PRACTICAL PAPER

The Use of Archival Landsat MSS and Ancillary Data in a GIS Environment to Map Historical Change in an Urban Riparian Habitat

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Abstract
Recent changes in the condition of the riparian habitat of the Tanque Verde Creek in Tucson, Arizona prompted an investigation of the dynamics of the native plant communities, hydrology, and climate in the area. The project was an initial attempt to assess and monitor the changing condition of native vegetation along the Tanque Verde Creek during the period 1983 through 1989, and to discover if mapped changes in vegetation patterns could be correlated with available ground data.

Analysis techniques involved the use and evaluation of archival Landsat Multispectral Scanner (MSS) multitemporal satellite data coupled with pertinent hydrologic and meteorologic measurements. The MSS data were used to develop indices of vegetation condition for the years 1983 through 1989. A wide array of multitemporal comparisons were constructed between the vegetation indices and well water levels, temperature, and precipitation. Varying levels of statistical correlation between changes in vegetation indices, water level, and climatic variables were discovered. Multitemporal maps of changing vegetation condition and well water levels reveal a definite decline in both after 1985. In addition, the multitemporal satellite data provide a viable and important historical view of changing vegetation condition within the Tanque Verde riparian area.

Introduction
Recent questions concerning the condition of the riparian habitat of Tanque Verde Creek in Tucson, Arizona indicated the need for an improved understanding of the dynamics of native plant communities and their relationship to hydrologic and climatic factors. This study was an initial attempt to assess and monitor the changing condition of native vegetation along Tanque Verde Creek and to determine if these changes could be related to variations in ground water levels or available meteorologic variables.

The specific goals of the study were (1) to determine if archival satellite data could be used to document changes in vegetation in the study area, and (2) to ascertain if any of the available well or meteorological data correlated with vegetation change as monitored by satellite.

Obviously, a great deal more information could be acquired and used for more detailed (tree-by-tree) analyses. However, this study was the logical first step in establishing if, when, and where vegetation changed during the past decade and how it might correlate with readily available field information.

A variety of analysis techniques were utilized in the study. Satellite data were examined using standard image processing software (ERDAS)* and the results of the digital processing were combined with geo-referenced well and hydrologic information using geographic information system (GIS) software (ARC/INFO).

Study Site
Tanque Verde Creek is an intermittent stream which flows for 25 kilometres (km) from its headwaters in the Rincon Mountains to its confluence with Pantano Wash in southern Arizona. The lower 10 km of the stream course and associated riparian habitat constituted the study area (Figure 1). Fremont cottonwood, Goodding willow, Arizona walnut, and other riparian trees are present at low densities along the stream channel which varies in width between 50 and 200 metres (m) along a relatively low gradient (0.2 m/km) at an average elevation of 800 m. Mesquite communities occupy the broad floodplain terraces adjacent to the stream channel. Mesquite are present in many sizes and comprise three-quarters of all large woody plants in this community. Mexican elderberry, velvet ash, netleaf hackberry, and desert willow comprise the majority of the remaining tree stems. Wolfberry, graythorn, and hackberries are the dominant understory shrubs (Stromberg *et al.*, 1992).

The hydrogeologic setting of the study area changes near the confluence of Tanque Verde Creek with Agua Caliente

* Trade names are included for the benefit of the reader and do not imply an endorsement of the product by California State University or The University of Arizona.

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Wash. Below the confluence there exists a structural trough of thick unconsolidated, highly permeable sediments which overlie older consolidated rocks (Stromberg *et al.*, 1992). About 2 km above the confluence, faulting and subsequent erosion have resulted in a relatively shallow depth to the older, lower permeability, consolidated sedimentary rocks.

Because of the greater hydraulic conductance and thickness of the younger, unconsolidated sediments, the downstream section of the study area has been more intensely developed in recent years as a source of high quality, low cost groundwater. Rates of groundwater withdrawal from the underlying aquifer increased in 1988 primarily due to the activation of several large capacity wells by the city of Tucson.

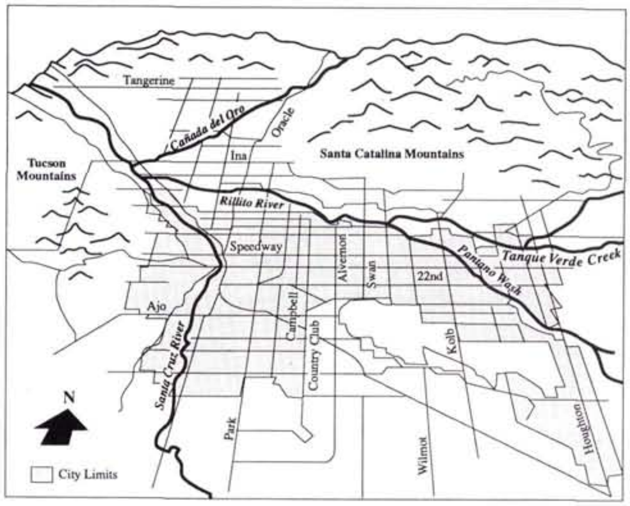

Figure 1. Location of the Tanque Verde Creek study site.

Methods

Data Description

Data utilized in this study consisted of digital satellite imagery, tabular information, and a variety of derived GIS data layers. Landsat Multispectral Scanner (MSS) images (57 by 79-m spatial resolution) for the years 1983, 1984, 1985, 1986, 1988, and 1989 were acquired for the purposes of the study. No cloud-free 1987 MSS images were available. Images from the early part of June were chosen in an attempt to analyze vegetation condition at its most naturally stressed level as a result of soil moisture deficiencies just prior to the onset of the summer monsoon. It is during this portion of the year that phreatophytic vegetation relies most heavily on direct withdrawals of available groundwater (Meinzer, 1927; Robinson, 1958). Thus, overdrafting of aquifer reserves would be most dramatic on riparian vegetation behaving as phreatophytes during this time period. A retrospective analysis of daily meteorological records indicated that there were no significant rainfall events prior to the image acquisition dates. The Landsat images were used to derive normalized difference vegetation index (NDVI) (Tucker, 1979) and soil adjusted vegetation index (SAVI) (Huete, 1988) images for the six years.

A May, 1988 SPOT image was also utilized to produce a land-use/land-cover classification map to aid in the analysis. However, it was not compared directly to the MSS images, primarily due to the differences in indices and classification introduced by its finer spatial resolution (20 m). Landsat Thematic Mapper (TM) data also provide a viable means of performing riparian assessments (Hewitt, 1990). However, consideration of cost and the availability of historical data make the assessment of the Landsat MSS data a cost-effective and logistically valid first step in projects of this kind.

Water level data were available from both state and local agencies. Based upon the consistency of measurement techniques, we elected to utilize the local data-set in our analyses. Data were collected during the minimum use periods of December and January, and after wells have been shut down for one to two weeks allowing water levels to reach a static state.

In addition to well data, meteorological records were acquired from the Tucson Magnetic Observatory station which is the only station in close proximity to the study area. Monthly temperature and precipitation records from the past 25 years were compiled and analyzed for the study.

Satellite Data Preprocessing

As a first step, the original Landsat data were subjected to a radiance transformation using previously derived calibration coefficients and the header records of the individual scenes. Using image processing software (ERDAS), the digital numbers (DNs) recorded by the MSS were converted to physical values of radiance (Price, 1987; Robinove, 1982) so that a meaningful comparison could be made between images recorded on different dates by two different Multispectral Scanners (Landsats 4 and 5). Band 4 images, which were originally recorded in 6-bit format, were then scaled to 8-bit format to allow for the derivation of vegetation index values during the data extraction phase.

Analysis of multi-date imagery also requires the matching of the spectral characteristics of the images by normalizing the scene histograms. This process acts as a first-order correction for differences in atmospheric conditions between different acquisition dates. This is not to be confused with absolute corrections for atmospheric scattering and absorption. Normalization procedures were applied because historical optical depth measurements that could be utilized in a radiative transfer code (e.g., LOWTRAN) (Holm *et al.*, 1989) were not available. There also were no appropriate targets in the study area to be able to apply a dark object correction for atmospheric scattering (Chavez, 1988).

The 1989 image was chosen as the standard for normalizing the other images. This choice was based on the fact that the image exhibited the least amount of offset of lowest DN values between bands and the greatest dynamic range of values throughout the image. The mean, standard deviation, and minimum and maximum values were in close agreement for all bands in all corrected images except for the green band (band 1) of the 1986 image. This was due to an area of clouds in the image which distorted the image statistics. This was not considered a problem because, although all bands of the images were processed, only bands 2 and 4 are used in the derivation of the vegetation indices.

Once the spectral preprocessing had been accomplished, the six images were geometrically rectified to a map base using 45 ground control points, resulting in a root-mean-square (RMS) error of 0.74 pixels, meaning that points on the image corresponded to within 60 m of their ground location.

The May 1988 SPOT image was subjected to the same radiometric and geometric correction techniques but did not require the matching of histograms because it was not compared directly to the multitemporal Landsat data.

Generation of Classification Map

An unsupervised (maximum-likelihood) classification was run on the SPOT multispectral data for the Tanque Verde study area. The resulting classification produced 16 unsupervised classes. The results were displayed and compared to land-cover/land-use maps of the area. Based upon this comparison, the 16 classes were combined into six general land cover types: (1) Bare Soil, (2) Urban Cover, (3) Residential Cover, (4) Desert Scrub (mixed cover), (5) Desert Scrub (mesquite), and (6) Dense Cover Vegetation.

Generation of Vegetation Indices and Maps

Numerous previous studies involving the monitoring of vegetation condition and change have been based on the normalized difference vegetation index or NDVI (Cihlar *et al.*, 1991; Tucker *et al.*, 1983; Tucker *et al.*, 1985; Marsh *et al.*, 1992). The differential reflection of green vegetation in the visible and near-infrared portions of the electromagnetic spectrum provides the theoretical basis for this method. The NDVI can be calculated from a variety of sensors carried on environmental satellites (i.e., NOAA-AVHRR, SPOT, and Landsat TM and MSS). The formula for the MSS data takes the following form: NDVI = CH4 − CH2/CH4 + CH2, where CH2 and CH4 are the reflectance in the visible red (0.6- to 0.7-micrometre) and near-infrared (0.8- to 1.1-micrometre) channels, respectively. Ultimately, the NDVI is determined by the degree of absorption by chlorophyll in the red wavelengths, which is proportional to leaf chlorophyll concentration, and by the reflectance of near infrared radiation, which is proportional to green leaf condition and area.

A more refined version of the vegetation index that compensates for the reflectance of background soil, called the Soil Adjusted Vegetation Index (SAVI) (Huete, 1988), was also calculated from the MSS data by employing the formula SAVI = CH4 − CH2/(CH4 + CH2 + 0.5)*(1.5). Interactive extraction and comparison of the SAVI and NDVI values for selected sites of known vegetation cover supported the concept that SAVI values exhibit a greater sensitivity to partial ground cover than does the traditionally used NDVI. Based on these findings, the SAVI vegetation index imagery was chosen as the primary satellite product for analysis of vegetation status in this study. Image subsets corresponding to the study area were extracted from the SAVI master images for the six available dates.

At this point the vegetation subset images contained 8-bit data values (0 to 255). By inverting the formula originally used to create the single band index image from the red and near-infrared bands of the Landsat MSS data, the true index values could be retrieved from the imagery. These index values ranged from 0.0 (absence of vegetation) to 0.7 (highest levels of vegetation). The 8-bit image data were retained on the image processing system both for display purposes and for the extraction of pixel array values corresponding to the well level data for regression analysis.

For conversion of the image raster data to vector format and the subsequent use of the vector data for temporal analysis and map generation, the image data-sets needed to be reduced in storage size as well as complexity while still retaining the highest possible level of information. To accomplish these multiple goals, the original range of values were re-coded to seven classes corresponding to 0.1 increments in the 0.0 to 0.7 range previously calculated for the vegetation index data.

The raster files were then imported into ARC/INFO vector format. Using an empirical approach, the lowest three classes (0.0 to 0.3) were combined into a single class (class 1) and the remaining classes were re-numbered, resulting in a five-class scheme. Classes 2, 3, 4, and 5 correspond to different vegetation conditions within the riparian zone (adjoining polygons with the same class code were also joined).

Results and Discussion

Multitemporal Data Analysis

As the first step in the analysis, a series of maps depicting the spatial distribution of vegetation index classes for the

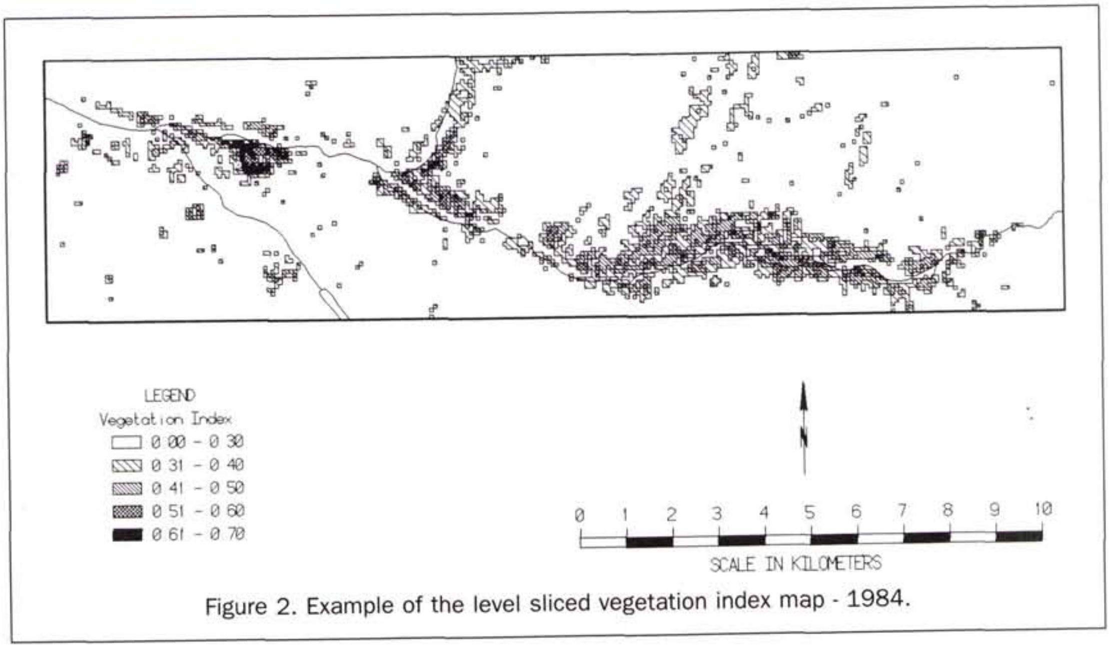

Figure 2. Example of the level sliced vegetation index map - 1984.

A.

1983 CLASS \ 1984 CLASS	1	2	3	4	5
1	.93	.06	.01	0	0
2	.50	.29	.15	.04	.02
3	.35	.30	.23	.11	.01
4	.28	.15	.22	.19	.16
5	.17	.20	.20	.13	.30

B.

1984 CLASS \ 1985 CLASS	1	2	3	4	5
1	.94	.05	.01	0	0
2	.44	.33	.18	.05	0
3	.20	.26	.36	.16	.02
4	.11	.24	.33	.24	.08
5	.12	.10	.14	.38	.26

C.

1985 CLASS \ 1986 CLASS	1	2	3	4	5
1	.98	.02	0	0	0
2	.52	.39	.08	.01	0
3	.16	.41	.35	.07	.01
4	.05	.19	.39	.27	.10
5	.01	.09	.16	.29	.45

D.

1986 CLASS \ 1988 CLASS	1	2	3	4	5
1	.98	.02	0	0	0
2	.62	.29	.07	.02	0
3	.37	.41	.17	.05	0
4	.19	.33	.27	.16	.05
5	.03	.14	.16	.38	.29

E.

1988 CLASS \ 1989 CLASS	1	2	3	4	5
1	.98	.02	0	0	0
2	.37	.53	.09	.01	0
3	.12	.41	.40	.07	0
4	.03	.18	.46	.30	.03
5	.03	0	.49	.18	.30

F.

1983 CLASS \ 1989 CLASS	1	2	3	4	5
1	.97	.03	0	0	0
2	.69	.23	.06	.02	0
3	.48	.30	.16	.04	.01
4	.39	.25	.29	.06	0
5	.54	.21	.21	0	.04

Figure 3. Vegetation index class value change analysis.

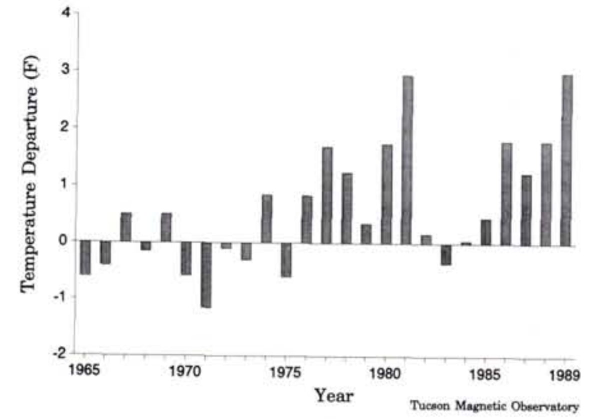

Figure 4. Twenty-five-year record of annual mean temperature departure.

years 1983 through 1989 for the image subsets were generated (1984 example - Figure 2).

Statistics generated during map compilation were displayed as a series of change matrices to facilitate analysis (Figure 3). The cells forming the diagonal in each matrix indicate the percentage of pixels in each vegetation class that remained unchanged between the two years. The cells above the diagonal are percentages of increase for various classes between the two years analyzed. The cells below the diagonal are the percentages of class decrease. These general trends are indicated by the plus symbol (+) in the upper right corner and the minus symbol (−) in the lower left corner. Class 1 is non vegetated surfaces and classes 2 through 5 include sequentially greater amounts of vegetation.

Analysis of the five year-to-year change matrices (Figures 3A through 3E) revealed the following patterns. The percentages are always larger below the diagonal than above (there is more vegetation class decrease than vegetation class increase). The percentages above the diagonal drop sequentially from year to year, and more cells are occupied by zero values through the years of the study (the amount of class increase drops in the latter years of the study).

Analysis of the cumulative change from 1983 through 1989 (Figure 3F) reenforces the yearly patterns of decline. Ninety-seven percent of the non vegetated surface remained in that class for the entire duration of the study. Only 31 percent of the class 2 pixels (the lowest vegetation class; the hinge between vegetated and non-vegetated) remained vegetated throughout the six year study period. Between 39 percent and 69 percent of the vegetation class pixels (classes 2 through 5) changed to non-vegetated status while only minor increases (1 to 6 percent) took place in any vegetation class during the same time period.

The change matrix analysis clearly documents the trend to decreasing vegetation index class values, but it does not provide insight into the spatial distribution of change. This is provided by visual analysis of the vegetation class maps. An increasing trend in vegetation cover and class exists for the years 1983, 1984, and 1985, with the peak for the study period being reached in 1985. The 1986 map exhibits a slight decrease from the previous year, with the trend accelerating for 1988 and 1989. The extent and density of the riparian zone shows a marked decline from levels exhibited in the 1983 through 1986 maps. These patterns are exhibited throughout the subset but are especially acute in the Sabino and Aqua Caliente tributaries.

SPOT Multispectral Data Analysis

Inspection of the SPOT classification map (Plate 1) demonstrates the difficulty of discriminating classes that are mixtures of desert vegetation and urban and residential cover. The bare soil class can be easily recognized as open fields and washes. The urban cover class represent mixtures of bright and dark man-made materials. The residential cover class is in general a mixture of desert vegetation with bright structures. Dense cover vegetation is generally planted or maintained areas such as golf courses. The desert scrub - mixed cover class is representative of Catalina Mountains foothills vegetation. The desert scrub - mesquite class is the most pertinent to this study and coincides with the riparian zones along the washes.

Vegetation Indices and Climatic Data

A 25-year data set of monthly precipitation and temperature data was used to derive a series of plots illustrating the relationships between meteorological variables as well as their relationship to vegetation indices for the study period. The 25-year mean was calculated for both temperature and precipitation using monthly values from 1955 to 1979 (Figures 4

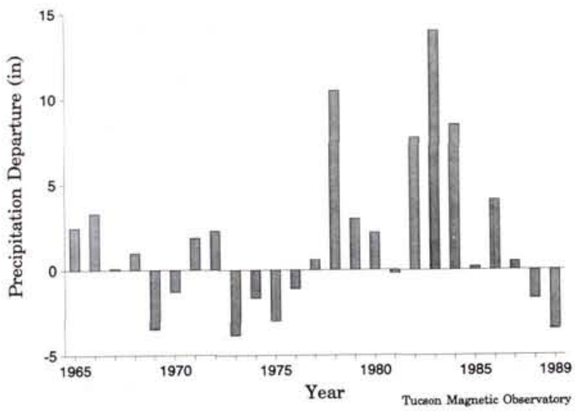

Figure 5. Twenty-five-year record of annual mean precipitation departure.

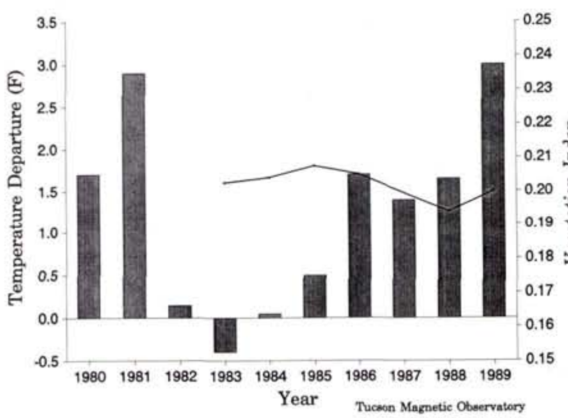

Figure 6. Ten-year record of temperature departure and vegetation index.

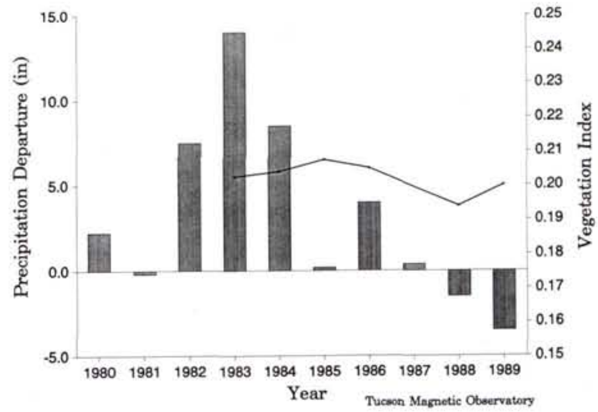

Figure 7. Ten-year record of precipitation departure and vegetation index.

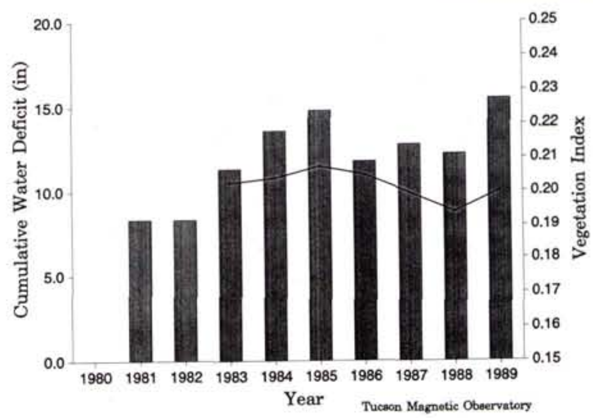

Figure 8. Thornthwaite water balance index and vegetation index.

and 5). These figures show the departure from the 25-year mean for the years 1965 through 1989. Only five of the 25 years plotted show both increases in temperature and decreases in precipitation. Furthermore, 1988 and 1989 are the only two consecutive years exhibiting these conditions, and the magnitude of the departures (especially temperature) are the greatest of the five years exhibiting these conditions. Additional plots were generated to compare temperature and precipitation values to mean values of the vegetation indices (1983-1989) for the vegetation index subsets (Figures 6 and 7). The small decline in the vegetation indices roughly parallels the decline in precipitation at the sites.

As a further index of aridity, Thornthwaite water balance indices (Thornthwaite and Mather, 1955) were calculated for the years 1981 through 1989. This index takes into account the actual and potential evapotranspiration as well as soil moisture storage to calculate water surplus or water deficit values in inches. Cumulative values for the months of April, May, and June were calculated for each of the study years and plotted together with vegetation index means (Figure 8). Based upon both parametric and nonparametric correlation analysis, no statistically significant relationship could be established between the two indices. A longer record of vegetation indices and water balance data may provide greater evidence for the correlation of these variables.

Vegetation Indices and Water Levels

The municipal well water level files were edited so that they contained location information in a format that permitted their input to the GIS database. The 64 wells that fit the criteria of having at least four years of data collected corresponding to the years of satellite image coverage were utilized. These data points, which were provided in latitude/longitude, were converted to UTM coordinates to allow for analysis and comparison with the satellite data. Again using an empirical approach, several distance buffers from the course of the channel were evaluated. A distance buffer of 1000 m provided the closest spatial match with the riparian vegetation distribution on the level sliced vegetation index maps. This resulted in a selection of 30 wells that had multitemporal well level data for 1983 through 1989 and were within 1000 m of the channel of the Tanque Verde and its major

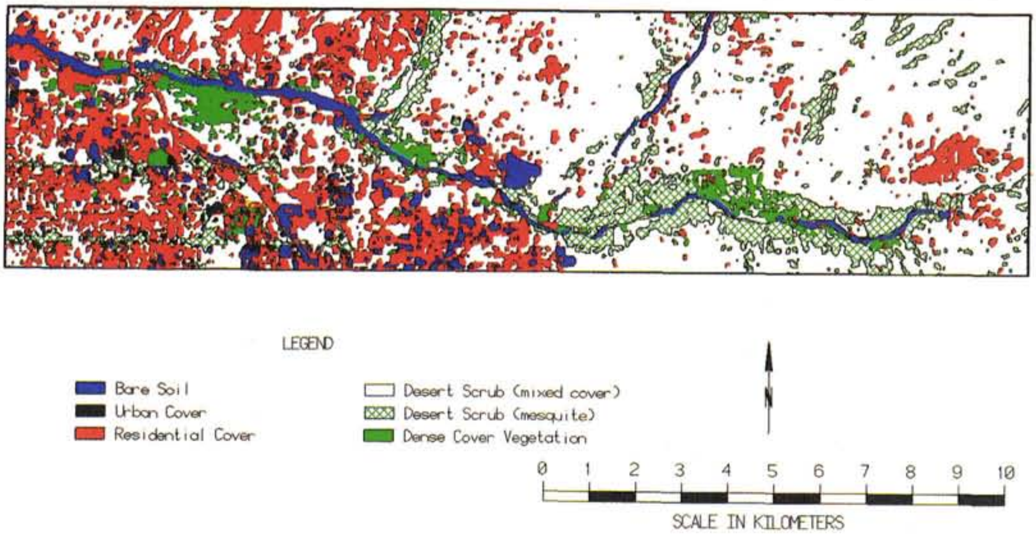

Plate 1. SPOT unsupervised classification map.

tributaries (and, therefore, included all city wells within the riparian zone). The well level data for these 30 wells were then added to the attribute table associated with the wells and were used to calculate the difference in well level from year to year over the study period.

To determine the spatial distribution of wells within the 1000-metre buffer in the Tanque Verde subset, a plot was created which displays both city and private well locations. To assess the relationship between yearly change in water level for Tucson City water wells and change in yearly vegetation index levels, a series of yearly change maps (Figures 9 to 13) were generated. While the 1983-1984 and 1984-1985 maps (Figures 9 and 10) show significant amounts of both increasing and decreasing vegetation index values, the trend shifts with the 1985-1986 map (Figure 11) to a pattern dominated by declining vegetation index values (Figures 12 and 13). Figure 14 shows the overall pattern of change for the study period (1983-1989) which may be a clearer representation of overall change than the year-to-year data. Also plotted on this series of maps is the yearly change in static water level for City wells falling within the 1000-metre zone along major channels. There is an obvious predominance of wells exhibiting increasing water levels on the 1983-1984 map (a result of a period of increased precipitation). From 1984-1985 onward, the water level in the majority of City wells show a net decrease.

By overlaying the desert scrub-mesquite class boundaries derived from the SPOT land cover classification with the

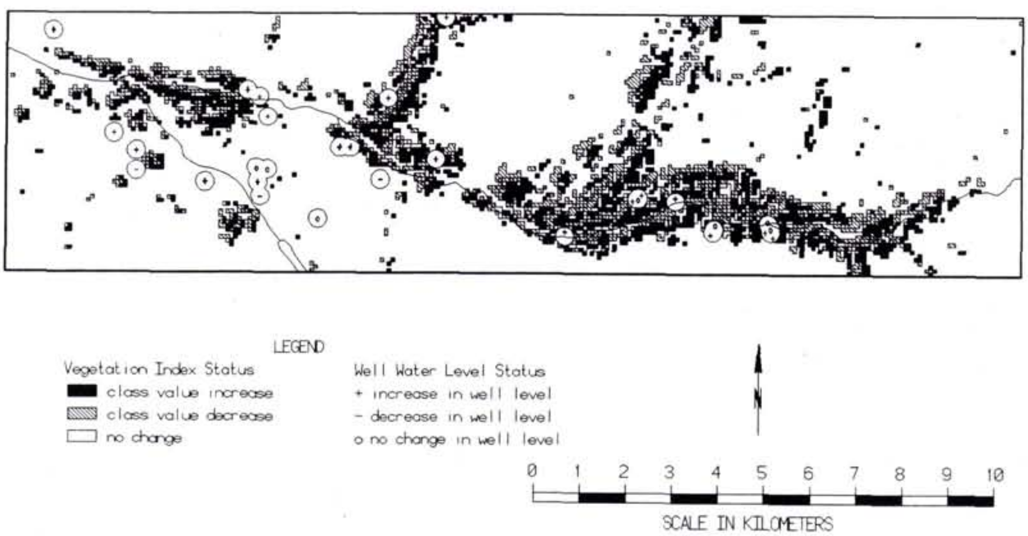

Figure 9. Well level and vegetation index change, Tanque Verde Wash, 1983-1984.

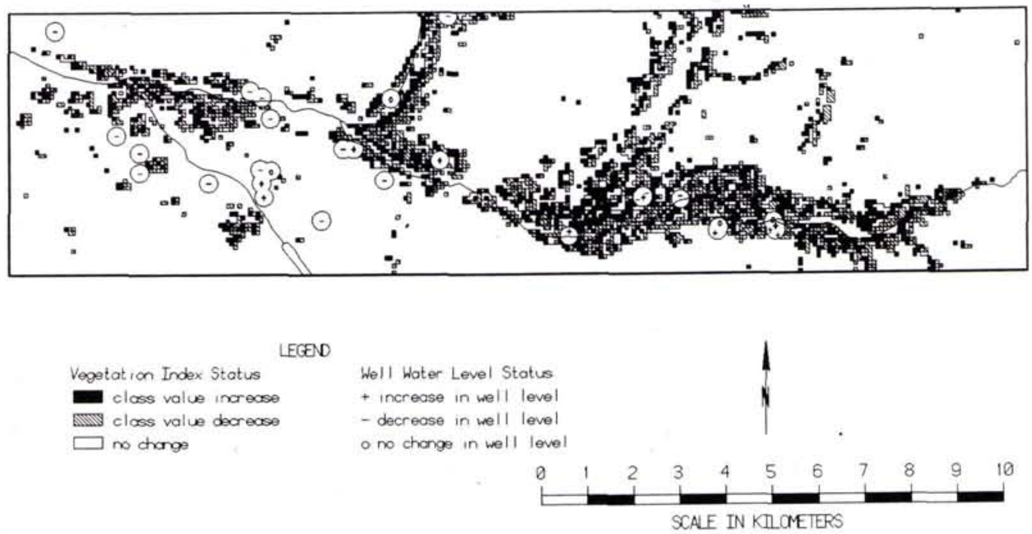

Figure 10. Well level and vegetation index change, Tanque Verde Wash, 1984-1985.

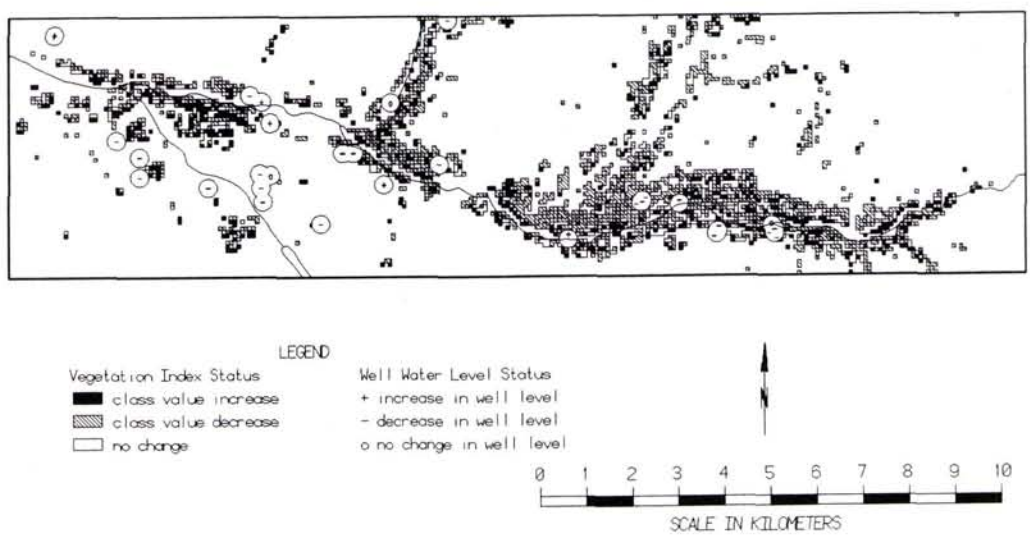

Figure 11. Well level and vegetation index change, Tanque Verde Wash, 1985-1986.

1983-1989 vegetation index change map (Figure 15), it was possible to stratify vegetation index changes in natural plant communities from other vegetated areas. The 1983-1989 change map presents a clear picture that vegetation in corridors bounding the stream channels has generally either not changed or has decreased.

Correlation Analysis

The use of a 1000-m buffer provides a good starting point for delineation of a riparian zone, but such diverse factors as geomorphology, zoning, and land ownership combine to modify the shape and extent of the riparian zone within this arbitrary spatial designation. As a result, many of the wells located within the southwestern portion of the Tanque Verde subset are actually in areas dominated by urban/residential land cover. To insure that the analysis was constrained to vegetation and ground water interactions, 13 wells were visually selected as truly lying within the floodplain of Tanque Verde Creek. These wells were located by their UTM coordinates on the vegetation index images using the image processing software.

Single-pixel and five-pixel array values were extracted at each well location from the six available Landsat MSS images. Pixel digital number (DN) values were then converted to vegetation indices, and vegetation index change values were computed between yearly values and for the entire range of study dates (1983 through 1989). Change values for well level data, which had previously been computed in ARC/

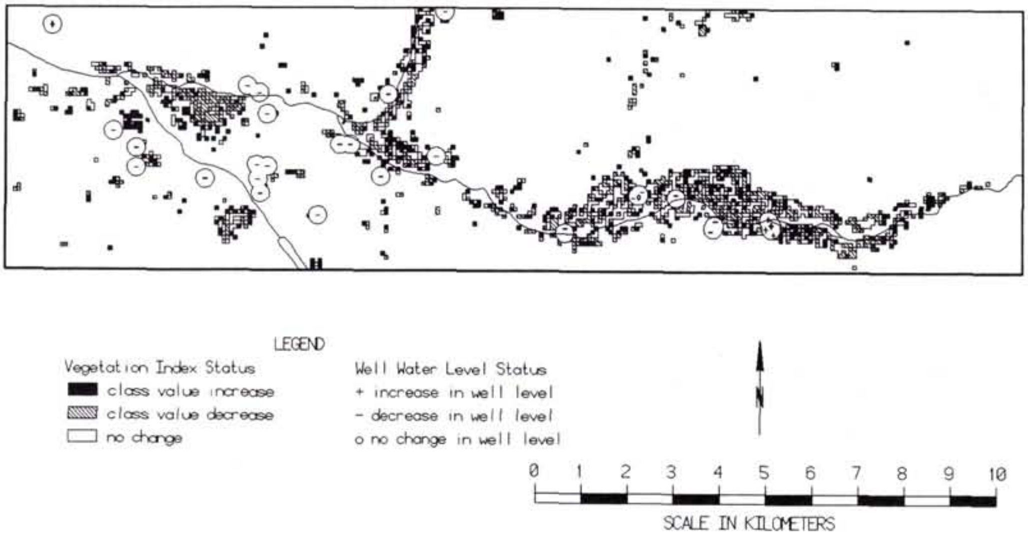

Figure 12. Well level and vegetation index change, Tanque Verde Wash, 1986-1988.

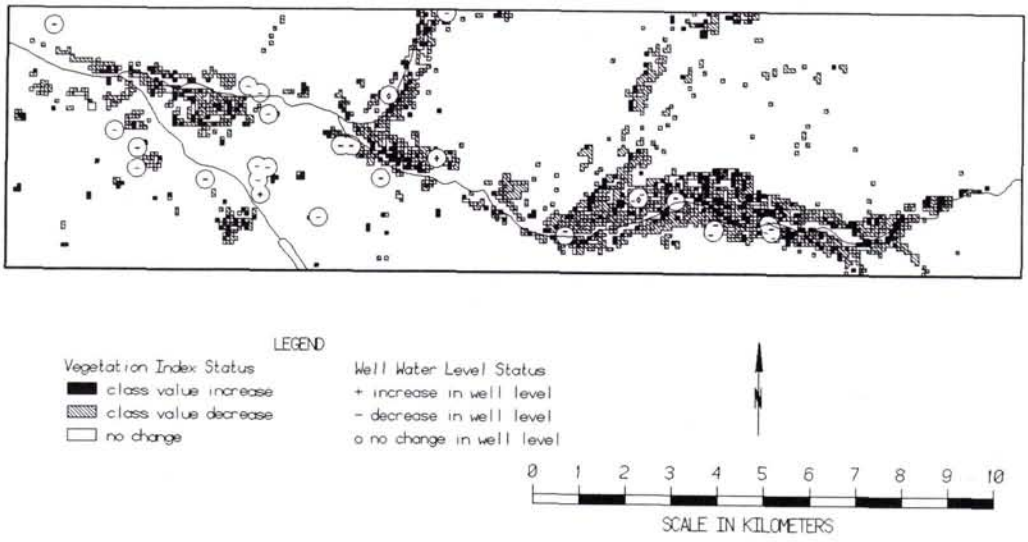

Figure 13. Well level and vegetation index change, Tanque Verde Wash, 1988-1989.

INFO, were entered into a statistical package along with the vegetation index change values. The data were then examined using regression analysis to explore relationships between yearly changes in ground water levels and vegetation indices. Comparisons were made between the variables, and no statistically significant correlation existed between changing vegetation index and changing water level.

Nonparametric correlation analysis was also applied to the data sets due to the unknown nature of the distribution of the sample populations. Spearman's rank correlation coefficient (Davis, 1986) was calculated based upon ranking the NDVI and well water level data on a well-by-well basis. Correlation coefficients ranged from 0.64 to 0.94 with a mean value of 0.79. The majority of the tested wells and the mean value for the wells exceeded the critical value at the 5 percent level of significance. This indicates that a definite relationship exists between water well level and NDVI.

Conclusions

Though there were varying levels of statistically significant relationships between changes in vegetation indices, water level, and climatic variables, the multitemporal satellite data do provide an important historical view of vegetation condition within the Tanque Verde riparian area. Multitemporal maps of changing vegetation condition and well water levels reveal a definite decline in both after 1985. A variety of spatial and temporal scale considerations may have played a role in the range of correlations evidenced by the data. This

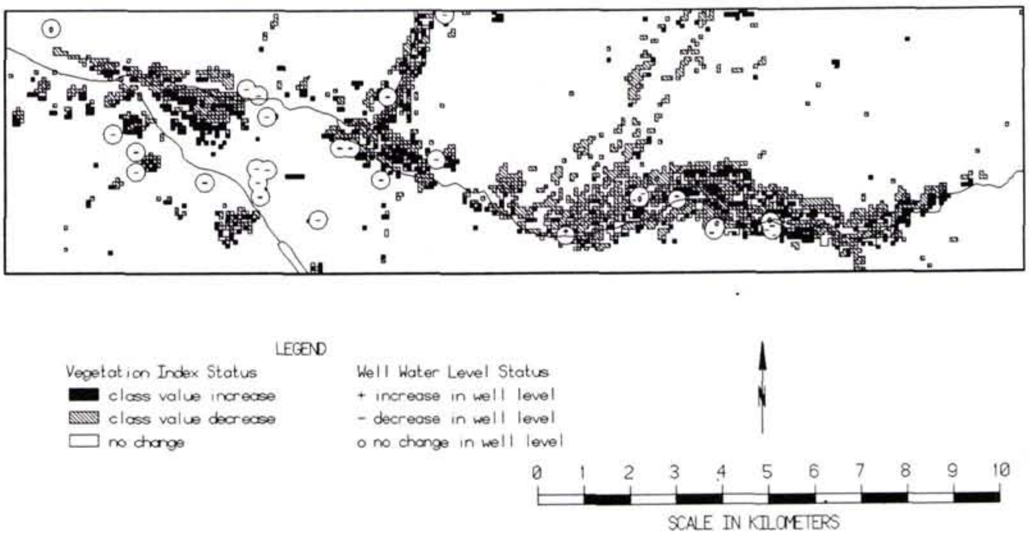

Figure 14. Well level and vegetation index change, Tanque Verde Wash, 1983-1989.

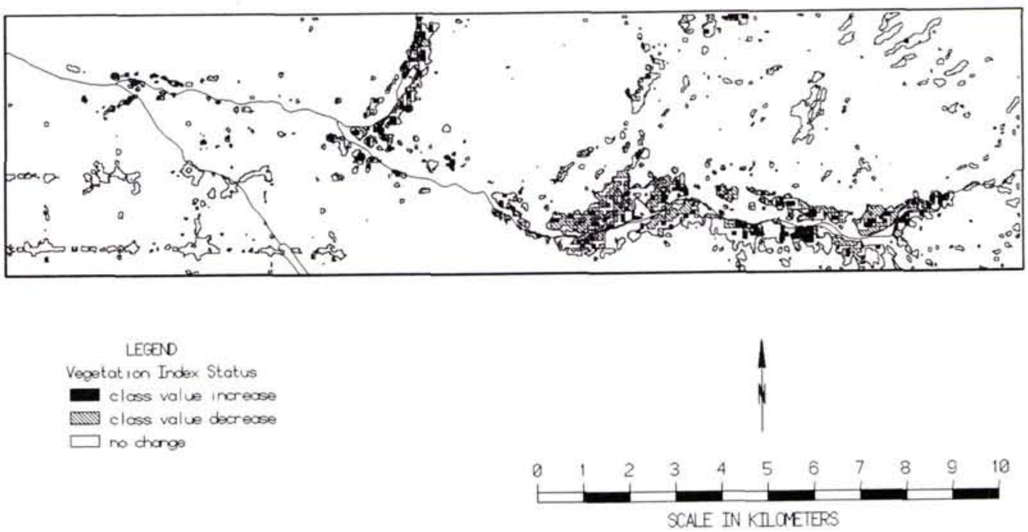

Figure 15. Vegetation index change (1983-1989) within the desert scrub mesquite class, Tanque Verde Wash.

variability is at least partially a result of the coarse spatial resolution of the Landsat MSS data (57 by 79 m) coupled with local variations in terrain and sub-surface hydrology. Certainly, a denser network of meteorological and hydrological gauging stations, more frequent measurements from these stations, and higher frequency multispectral satellite data could provide greater insight into the role and correlation of these variables.

No chance exists to use remote sensing data to finely dissect the past in order to provide instant, quantitative, and definitive answers. This study was significant in that it does provide, for the first time, maps depicting the nature and spatial extent of changing vegetation patterns in one of Arizona's most important urban riparian habitats. The results of this study illustrate the potential of the available 20-year archival Landsat MSS database to yield important information on the historical dynamics of urban riparian habitats.

With proper attention to preprocessing of the images to normalize variations in sensor response and atmospheric effects, these satellite data can be input and analyzed in a GIS environment. Use of a GIS to analyze changes in vegetation index categories provides useful quantitative information concerning the percentage of vegetation class change throughout a given area and provides a means for producing hard-copy outputs which illustrate the qualitative relationship between vegetation class changes and the fluctuations in the local water table. Use of classified satellite images to help stratify areas undergoing change due to stress versus those being converted to other land uses further helps in extracting useful information from this valuable archival data set.

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References

Chavez, P.S., Jr., 1988. An improved dark-object subtraction technique for atmospheric scattering correction of multispectral data, *Remote Sensing of Environment*, 24:459-479.

Chilar, J., L. St.-Laurent, and J.A. Dyer, 1991. Relation between the normalized difference vegetation index and ecological variables, *Remote Sensing of Environment*, 35:279-289.

Davis, J.C., 1986. *Statistics and Data Analysis in Geology*, John Wiley and Sons, New York, N.Y., pp. 92-101.

Hewitt, M.J., III, 1990. Synoptic inventory of riparian ecosystems: the utility of Landsat thematic mapper Data, *Forest Ecology and Management*, Vol. 33/34: 605-620.

Holm, R.G., M.S. Moran, R.D. Jackson, P.N. Slater, P.N., B. Yuan, and S.F. Bigger, 1989. Surface reflectance factor retrieval from Thematic Mapper Data, *Remote Sensing of Environment*, 27:47-57.

Huete, A.R., 1988. A Soil-Adjusted Vegetation Index (SAVI), *Remote Sensing of Environment*, 25:295-309.

Marsh, S.E., J.L. Walsh, C.T. Lee, L.R Beck, and C.F. Hutchinson, 1992. Comparison of multi-temporal NOAA-AVHRR and SPOT-XS satellite data for mapping land-cover dynamics in the West African Sahel, *International Journal of Remote Sensing*, 13(16): 2997-3016.

Meinzer, O.E., 1927. *Plants as Indicators of Ground Water*, U.S. Geological Survey Water Supply Paper 577, U.S. Government Printing Office, Washington, D.C., 95 p.

Price, J.C., 1987. Calibration of satellite radiometers and the comparison of vegetation indices, *Remote Sensing of Environment*, 21: 15-27.

Robinove, C.J., 1982. Computation with physical values from Landsat digital data, *Photogrammetric Engineering & Remote Sensing*, 48(5):781-784.

Robinson, T.W., 1958. *Phreatophytes*, U.S. Geological Survey Water Supply Paper 1423, U.S. Government Printing Office, Washington, D.C., 85 p.

Stromberg, J.C., J.A. Tress, S.D. Wilkens, and S.D. Clark, 1992. Response of velvet mesquite to groundwater decline, *Journal of Arid Environments*, 23:45-58.

Thornthwaite, C.W., and J.R. Mather, 1955. The water balance, *Publications in Climatology*, Laboratory of Climatology, Drexel Institute of Technology, Centerton, N.J., 8:1-104.

Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation, *Remote Sensing of Environment*, 8:127-150.

Tucker, C.J., C. Vanpraet, E. Boerwinkel, and A. Gaston, 1983. Satellite remote sensing of total dry matter production in the Senagalese Sahel, *Remote Sensing of Environment*, 13:461-474.

Tucker, C.J., C. Vanpraet, M.J. Sharman, and G. Van Ittersum, 1985. Satellite remote sensing of total herbaceous biomass production in the Senegalese Sahel: 1980-1984, *Remote Sensing of Environment*, 17:233-249.

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