Non-point Source Pollution Assessment of the San Antonio - Nueces Coastal Basin

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Abstract

The amount of pollution from non-point sources flowing in the streams of the San Antonio - Nueces coastal basin in South Texas is estimated by a GIS-based method using rainfall, runoff and land use data. A fine grid of cells 100m in size is laid over the landscape. For each cell, mean annual runoff is estimated from rainfall, and expected pollutant concentration is estimated from land use. The product of runoff and concentration gives expected pollutant loading from that cell. These loadings are accumulated going downstream to give expected annual pollutant loadings in streams and rivers. By dividing these accumulated loadings by the similarly accumulated mean annual runoff, the expected pollutant concentration from non-point sources is determined for each location in a stream or river. Observed pollutant concentrations in the basin are averaged at each sample point and compared to the expected concentrations at the same locations determined from the grid cell model.

Results for phosphorus indicate that non-point source pollution in the Mission and Copano watersheds, which have largely rangeland and forest land use, is at relatively low levels in the 0 - 0.2 mg/l range, and is consistent with observed concentrations. There don't appear to be significant point sources of pollution in these watersheds. In the Aransas watershed, primarily of agricultural land use, observed concentrations are greater than non-point sources alone would indicate and there is evidence that a point source in the town of Beeville has been contributing a significant amount of phosphorus to the Aransas River. Results for Nitrogen suggest that observed pollutant levels in most parts of the basin are higher than expected, especially in the Aransas watershed, where the City of Beeville again appears to have been a significant point source contributor.

Introduction

The Texas Clean Rivers Program, a product of Texas Senate Bill 818, calls upon the Texas Natural Resource Conservation Commission to make a report to the Governor each two years on the condition of the water quality in Texas streams and rivers. Water quality status reports have been prepared for each basin assessing the frequency of exceedance of various pollutant levels in designated river segments as a means of identifying the location and types of significant contamination. Most of these reports have been prepared by the River Authorities responsible for particular river basins, but a few river basins, among them the San Antonio - Nueces Coastal Basin, do not fall within the jurisdiction of a River Authority and the TNRCC itself prepares assessments for these basins (TNRCC, 1994). The San Antonio - Nueces Coastal Basin drains into the coastal inland waterway system of Texas to the Northeast of Corpus Christi, as shown in Figure 1.

San Antonio-Nueces Coastal Basin

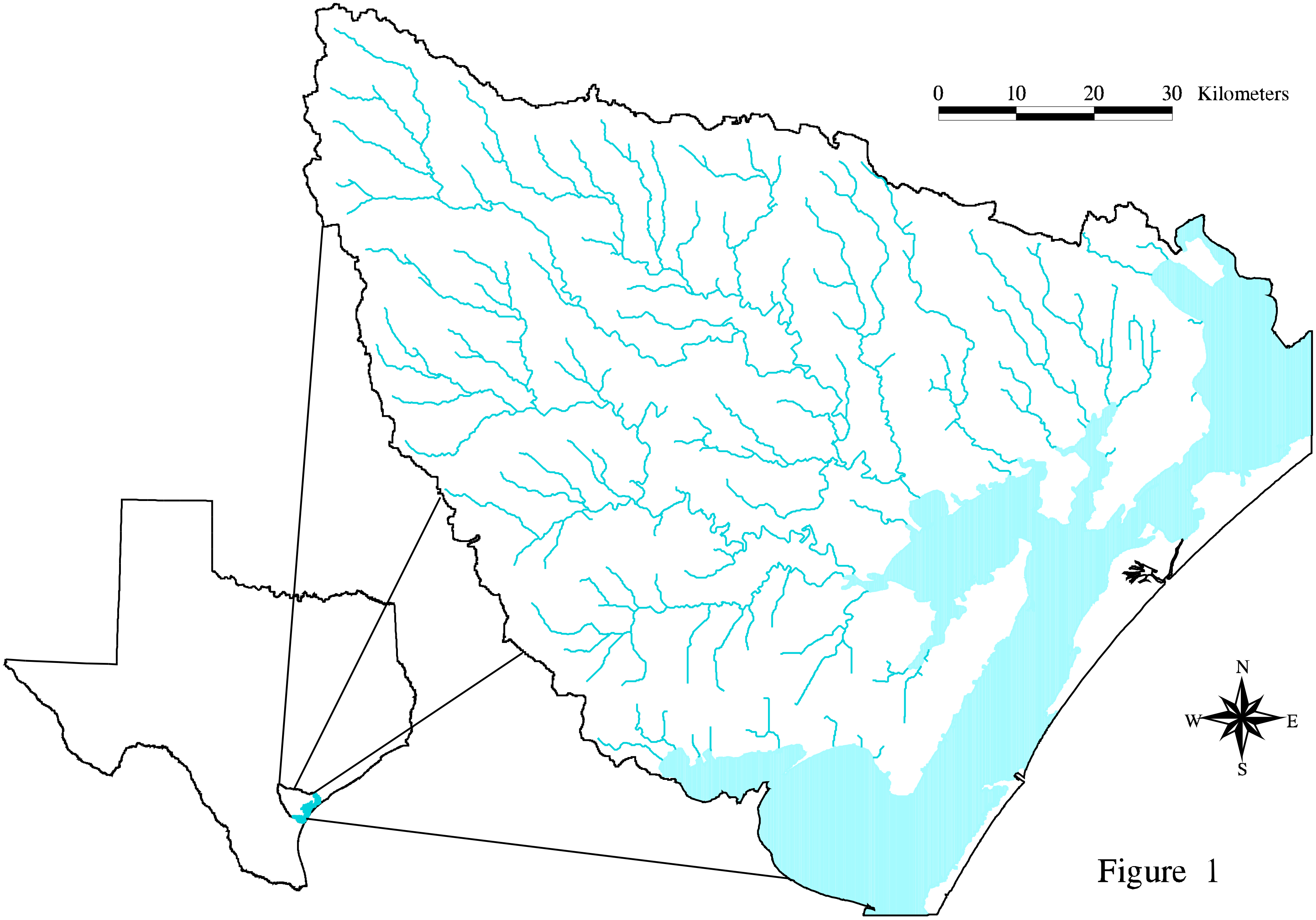


Figure 1

At present, a national estuary study is being conducted in the region, called the Corpus Christi Bay National Estuary Program. Participants in this study have expressed concern that estimates of pollution to the bay and estuary system derived from data measured outside the region might not reflect conditions within the region. They are initiating programs for conducting additional sampling of pollutant concentrations and have asked for some guidance as to the most appropriate locations at which sampling might be conducted. The research reported here addresses these concerns and issues.

As part of the water quality assessment of the San Antonio - Nueces basin, a study is needed of pollutant sources, and in particular of non-point sources of pollutants, since even if all the point sources of contamination are eliminated, non-point sources can still be sufficient to degrade water quality to unacceptable levels. Non-point sources of pollution include runoff from agricultural lands contaminated with chemicals from fertilizer and herbicide applications, urban runoff from streets and parking lots which contain oil and grease, bacterial pollution, and other sources.

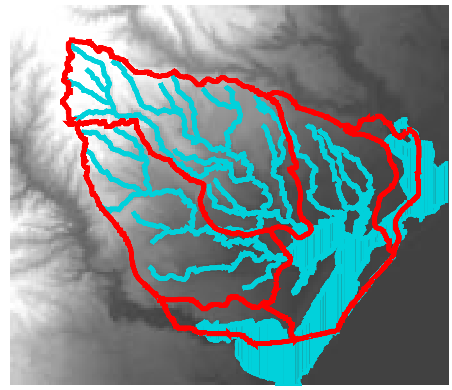
A method of assessing non-point source pollution in river basins is thus needed. The traditional approach to this task has been to use a water quantity and quality computer model, such as HSPF (Hydrologic Simulation Program - Fortran), to simulate the physical and chemical processes governing runoff and contamination in a basin as a function of time. An examination of the application of this model has been made in Oso Creek, a 200 km^2 watershed near Corpus Christi (USDA - NRCS, 1995). The results suggest that the mean annual runoff can reasonably be reproduced by such a model but there are differences between observed and predicted runoff in individual years. Models such as HSPF contain many parameters and require a considerable amount of work to be calibrated for large basins. The San Antonio - Nueces Coastal basin, with an area of approximately 7000 km^2, is about thirty times larger than Oso Creek.

Methodology

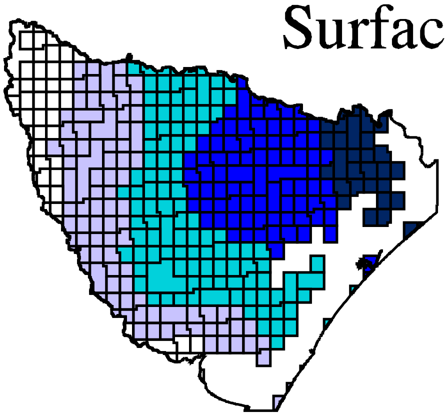
In this report a simplified method of non-point source pollution assessment developed using the Arc/Info geographic information system is presented. The result of this method is an estimate of the mean annual runoff, pollutant concentration and pollutant loading for each cell in a fine mesh laid over the landscape of the basin. The steps involved in the method proposed are outlined in Figure 2 and described below:

(1) Grid model of surface drainage: A fine mesh of 100m cells is laid over the landscape based on standard 3 arc-second USGS digital elevation data. In Figure 3 is shown the gray-shaded image of the digital elevation data and an overlay of the principal streams and watersheds of the basin. There are approximately 1.7 million of these cells within the basin. The conceptual basis for the surface drainage path determination is illustrated in Figure 4. Drainage can pass from each cell to only one of its eight neighboring cells (four on the principal axes and four on the diagonals) in the direction of steepest descent, as defined by the digital elevation data grid, thus generating a flow direction for each grid cell. By tracing these cell to cell drainage connections downstream, the drainage path from every cell to the watershed outlet is determined,

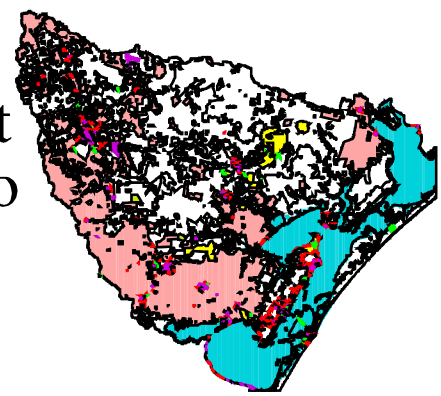
Nonpoint Source Pollution Assessment Method



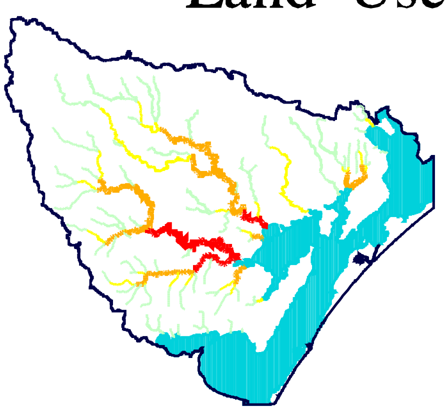
1. Assembly of Data
2. Grid Model of Surface Drainage



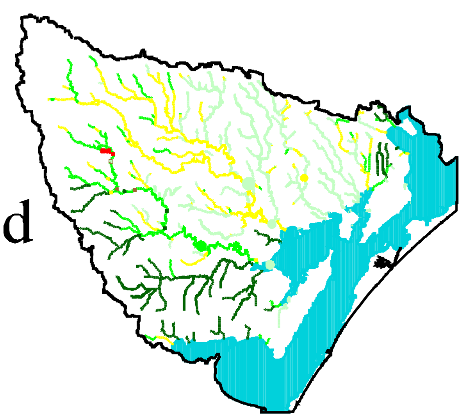
3. Mean Annual Runoff Computed from Rainfall



4. Expected Mean Pollutant Concentration Related to Land Use



5. Downstream Pollutant Loadings Determined



6. Downstream Pollutant Concentrations Compared to Observations

Figure 2

Digital Elevation Model for the San Antonio-Nueces Basin Area (Texas State Mapping System)

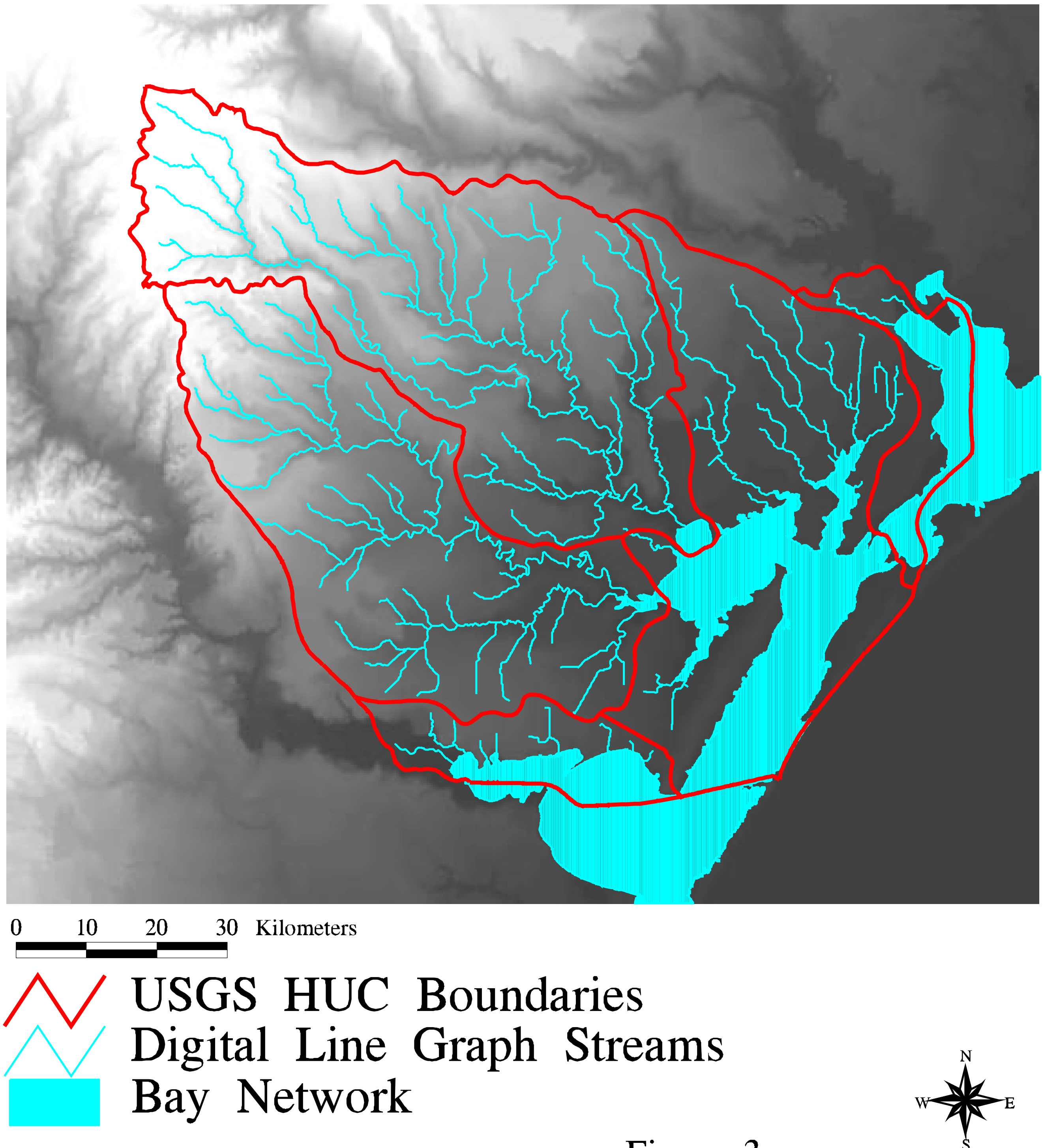


Figure 3

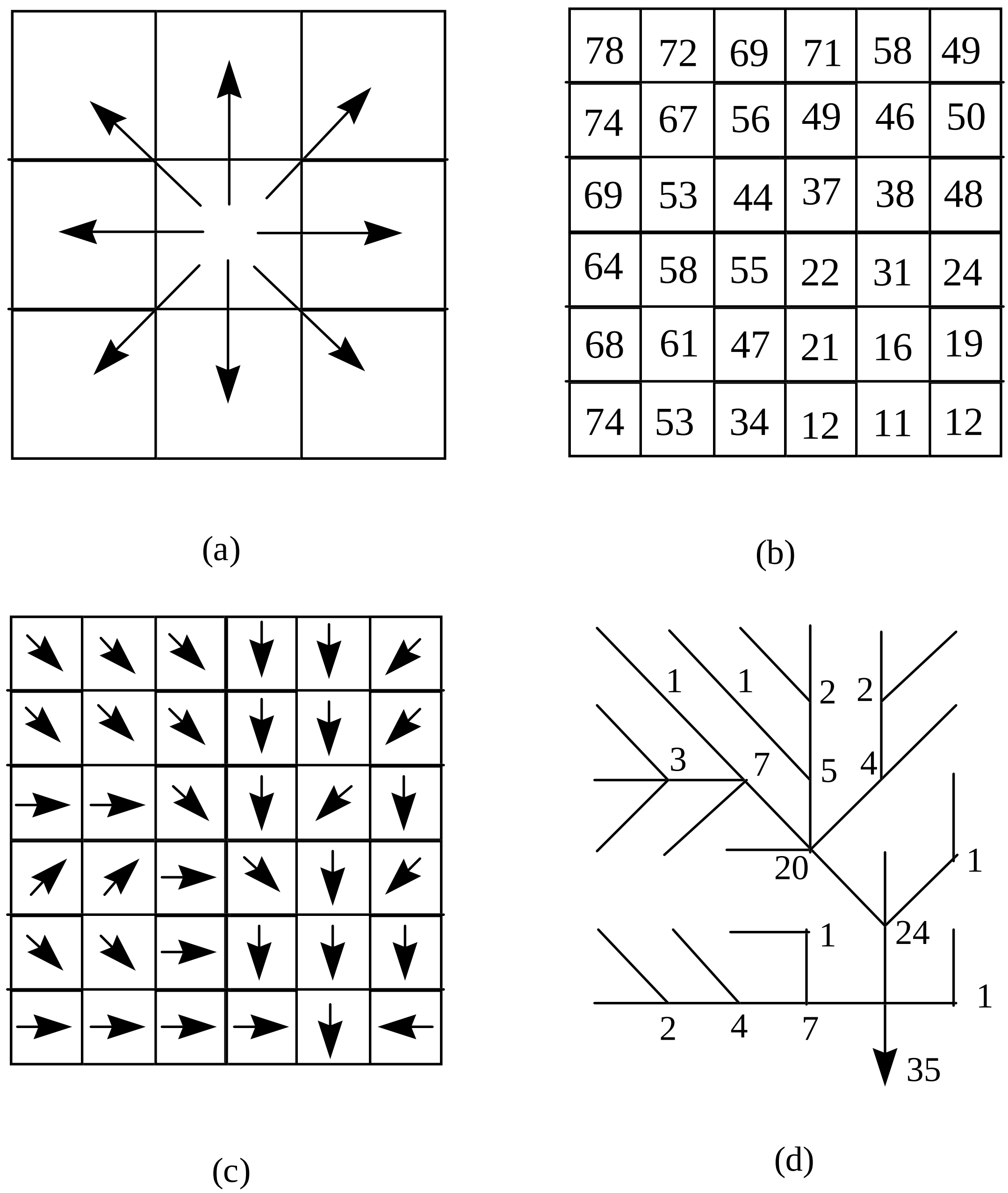


Figure 4: Processing of Digital Elevation Data.
(a) the 8-direction pour point model; (b) a grid of elevation values; (c) flow direction grid; (d) flow accumulation grid.

thus generating a flow connectivity network through the whole basin. From any cell, the number of cells upstream can be counted, which is called the flow accumuation grid. Streams are identified as lines of cells whose upstream drainage area exceeds a threshold value; watersheds are identified as the set of cells whose drainage passes through a particular outlet cell on a stream.

In the very flat areas near the coast, the observed drainage network contains many straight constructed channels and to ensure that the mapped streams are correctly reproduced in the drainage paths derived from the digital elevation data, the mapped streams were "burned in" to the landscape by artificially raising the elevation of all the off-stream cells by an arbitrary amount (Saunders and Maidment, 1995). This device ensures that the grid streams and the mapped streams are completely consistent at some expense of some distortions in the watershed boundaries where the mapped streams and the digital elevation data are not completely in harmony with one another. Production of an improved digital elevation model for the basin from digital orthophotoquads would help to overcome this problem.

(2) Mean annual runoff computed from rainfall: Five stream gages in the basin (Aransas, Chiltipin, Copano, Medio, and Mission) were used, of which Chiltipin and Medio are now closed and the Mission River record is the longest (1960 to present). For each gage, the watershed drainage area was delineated from the grid model, as shown in Figure 5. The derived drainage areas generally are within 3% of the corresponding drainage areas tabulated in the USGS gage records.

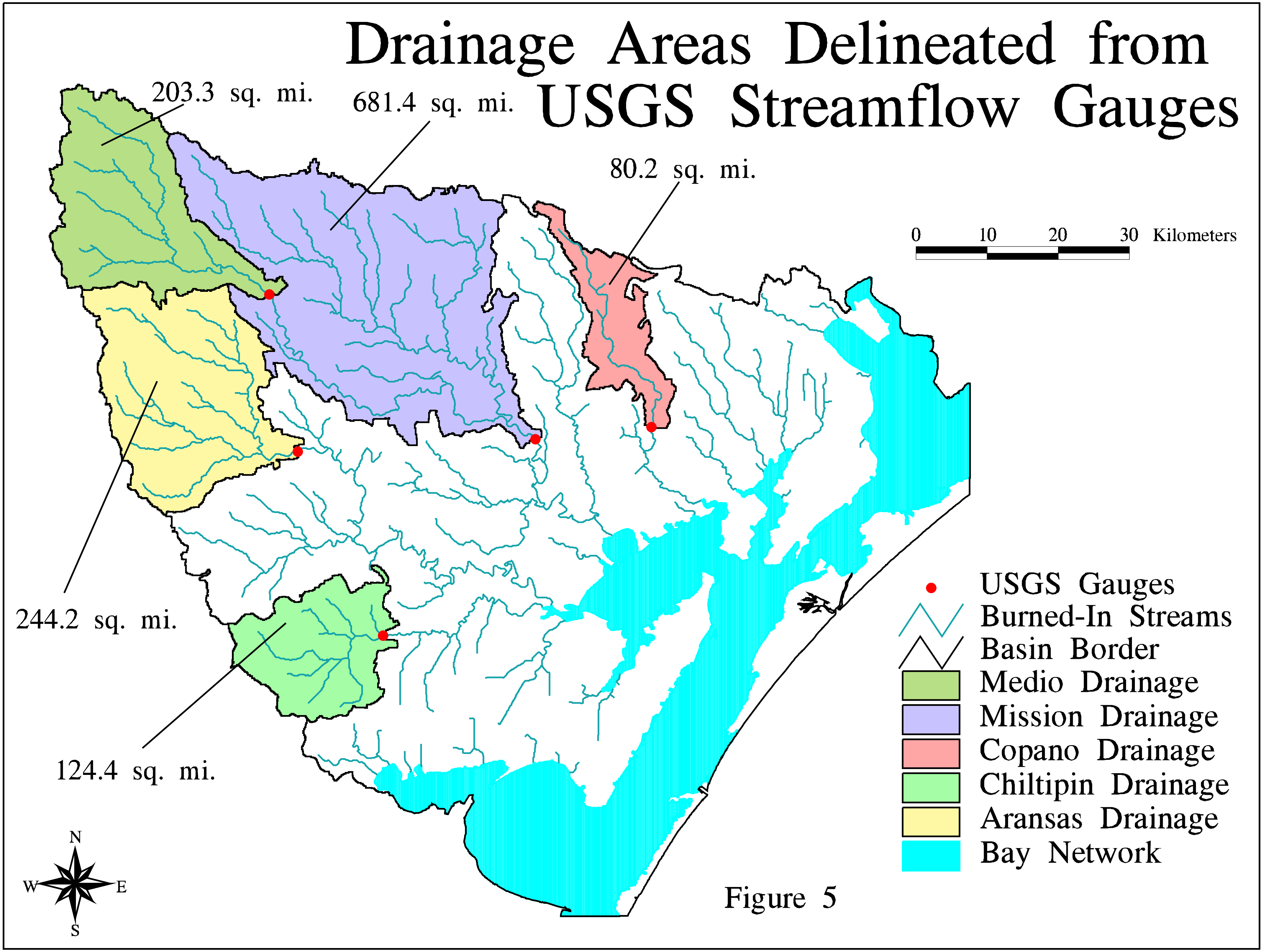
The mean annual rainfall on each 100m cell is found by using a standard mean annual precipitation grid for the US for 1961-1990 developed by Oregon State University and the USDA Natural Resources Conservation Service (Daly, et. al., 1994), for which the portion overlying the San Antonio - Nueces basin is shown in Figure 6(a). The mean annual precipitation for each gage was determined by spatially averaging the precipitation over the cells in its drainage area. The mean annual flow, Q_g, at a specific gage for the period 1961-1990 is estimated from the mean annual flow for that period at the Mission gage, Q_m, by calculating the ratio of the mean annual flow at the gage, q_g, with that at the Mission gage, q_m, for the periods when records are available at both gages, according to the relation:

$$Q_g = Q_m \frac{q_g}{q_m} \qquad (1)$$

The mean annual flow so computed is divided by the drainage area to give a result in mm/yr and plotted against mean annual precipitation, also in mm/yr, for the corresponding drainage area, as shown in Figure 6(b). A straight line fit is made to these five points, which yields the equation:

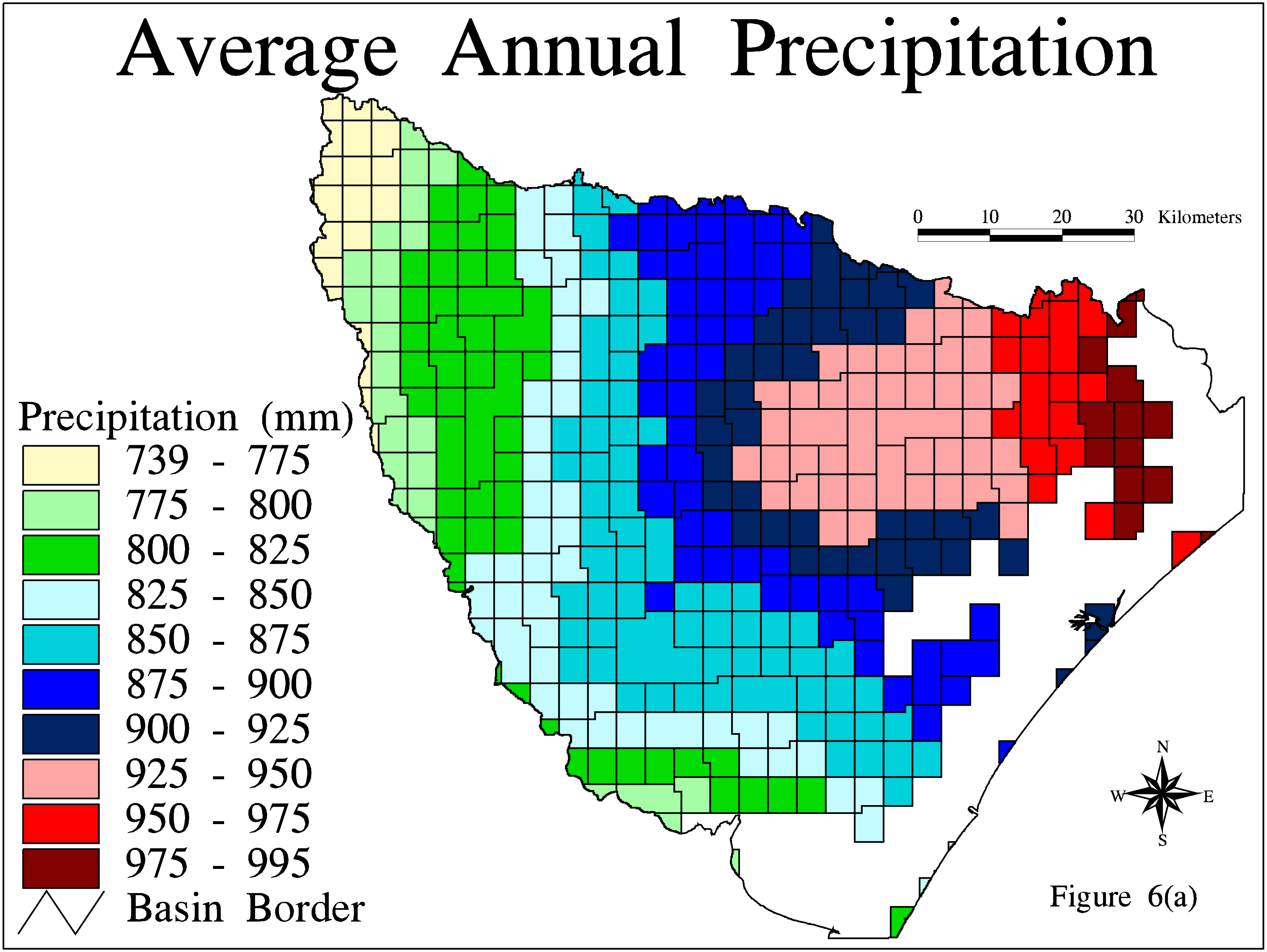
$$Q = 1.0527 * P - 799.37 \qquad (2)$$

The mean annual runoff can be found for each cell by applying Eq. (2) to the precipitation grid shown in Figure 6(a), to produce a grid of runoff per unit area, Q, in mm/yr as shown in Figure 6(c).



Drainage Areas Delineated from USGS Streamflow Gauges
203.3 sq. mi.
681.4 sq. mi.
80.2 sq. mi.
244.2 sq. mi.
124.4 sq. mi.
0 10 20 30 Kilometers
USGS Gauges
Burned-In Streams
Basin Border
Medio Drainage
Mission Drainage
Copano Drainage
Chiltipin Drainage
Aransas Drainage
Bay Network
N
W
E
S

Figure 5


Average Annual Precipitation
0
10
20
30
Kilometers
Precipitation (mm)
739 - 775
775 - 800
800 - 825
825 - 850
850 - 875
875 - 900
900 - 925
925 - 950
950 - 975
975 - 995
Basin Border
N
W
E
S
Figure 6(a)

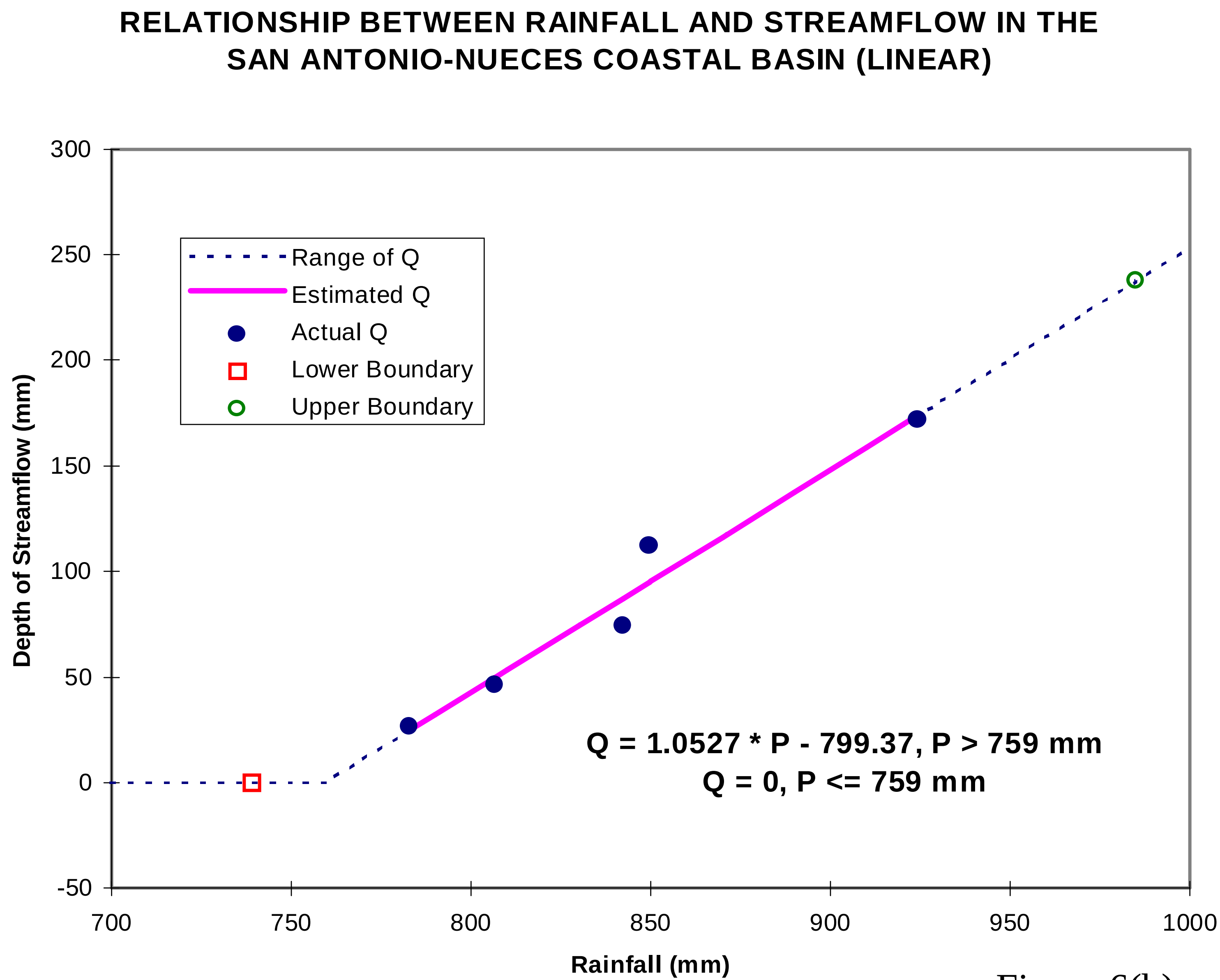
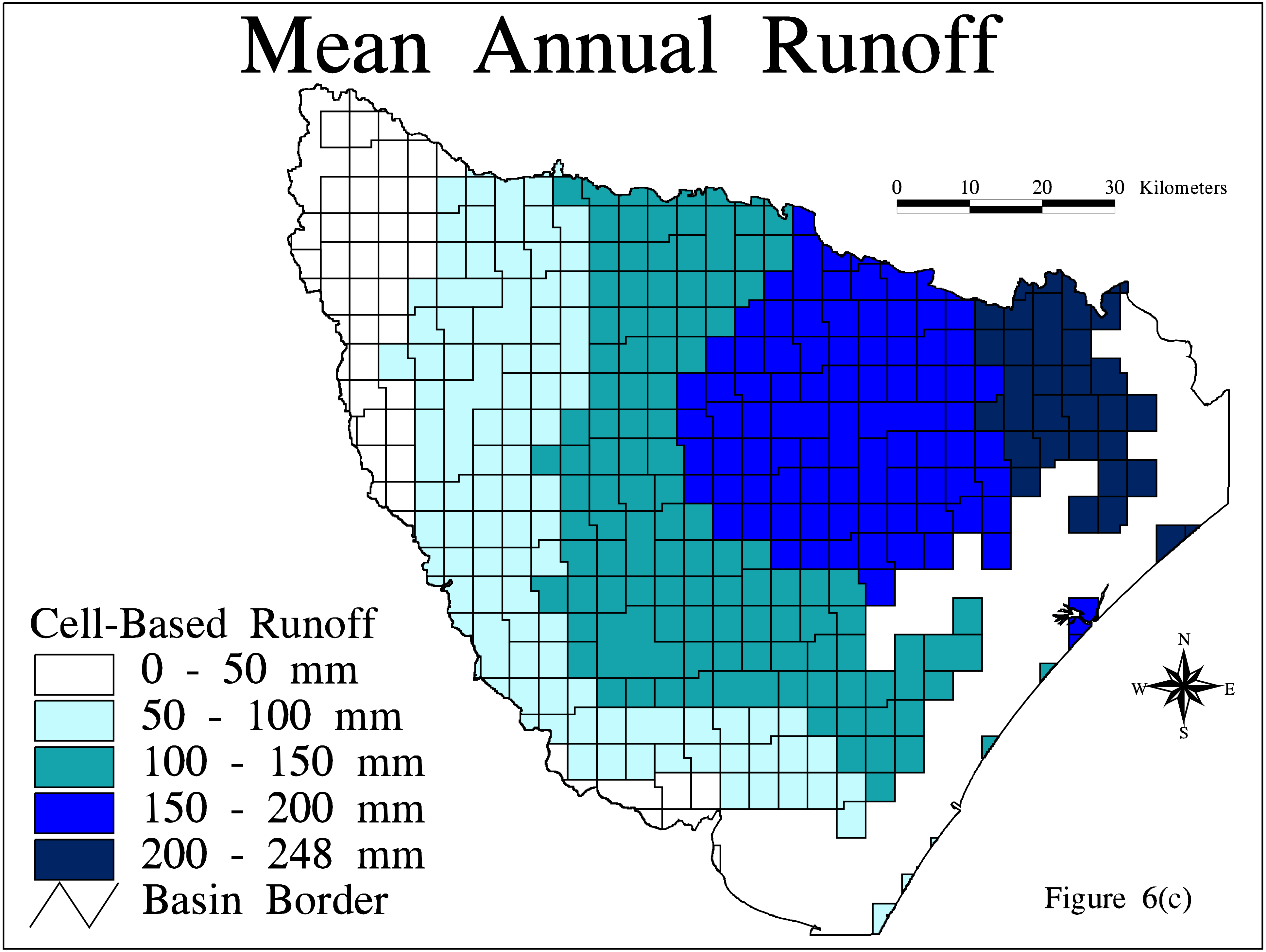

RELATIONSHIP BETWEEN RAINFALL AND STREAMFLOW IN THE SAN ANTONIO-NUECES COASTAL BASIN (LINEAR)
300
250
200
150
100
50
0
-50
Depth of Streamflow (mm)
Range of Q
Estimated Q
Actual Q
Lower Boundary
Upper Boundary
Q = 1.0527 * P - 799.37, P > 759 mm
Q = 0, P <= 759 mm
700
750
800
850
900
950
1000
Rainfall (mm)

Figure 6(b)


Mean Annual Runoff
0 10 20 30 Kilometers
Cell-Based Runoff
0 - 50 mm
50 - 100 mm
100 - 150 mm
150 - 200 mm
200 - 248 mm
Basin Border
N
W
E
S
Figure 6(c)

The set of values for which Eq. (2) is derived ranges from P = 783 mm, Q = 34 mm at the Medio gage to P = 924 mm, Q = 181 mm at the Copano gage. In applying this equation to the precipitation grid to determine the runoff from each cell, the equation was applied over a wider range from 739 mm to 985 mm/yr of precipitation, mostly including the wetter areas near the coast for which there are no stream gaging records in this basin. While Eq. (2) gives a reasonable estimate for the inland portion of the basin for which stream gaging records exist, it would be more reliable to add data from gages in adjacent basins which have greater and less precipitation than that in the San Antonio - Nueces basin so that the range of application of the rainfall-runoff relation can be extended and its form estimated more accurately. In fact, if precipitation P falls below 759 mm/yr (30"/yr), then Q goes to 0 in Eq. (2), so this equation should not be applied outside this basin without further testing and addition of further gages.

(3) Expected Pollutant Concentration Related to Land Use: The measure of pollutant level during a runoff event is the *expected mean concentration*, or EMC, measured in mg/liter or mg/l, defined as the ratio of the mass of pollutant in the event divided by the volume of runoff. The expected mean concentration has a statistical distribution, and varies in value from event to event but that statistical variation was not included in this study. It is assumed that the expected mean concentration is directly related to the land use in the drainage area. For the San Antonio - Nueces basin, the land use is defined by the USGS Land Use/Land Cover files which use a two level land use classification called the Anderson system. At the first level, major land use types are distinguished (Urban, Agriculture, Rangeland, Forest, Water, …) while subcategories of these types are identified at the second level. Figure 7 shows the land use in the San Antonio - Nueces basin. In the Mission and Copano watersheds to the North and East, the land use is primarily rangeland and low forest; in the Aransas watershed to the South and West, the land use is primarily agriculture. The USGS land use study which underlies the data presented in Figure 7 was conducted during the 1970's using interpretation of remotely sensed images. It is likely that in some areas of the basin, the land use has altered since that time and it would be useful to have a more up to date land use map.

As part of the Oso Creek study, the Natural Resource Conservation Service compiled expected mean concentration values for non-point source pollution for various land uses, as shown in Table 1, and they kindly made these estimates available for our study. Using the GIS, the land use in each 100 m cell was determined, and by employing Table 1, the corresponding expected mean concentration for various pollutants was determined for each cell, as shown in Figure 8 for total phosphorus.

(4) Downstream Pollutant Loadings Determined: The contribution, L (kg/yr), that each cell makes to downstream pollutant loading can be found by taking the product of the cell area, A, from Step 1 (A = 10,000 m^2), the runoff per unit area, Q (mm/yr), from Step 2, and the expected concentration, C (mg/l), from Step 3, using the equation:

$$L = KQCA \qquad (3)$$

where $K = 10^{-6}$ is a constant to make the units consistent. A value of L is computed for each cell in the landscape to represent its local contribution to contaminant loading. The accumulated

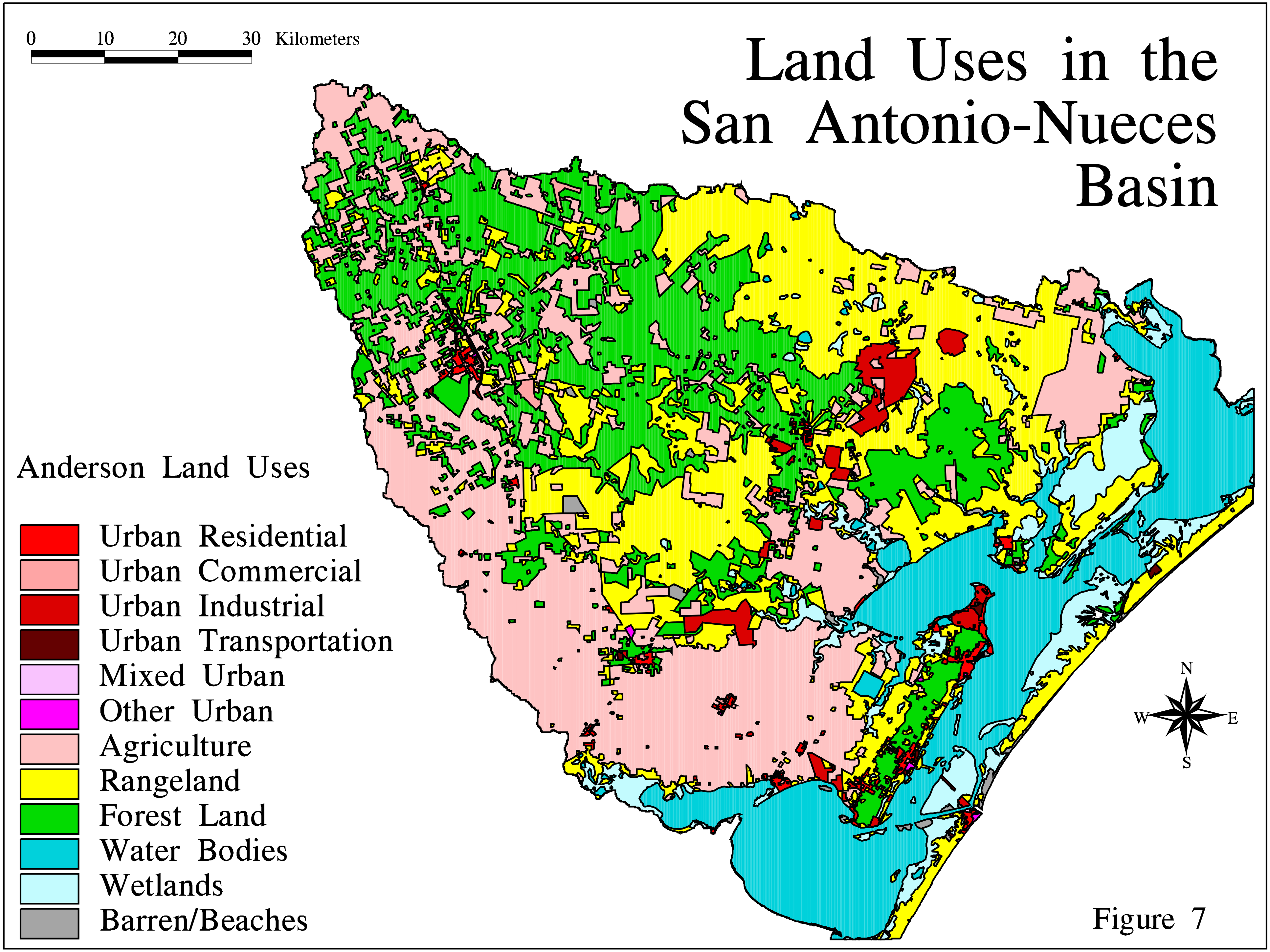

0
10
20
30
Kilometers
Land Uses in the San Antonio-Nueces Basin
Anderson Land Uses
Urban Residential
Urban Commercial
Urban Industrial
Urban Transportation
Mixed Urban
Other Urban
Agriculture
Rangeland
Forest Land
Water Bodies
Wetlands
Barren/Beaches
N
W
E
S

Figure 7

Constituent	Urban Res 11	Urban Comm 12	Urban Ind 13	Urban Trans 14	Urban Mixed 16/17#	Agr 2*	Range 3*	Undev/ Open 7*
Total Nitrogen (mg/L)	1.82	1.34	1.26	1.86	1.57	4.4	0.7	1.5
Total Kjeldahl N. (mg/L)	1.5	1.1	1	1.5	1.25	1.7	0.2	0.96
Nitrate + Nitrite (mg/L as N)	0.23	0.26	0.3	0.56	0.34	1.6	0.4	0.54
Total Phosphorus (mg/L)	0.57	0.32	0.28	0.22	0.35	1.3	<0.01	0.12
Dissolved Phos (mg/L)	0.48	0.11	0.22	0.1	0.23			0.03
Suspended Solids (mg/L)	41	55.5	60.5	73.5	57.9	107	1	70
Dissolved Solids (mg/L)	134	185	116	194	157	1225	245	
Total Lead (µg/L)	9	13	15	11	12	1.5	5	1.52
Total Copper (µg/L)	15	14.5	15	11	13.9	1.5	<10	
Total Zinc (µg/L)	80	180	245	60	141	16	6	
Total Cadmium (µg/L)	0.75	0.96	2	<1	1.05	1	<1	
Total Chromium (µg/L)	2.1	10	7	3	5.5	<10	7.5	
Total Nickel (µg/L)	<10	11.8	8.3	4	7.3			
BOD (mg/L)	25.5	23	14	6.4	17.2	4	0.5	
COD (mg/L)	49.5	116	45.5	59	67.5			40
Oil and Grease (mg/L)**	1.7	9	3	0.4	3.5			
Fec Coliform (col./100 ml)**	20,000	6,900	9,700	53,000	22,400		200	
Fecal Strep (col./100 ml)**	56,000	18,000	6,100	26,000	26,525			

calculated as average of land uses 11-14
* applied to all subcategories within the land use type
**average concentrations base on instantaneous rather than flow-averaged samples

Table 1 : Relationship Between Land Use and Expected Pollutant Concentrations

Phosphorus EMC Values

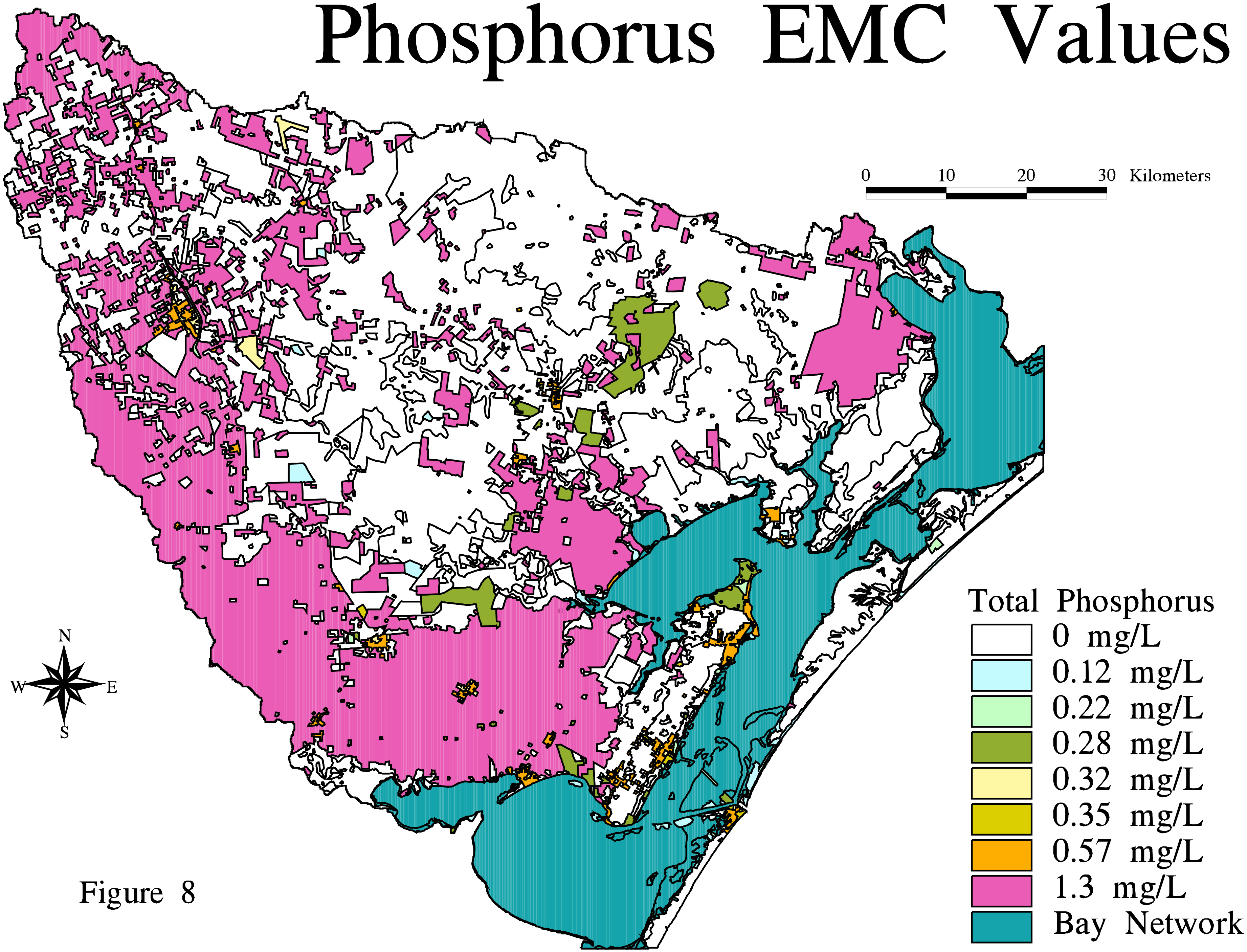


Figure 8

loading going downstream is determined by summing the loadings arising from all upstream cells. The result for phosphorus concentration is shown in Figure 9. Not surprisingly, the highest loadings arise in the Aransas watershed, because of its agricultural land use, and in the Mission watershed because it has the largest drainage area.

An important assumption made in this computation is that the downstream transport process is conservative, that is, the pollutant concentration is not modified by instream water quality processes. A second important assumption is that the expected mean concentration from a runoff event is here applied to the mean annual runoff, which is the sum of all runoff events and the base flow that occurs between events.

(5) Downstream Pollutant Concentrations Compared to Observations: The pollutant concentration sampled at a particular location on a stream is the result of a mixture of all the flows and pollutant loadings that drain from upstream of that location. This mixing process can be approximated for the grid model by taking the accumulated loadings computed in Step 4, and dividing them by similarly accumulated mean annual flows derived from the runoff per unit area found in Step 2. In other words, for each cell on a stream, if one knows the total mean annual pollutant loading, L_a, and the mean annual runoff, Q_a, from the upstream drainage area, the modeled concentration, C_a, at that location is:

$$C_a = \frac{L_a}{Q_a} \qquad (4)$$

Pollutant concentrations have been sampled in the basin at various locations and at various times. Some locations have more data than others. A simplifying assumption is made that the expected concentration observed at a sampling site is simply the average of the measurements made there. In other words, at each sampling point if C_i is the ith measured concentration, i = 1, 2, ..., n, then the average observed concentration, C_o, is:

$$C_o = \frac{1}{n}\sum_{i=1}^{n} C_i \qquad (5)$$

This is equivalent to assuming that the observed pollutant concentrations, C_i, are statistically stationary through time, from year to year, and also within a year, so that seasonal effects are neglected. In studies of agricultural chemical contamination in the Midwest we are taking seasonal variations into account, but the intensity of agrichemical use in the Midwest is much higher than in the San Antonio - Nueces basin.

Average Annual Phosphorus Loads

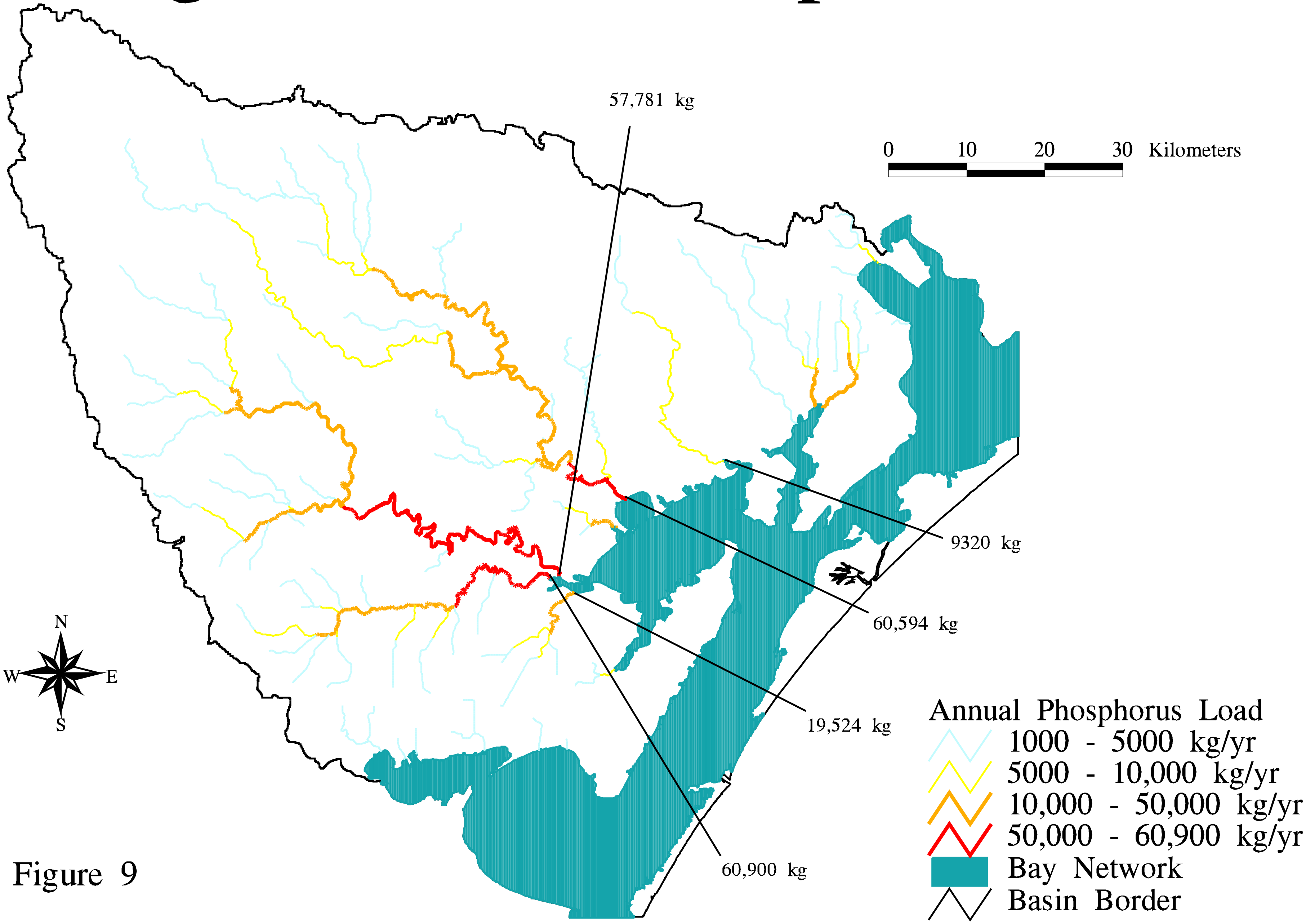


Figure 9

Results

Phosphorus

Colored maps can be created to compare the modeled and observed concentrations, as shown for Phosphorus in Figure 10(a). In this map, the cells along the streams have concentration, C_a, computed by Eq. (4), and are color coded by concentration level. The same color coding scheme is used to shade the circles at each sampling location where the color shown indicates the observed concentration, C_o, found from Eq. (5). The size of the circles at each sample location is proportional to the number of measurements made there. It is apparent by comparing the shading of the modeled streams and the sampled circles that, for total phosphorus, the expected concentration in the Mission and Copano watersheds is consistent with the values observed, a minimal level of approximately 0 - 0.2 mg/l. In the Aransas watershed, the observed phosphorus concentrations are higher than expected, in particular just downstream of the City of Beeville, which appears to have been a significant point source of phosphorus. This conclusion should be tempered by the fact that the data plotted in this figure at that location are mostly from a period in the early 1980's and it is possible that they are not representative of the current situation at Beeville.

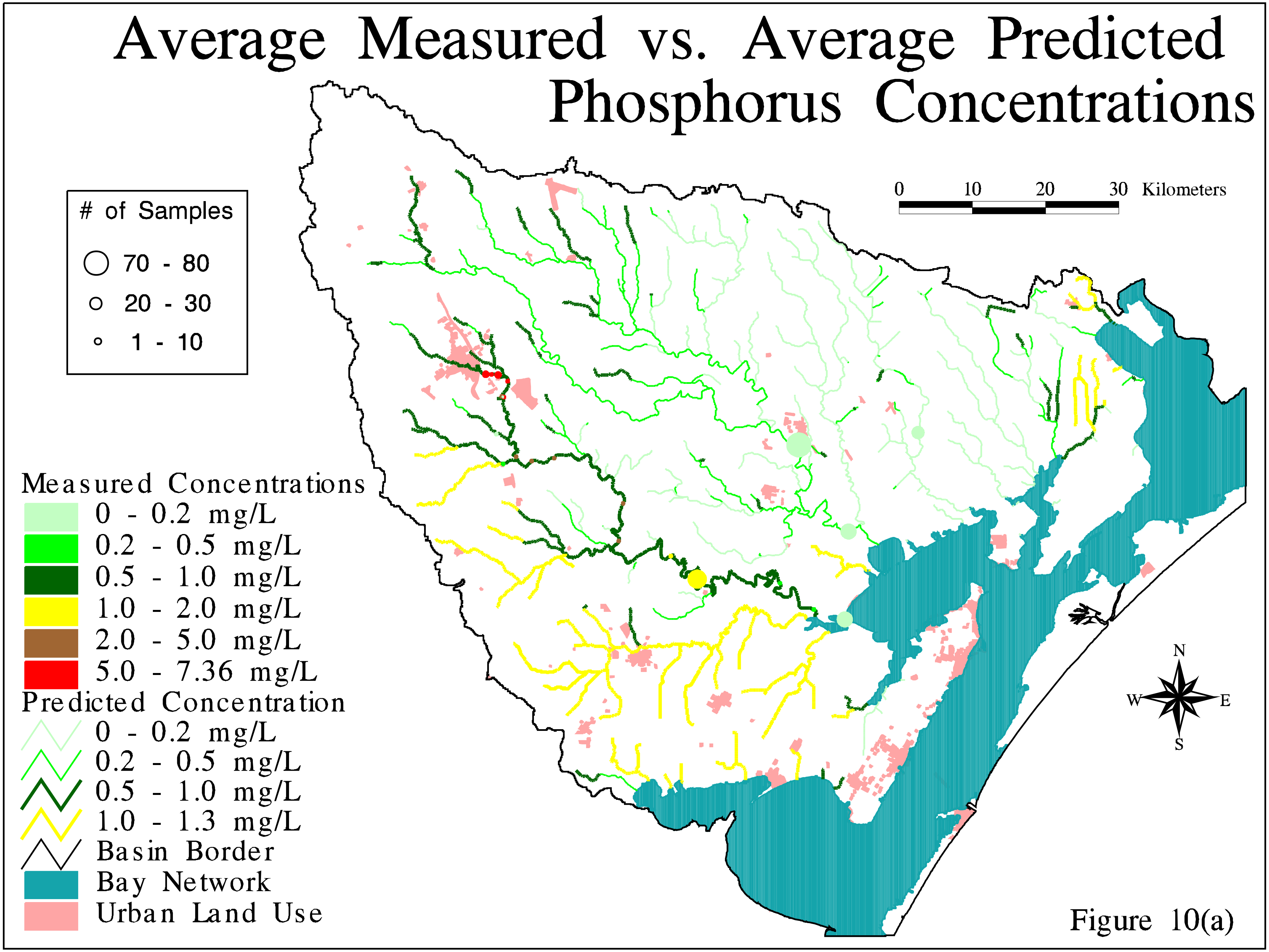
The observed data show an interesting pattern downstream of Beeville, as shown in Figure 10(b). It appears that water with a higher level of contamination gradually becomes diluted as it flows downstream, by the influence of cleaner water coming from downstream tributaries to the Aransas River. The map display of the data provides a useful way of interpreting the spatial pattern of the observed concentrations, as well as of the relation between the modeled and the observed values.

Nitrogen

Figure 11 shows a similarly constructed map comparing observed and modeled concentrations of total nitrogen. In this case, observed levels are everywhere higher than the expected values, with the discrepancy being larger in the Aransas watershed than it is in the Mission and Copano watersheds. It appears that the expected mean concentration levels for nitrogen for all land uses need to be adjusted upward to reflect conditions in this basin. Also, there again appears to be a significant point source effect from the City of Beeville.

Cadmium

Similar calculations to those presented for nitrogen and phosphorus were determined for Cadmium but there are very few observations (a total of 7 measurements) by which the computations can be evaluated and so the concentration map is not presented here.


Average Measured vs. Average Predicted Phosphorus Concentrations
# of Samples
70 - 80
20 - 30
1 - 10
0
10
20
30
Kilometers
Measured Concentrations
0 - 0.2 mg/L
0.2 - 0.5 mg/L
0.5 - 1.0 mg/L
1.0 - 2.0 mg/L
2.0 - 5.0 mg/L
5.0 - 7.36 mg/L
Predicted Concentration
0 - 0.2 mg/L
0.2 - 0.5 mg/L
0.5 - 1.0 mg/L
1.0 - 1.3 mg/L
Basin Border
Bay Network
Urban Land Use
N
W
E
S
Figure 10(a)

Comparison of Concentrations for Samples Taken Just Downstream of Beeville

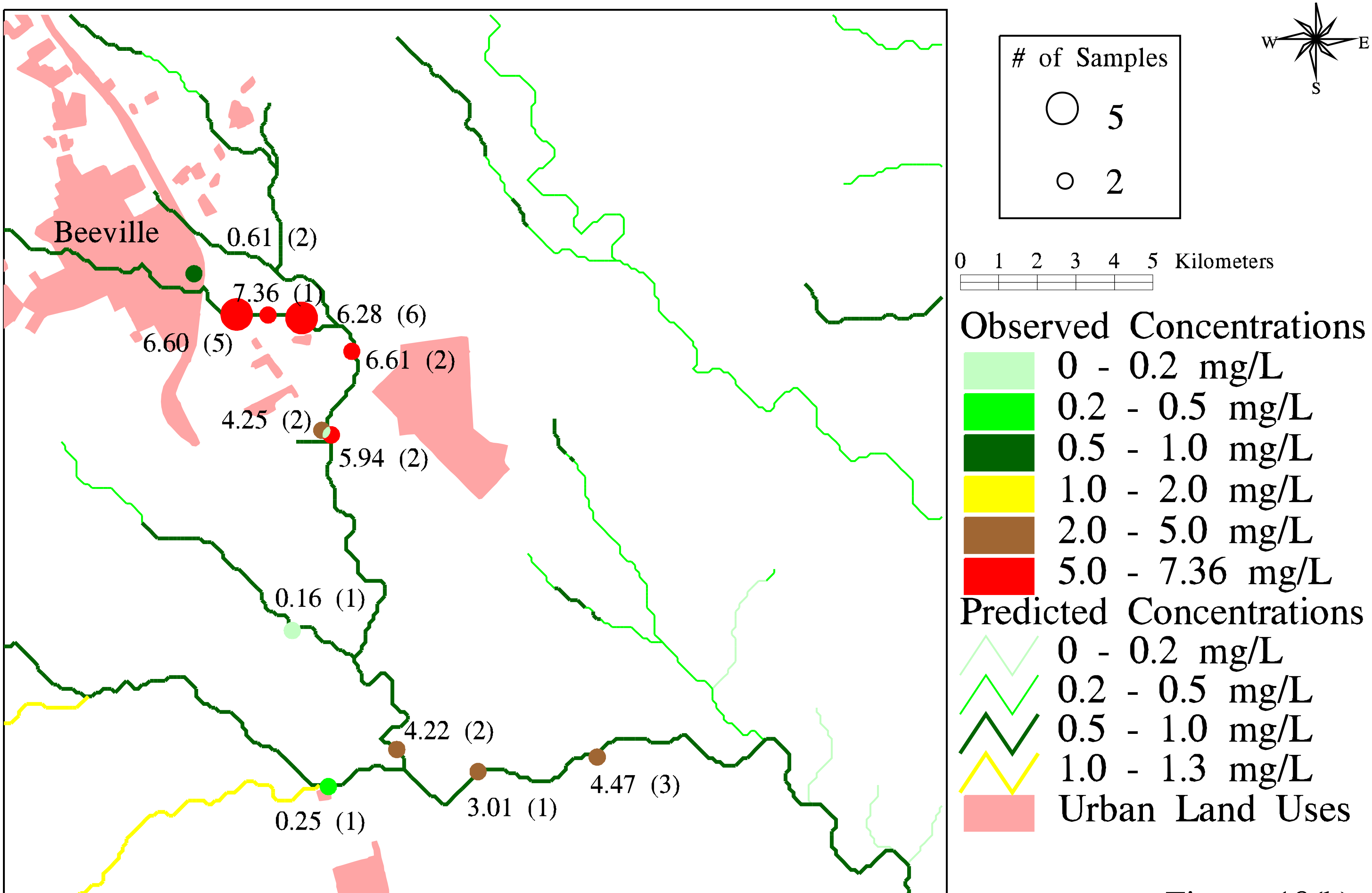


Figure 10(b)

Average Measured vs. Average Predicted Total Nitrogen Concentrations

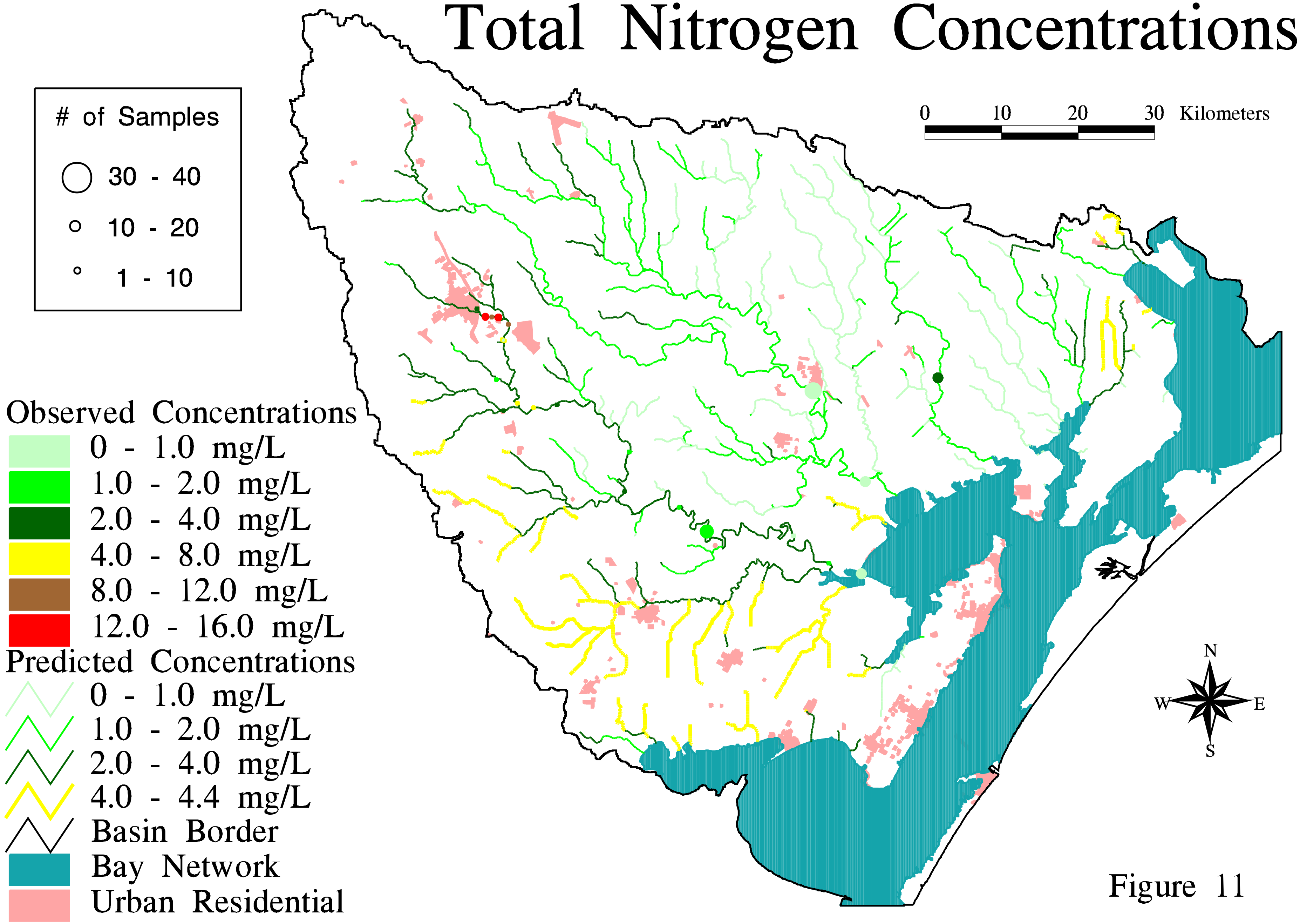


Figure 11

Conclusions

The non-point source pollution assessment method described here has a number of limitations:

- the results given are for mean annual flow and no variations within years or from year to year are given. Flows are highly correlated in space throughout the basin, especially when monthly or annual flows are considered, so a simple way to determine time sequences of runoff values would be to take the runoff data from the Mission gage as an index and use the spatial distribution of runoff per unit area shown in Figure 6(c) to infer the time pattern of flows and pollutant loadings at other locations in the basin.

- pollutant concentration from local runoff is assumed to be directly related to land use in that area and not to vary from event to event. This assumption might be relaxed by statistically sampling from a distribution of event mean concentration values and applying the result to the various cells in the grid mesh, rather than assuming a unique concentration value for each land use.

- pollutant transport is conservative in streams and rivers. No instream processes significantly alter concentrations. This assumption can be relaxed by applying the loadings determined to a water quality simulation model, such as WASP.

- the modeled downstream concentrations are compared to the average of the observed concentrations without differentiating whether the observed concentrations occurred during periods of high flow or base flow. A more detailed study might classify the observations according to the state of the flow at which they were measured to determine if concentration shows significant variations with discharge.

- point sources have not been separately accounted for in the pollutant loading calculations, although it is clear that the City of Beeville is potentially a significant point source.

The advantages of the GIS-based non-point source pollution assessment method described here are:

- it makes use of all the recorded flow and concentration data in the basin and synthesizes them in a logical way that is consistent across the basin.

- the data sources used are all publicly available in digital form. The work of making such a study on a region of several thousand square kilometers in area is not large. The procedures to be employed use standard GIS routines without the need for special programming extensions.

- the principal data imported from outside the South Texas region is the table of values relating land use to expected pollutant concentration (Table 1). By comparing observed stream concentrations with those computed from the tabular relation, the validity of the relation can be examined and adjusted for each pollutant. For phosphorus, the expected concentrations used for rangeland and forest appear to be appropriate for the San Antonio - Nueces Coastal Basin while those for agricultural land may be too low. For nitrogen, the expected concentrations used are too low for all land uses and need to be adjusted upward.

- the spatial analysis over the basin shows spatial patterns of pollutant levels and highlights areas where additional sampling is needed. In particular, sampling should be conducted on agricultural land use areas in the Aransas watershed, and in the Aransas river downstream of Beeville.

Acknowledgments

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