and demand calculations driving the MBDI were done at the scale of individual grid cells (shown as pixels on the graphics) before being summed for the watershed or basin. The same approach was used to assess the skill of the SPI, except calculations included only supply (precipitation) and not demand (potential evapotranspiration).

More details on these results can be found in an article submitted for publication to Water Resources Research or by clicking here.

Caption for intext graphic: The locations of the wells used for the Arizona groundwater study are shown as red dots. In the graphic of the Colorado River Basin, the locations of the gages measuring river flow are shown as red dots, while the reservoirs used for the case study are shown as blue dots.
Credit: Andrew Ellis and Jorge Arteaga

To Depth to Well Water -->

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Figure 3. MBDI website Water Resource Fluctuations page. This and other pages explain applications of the MBDI to resource management, including index validation results.

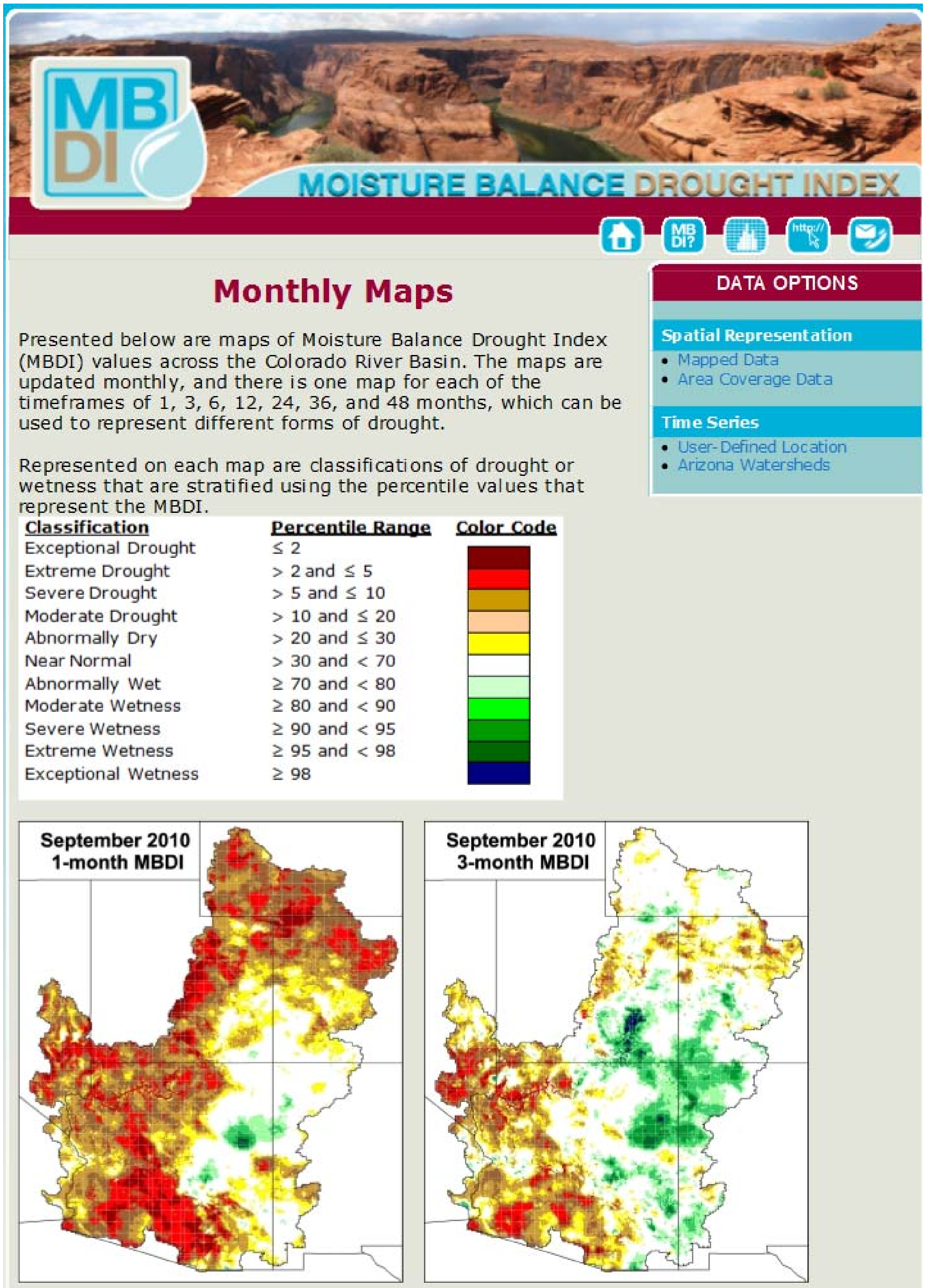
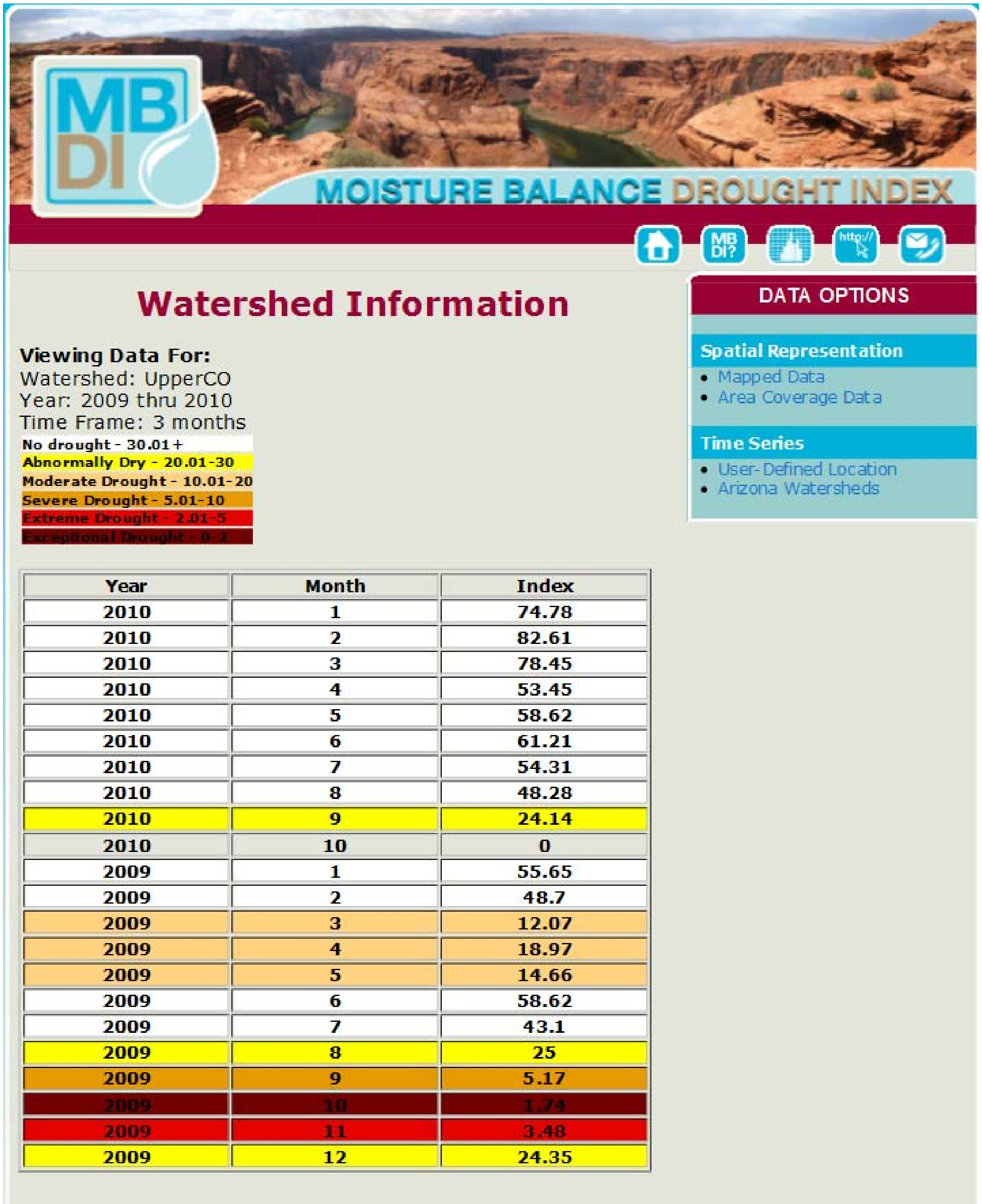


Figure 4. MBDI website Monthly Maps page (excerpt). This page displays MBDI values for pre-defined aggregations of the index (1-, 3-, 6-, 12-, 24-, 36-, 48- months), using the same color scale as the U.S. Drought Monitor.



MBDI
MOISTURE BALANCE DROUGHT INDEX

DATA OPTIONS

Spatial Representation
- Mapped Data
- Area Coverage Data

Time Series
- User-Defined Location
- Arizona Watersheds

Watershed Information

Viewing Data For:
Watershed: UpperCO
Year: 2009 thru 2010
Time Frame: 3 months

No drought - 30.01+
Abnormally Dry - 20.01-30
Moderate Drought - 10.01-20
Severe Drought - 5.01-10
Extreme Drought - 2.01-5
Exceptional Drought - 0-2

Year	Month	Index
2010	1	74.78
2010	2	82.61
2010	3	78.45
2010	4	53.45
2010	5	58.62
2010	6	61.21
2010	7	54.31
2010	8	48.28
2010	9	24.14
2010	10	0
2009	1	55.65
2009	2	48.7
2009	3	12.07
2009	4	18.97
2009	5	14.66
2009	6	58.62
2009	7	43.1
2009	8	25
2009	9	5.17
2009	10	1.74
2009	11	3.48
2009	12	24.35

Figure 5. MBDI website Watershed Information page (example). This page displays data for user-defined watersheds, time periods, and MBDI aggregation (in this case, 3-month MBDI values). The table is color-coded according to the U.S. Drought Monitor color scale. Tables can be cut-and-pasted into a spreadsheet, using the "Paste Special" command. Similar tables can be generated for individual 4 km grid cells.