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Inventory of Ponds in the Brazos and Colorado River (Texas) Drainages, from NASA Color Infrared Photography

THE TEXAS AGRICULTURAL EXPERIMENT STATION / Neville P. Clarke, Director / The Texas A&M University System / College Station, Texas

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SUMMARY

NASA color infrared photography was used to inventory the farm ponds of the Colorado and Brazos River basins in Texas. Ponds in randomly selected blocks within larger photographic frames were counted and placed in size classes. In the 65 photographic frames examined of the Colorado River basin 12,367 ponds were identified, and 2,598 ponds were identified in the 7 frames examined of the Brazos River basin.

Ponds were assigned to five size classes: class 1, <1.25 ha; class 2, 1.25-2.5 ha; class 3, 2.5-5 ha; class 4, 5-11.25 ha; class 5, $>$ 11.25 ha. Densities in ponds per km^2 by size class for the Brazos and Colorado River basins respectively were: class 1 - 1.7, 0.97; class 2-0.1, 0.06; class 3-0.02, 0.01; class 4-0.003, 0.003; and class 5-0.002, 0.004.

In the Colorado River basin 92.8 percent of the total ponds counted fell into size class 1 (<1.25 ha) and 5.6 percent of the total count fell into size class 2 (1.25-2.50 ha). In the Brazos River basin these two size groups constituted 93.3 and 5.5 percent of the total ponds counted respectively. Counts in all other size groups were 1 percent or less of the total.

The Colorado River basin pond densities (number per unit area) tended to be low ($>$ 1.5 pond/ha) in the immediate vicinity of the Gulf Coast, and in the Texas High Plains, with a wide range of densities (1.5-3.25 ponds/ha) in the region between the Coastal Plain and the High Plains. In the Brazos River basin, densities tended to increase with distance from the coast. The counting blocks were from 2.1 to 2.3 km^2 wide, and there was no significant change in pond density with distance from the river channel at this resolution.

In a 10 factor stepwise regression model, the factor which explained the most variation in pond count density was average slope, (here defined as the maximum elevation in the county minus the minimum elevation) followed by population density and rainfall, in order of importance. Using the simplifying assumption that all ponds have watersheds which are hydrologically independent, we calculate that in 28 percent of the frames, over one half of land surface would have to be in pond watershed to maintain the pond surface area in the frame. The data also suggest that there may be significant differences in pond density among soil associations ranging from 3.028 ± 0.197 ponds/km^2 in the Castell-Ponotoc-Lignon Soil Association to 0.172 ± 0.123 ponds/km^2 in the Amarillo-Acuff-Mansker Soil Association.

Using pond density data from this study it is estimated that the number of ponds 1.25 ha and smaller is 102,000 for the Colorado River basin, and 191,000 for the Brazos River basin. If the mean density for the two watersheds is applied to the State of Texas, with the Rio Grande River basin excluded, there were an estimated 782,000 ponds 1.25 ha and smaller, and an estimated 840,000 ponds of all sizes in the state, as of 1970.

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INTRODUCTION

Small ponds are abundant in central and eastern Texas. Most are fed by runoff, a few by pumped ground water. These ponds are usually under landowner control and are small enough to be managed for the objectives of the owner.

The extent of the resource is poorly known. Acreage data for ponds larger than 2 acres but smaller than 40 acres have been published by the Soil Conservation Service for 1958 (457,901 acres) and 1967 (456,549 acres) (SCS 1970). Although the reported areas show a slight decrease from 1958 to 1967 some counties show drastic and unexplained decreases which call the quality of the data into question: Denton County decreased from 36,200 acres to 2,049; Andrews County from 2,000 to 10; Cottle County from 5,000 to 0. Pond numbers were reported for the first time in the 1977 SCS National Erosion Inventory Estimates, (SCS 1978) where Texas is listed with 126,881 ponds smaller than 40 acres, with total pond surface area of 409,000 acres.

The SCS also reports another estimate of pond numbers in Texas, which is a cumulative count of the number of ponds for which the SCS has participated in design or construction. This figure was 299,038 as of 1981 (per. comm., J. W. Hill, Assistant State Conservationist for Water Resources). A much more intensive inventory by the SCS is currently under way.

The current study is based on color infrared photographs taken by a NASA aircraft. The film consists of continuous frames of the Colorado River basin taken on three flight lines between the river mouth at the Gulf of Mexico and the headwaters near the New Mexico border. A smaller number of frames taken on one flight down the Brazos River watershed is also analyzed. The film, along with the flight documentation provided by NASA, provides an excellent opportunity to investigate the relationship of pond distribution to a variety of parameters.

MATERIALS AND METHODS

The photographs analyzed are from Mission 123, Test Site 213, Colorado River, taken on 13 March 1970. The photographs were taken using an RC-8 camera with a 6-inch focal length lens, 9-inch color infrared film (SO-117), and filter No. 12 (500-nm). The roll examined was a duplicate of the original positive transparency film. The roll contained 195 frames of the Colorado River watershed and 22 frames of the Brazos River watershed. Contiguous frames overlapped approximately 30 percent and every third frame was examined, with 65 frames examined in the Colorado River watershed and seven frames in the Brazos River watershed. The flight paths are shown in Figure 1.

The film was examined on a light table equipped with a movable stereomicroscope. A clear plastic overlay was constructed which divided the central 200 × 200 cm area of the frame into 100 blocks, each 2 cm^2, making 10 rows of 10 blocks each. In eight frames spaced at intervals along the watershed, all 100 blocks were examined. For the majority of the frames, three of the 10 rows were selected at random and all 10 blocks in each row were examined. The rows were at right angles to the river. In all, 2,370 blocks were examined. Flight altitude and surface elevation varied along the flight paths, with the area covered by the counting grid varying from 450 to 529 km^2 (174 to 204 square miles). This made the block, or counting unit, 2.12 to 2.30 km on a side. Flight book data permitted the calculation of actual plane to ground distance for each frame, and area conversions were calculated for each frame to correct count data used for density estimates and statistical procedures. The ponds counted were scored, by observation, into five size classes by comparing them to a set of reference areas of known size. (Table 1).

The number of blocks between the examined block and the river

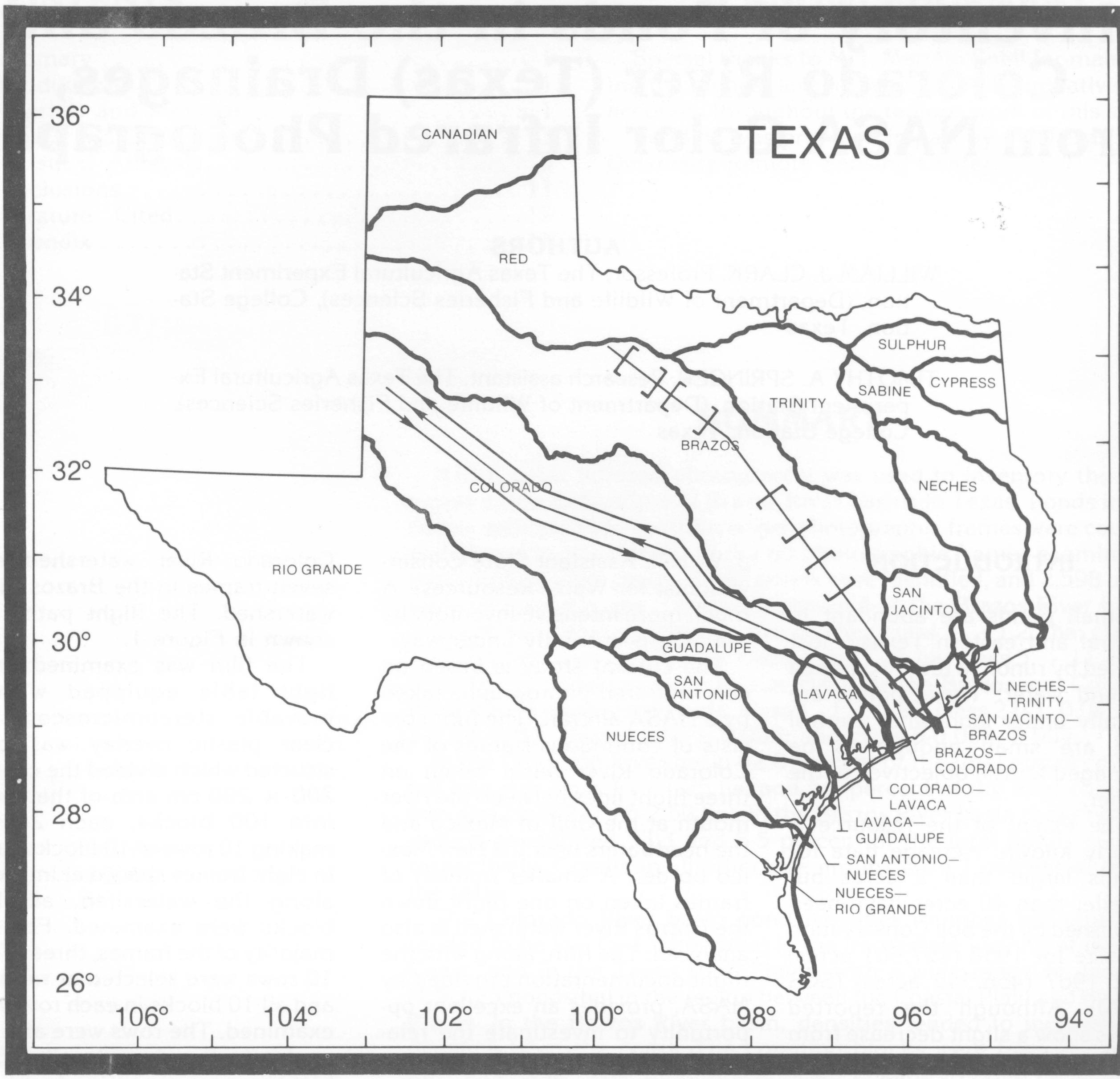

Figure 1. Watersheds of Texas rivers, with lines showing flight paths of NASA Mission 123. Sections of flight path in the Brazos River basin where photographs were taken are shown by brackets.

was also recorded. The photographic frames used were located on the Geological Highway Map of Texas (Renfro and Feray 1973) and on the General Soils Map of Texas (Godfrey, et al. 1973) using the location data provided on maps in the flight information publication. Each frame counted was then classified as to geology and soil type using the following scheme:

1. Geology
   a. The color coded categories of the geological map (basically rock systems) were used as the units of classification, and each system present in the block was recorded.
   b. For each frame the following were recorded:
      1. dominant formation in frame,
      2. subdominant formation in frame, and
      3. number of formations found within the frame.
2. Soils
   a. The color coded categories of the soil map (major soil associations) were used as units of classification.
   b. For each frame the following were recorded:
      1. dominant soil association in frame,
      2. subdominant soil association in frame, and
      3. number of soil associations found within the frame.

The following information was recorded for each county within which frames were censused:

1. Average rainfall (Pass 1980)

TABLE 1. PARAMETERS FOR POND SIZE ESTIMATION

Size of Reference Areas	Corresponding* Area on the Ground (hectares)	Pond Size Classes	Class Size Ranges
—	< 1.25	1	< 1.25 ha (< 3.1 acres)
1 mm^2	1.25 (1.1-1.3)	2	1.25-2.5 ha (3.1-6.2 acres)
2 mm^2	2.5 (2.3-2.6)	3	2.5-5 ha (6.2-12.6 acres)
4 mm^2	5 (4.5-5.3)	4	5-11.25 ha (12.6-27.8 acres)
9 mm^2	11.25 (10.1-11.9)	5	> 11.25 ha (> 27.8 acres)

*Flight altitude aboveground varied somewhat, and a mean area value was used in the calculations. The range is given in parenthesis.

2. Agricultural region (BBR 1976)
3. Cattle numbers (TCLR 1976)
4. Runoff (USGS 1966)
5. Slope (maximum altitude - minimal altitude)
6. Irrigated acreage (TCLR 1976)
7. Rural population (USBC 1971)
8. Land resource areas (Godfrey et al. 1973)

RESULTS AND DISCUSSION

A total of 14,965 ponds was enumerated, 2,598 in the Brazos River watershed and 12,267 in the Colorado River watershed. Distribution by size group is given in Table 2. Ponds as small as 0.2 ha could be recognized, and the overwhelming number of ponds in both watersheds is smaller than 1.2 ha. The distribution by size is very nearly the same in the two watersheds.

Mean densities by size group are given in Table 3. Mean values for block area were used in the density calculations. Ponds of the two smaller size groups were approximately twice as abundant per unit area in the Brazos River watershed as in the Colorado River watershed. However, the area covered in the Brazos River watershed is just over 10 percent of that covered in the Colorado River watershed, and the two watersheds differ in climatic and "soil-influenced" characteristics. Figure 6a shows many frames of very low pond density in the upper Colorado, while the upper Brazos has its greatest densities in the uppermost reaches which were photographed. No photography was taken in the upper part of the Brazos River basin, where land use would be similar to that of the upper Colorado River basin, and where pond densities would probably be similar. The highest densities per frame found in the study were in the Central Colorado drainage. The pond numbers in the two larger size classes are too small to permit meaningful comparisons.

In an unpublished study of Brazos County ponds, where all ponds from SCS photography, were counted, the pond density was 0.93 ponds/km^2, in general agreement with densities reported in this study.

Frequency distributions of counts per block are given in Figures 2 to 4. Counts of over one pond per block were rare for the three larger size classes in either watershed, and are not shown. For size class 2 (1.25-2.5 ha) both watersheds had one instance each of 5 and 6 ponds per block, otherwise counts were predominantly 1 or 2 ponds per block.

The pattern of distribution of size class 1 pond counts differed significantly between watersheds. For the Colorado River basin (Fig. 2), the frequency declined exponentially from 1 to 22 ponds per block, and then remained fairly constant. For the Brazos River basin (Fig. 3), the frequency of counts remained quite stable from 1 to 14 ponds per block, and then declined from 14 to 27 ponds per block, with the maximum density reported at 38 ponds per block. There is no ready explanation for the difference in frequency distribution; more detailed information on size of land holdings, differences in land use and other demographic data might suggest reasons. Of the 26 blocks with counts > 30 in the Colorado River basin, 20 came from three frames in Llano and San Saba Counties. Two of these blocks had the highest pond counts observed (74 and 92 ponds). They included eight class 5 ponds (> 11.25 ha), more than any other frame and 17 percent of the total class 5 ponds counted. The number of blocks with no ponds was twice as great

TABLE 2. POND DISTRIBUTION BY SIZE CLASS, NUMBER, AND PERCENT FOR THE AREAS SURVEYED IN THE COLORADO RIVER AND BRAZOS RIVER WATERSHEDS

Watershed		Pond Size Class					Total Ponds
		1	2	3	4	5	
	(hectares)	< 1.25	1.25-2.5	2.5-5	5-11.25	> 11.25	
	(acres)	< 3.1	3.1-6.2	6.2-12.4	12.4-27.8	> 27.8	
Colorado	No.	11,477	693	120	30	47	12,367
	%	92.8	5.6	1	0.2	0.4	
Brazos	No.	2,424	142	25	4	3	2,598
	%	93.3	5.5	1	0.2	0.1	
TOTAL	No.	13.901	835	145	34	50	14,965
	%	92.9	5.6	1	0.2	0.3	

TABLE 3. MEAN POND DENSITIES (PONDS/km^2) BY POND SIZE FOR THE AREAS SURVEYED IN THE COLORADO AND BRAZOS RIVER WATERSHEDS

Watershed	Pond Size Class				Total Ponds
	1	2	3	4	5
(hectares)	< 1.25	1.25-2.5	2.5-5	5-11.25	> 11.25
(acres)	< 3.1	3.1-6.2	6.2-12.4	12.4-27.8	> 27.8
Colorado	0.97	0.06	0.01	0.003	0.004
Brazos	1.7	0.1	0.02	0.003	0.002

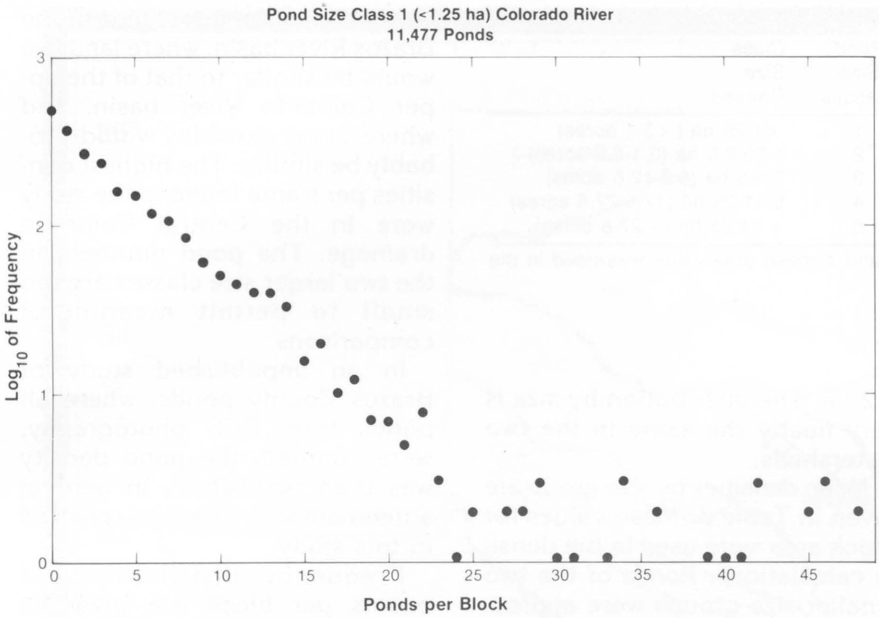

Figure 2. Frequency of counts of ponds per block, for pond size class 1 (< 1.25 ha), in the Colorado River watershed.

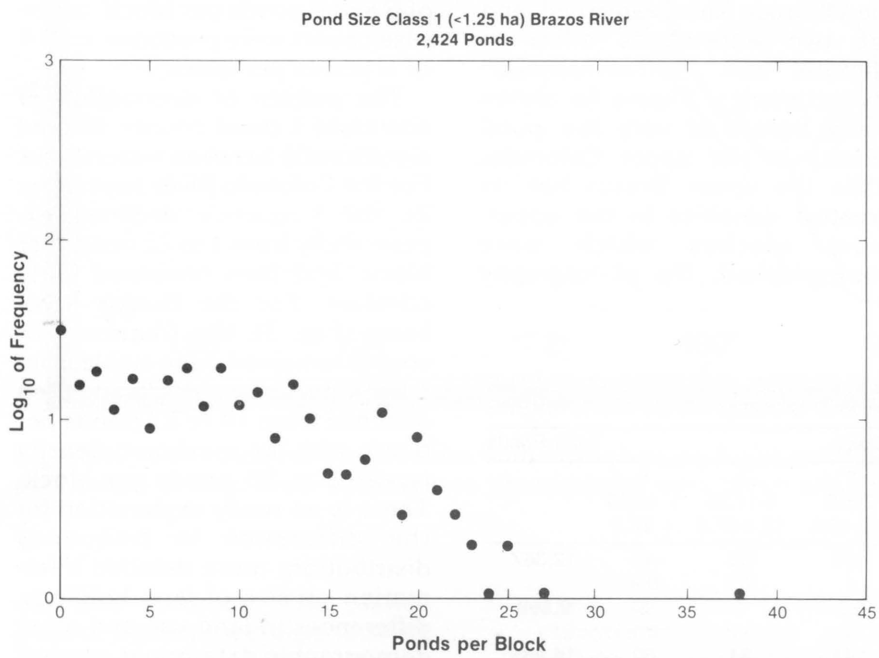

Figure 3. Frequency of counts of ponds per block for pond size class 1 (< 1.25 ha), in the Brazos River watershed.

in the Colorado River basin as in the Brazos River basin. The distribution of counts for size class 2 ponds (1.25-2.5 ha) was similar in the two watersheds (Fig. 4).

Variations in pond density with distance from the Colorado River are shown in Figure 5. Assignment to the first category (one block from river) means that the river was in the block being examined. Since a block was from 2.12 to 2.3 km across, any change in pond density near the river must occur in a fairly narrow band or the effect would be evident in Figure 5. However, no trends are apparent.

The flight path of the photographic aircraft was more or less at a right angle to the Gulf Coast. Densities of ponds versus distance from the coast are presented in Figure 6 as average densities per frame. The data set for the Brazos is small, but the data are internally consistent and suggest significant differences between the two basins in pond distribution for size class 1 ponds (<1.25 ha) and to a lesser extent for size class 2 ponds (1.25-2.5 ha). There were no significant trends in pond count with distance for size class 3 ponds (2.5-5 ha), and there were too few size class 4 or 5 ponds for reliable analysis. The data suggest that the parameters controlling the distribution of smaller ponds (<2.5 ha) differ from those controlling larger ponds (> 2.5 ha). Differences in counts between watersheds are greatest for the smallest ponds. For the Brazos there is a consistent increase in pond density with distance from the Gulf. The Colorado River basin is more complex. Like the Brazos, densities are low near the coast, perhaps limited in both watersheds by topography and land use. Away from the Gulf the Colorado densities first increase, and then in the middle distances show an extremely erratic distribution, coincident with the southern Edwards Plateau. The geology here consists of fractured and porous limestone and has high relief, both of which interfere with pond construction, except in stream valleys where ponds are concentrated. In the upper part of

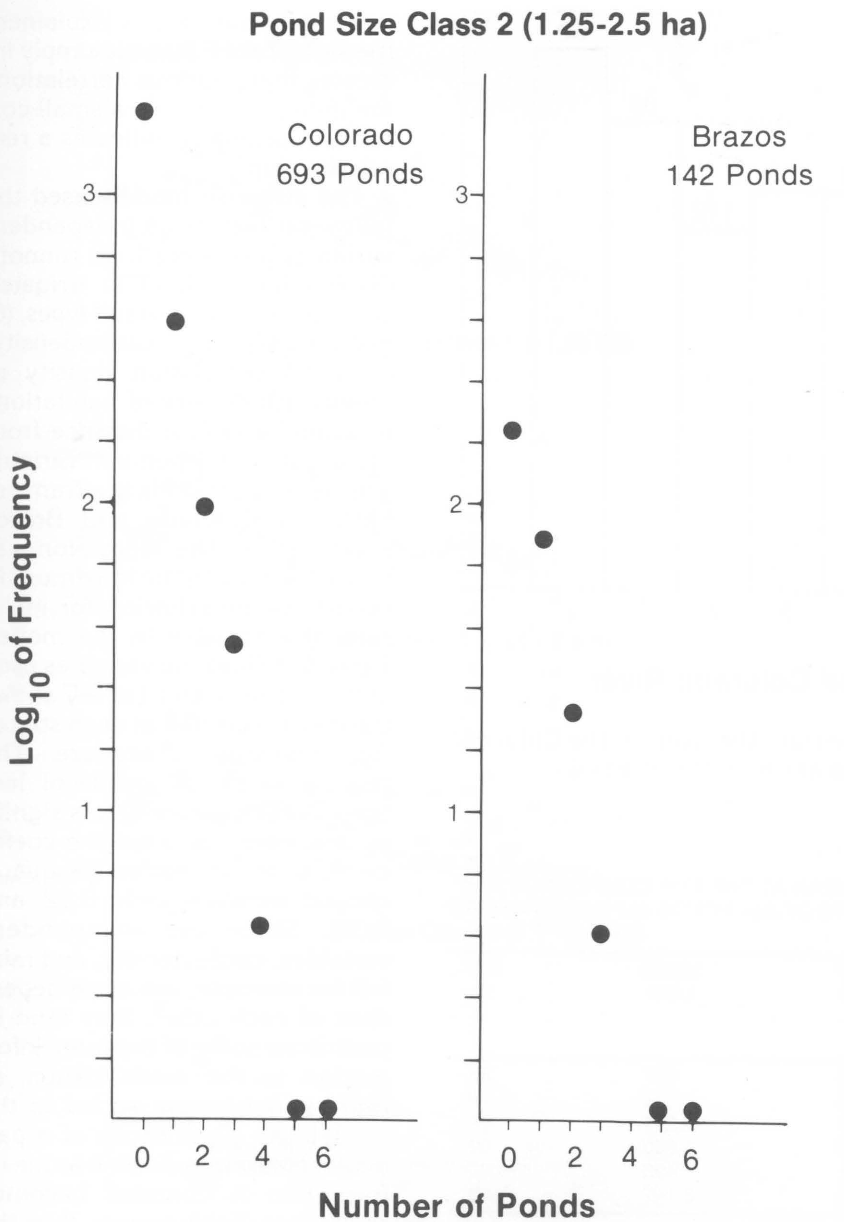

Figure 4. Frequency of counts of ponds per block for pond size class 2 (1.25 - 2.5 ha), in the Colorado and Brazos River watersheds.

the Colorado (High Plains) rainfall is low, evaporation high, and few ponds can persist. In contrast, the Brazos River basin, at the uppermost reaches photographed, has higher rainfall, and land use patterns are more favorable for pond construction. Pond densities in the extreme upper Brazos River basin would probably be similar to the upper Colorado River basin.

The amount of watershed area that would be required to support the ponds in each frame was estimated using data from TSPE (1974) and pond density data from this study. The calculation procedure is given in Appendix A. Figure 7 shows the fraction of the surface area which would be required to support the observed density of ponds of the size indicated, if each pond's water supply were hydrologically independent from the others. Under this assumption, 28 percent of the frames would require more than half of their surface areas to be in pond watersheds to maintain the pond surface they contained. Pond densities for the two larger size classes were to low to show clear trends. For the Brazos River basin the fraction of land surface required to support size class 1 and 2 ponds closely follows the density distribution from the coast inland. For size class 3, the fraction of land surface required shows a trend of increase as distance from the cost increases, though the count density does not. The size class 3 densities are uniformly low. For the Colorado River basin, the fraction of land surface required to support size class 1 ponds also follows the density distribution along the watershed. The fraction of surface area required to support size class 2 ponds parallels pond density in the lower reaches, but shows an inverse relationship with pond number in the upper part. This reflects the increase in evaporation losses and low precipitation in the upper part of the basin. Low count densities obscure any relationship between counts and the fraction of watershed required to support size class 3 ponds. Note that if a large percentage of the ponds intercept the outflow from other ponds, then the estimate of the fraction of the land surface area which is in watersheds is inflated. Hence, it is possible to estimate that more than 100 percent of the available surface area would be required to maintain the ponds.

STATISTICAL ANALYSIS

The statistical characteristics of the distribution of ponds vary considerably between photographic frames. We calculated coefficients of variation (C.V.) and the 95 percent confidence intervals (C.I.) around the means of pond densities in photographic frames where all 100 blocks were counted. The results are given in Table 4.

Sampling errors are fairly large relative to the densities being measured. The skewness (shifting of the peak of the distribution right or left) and kurtosis (a measure of the "heaviness" of the tails of the distribution) of the underlying distributions were calculated. Data

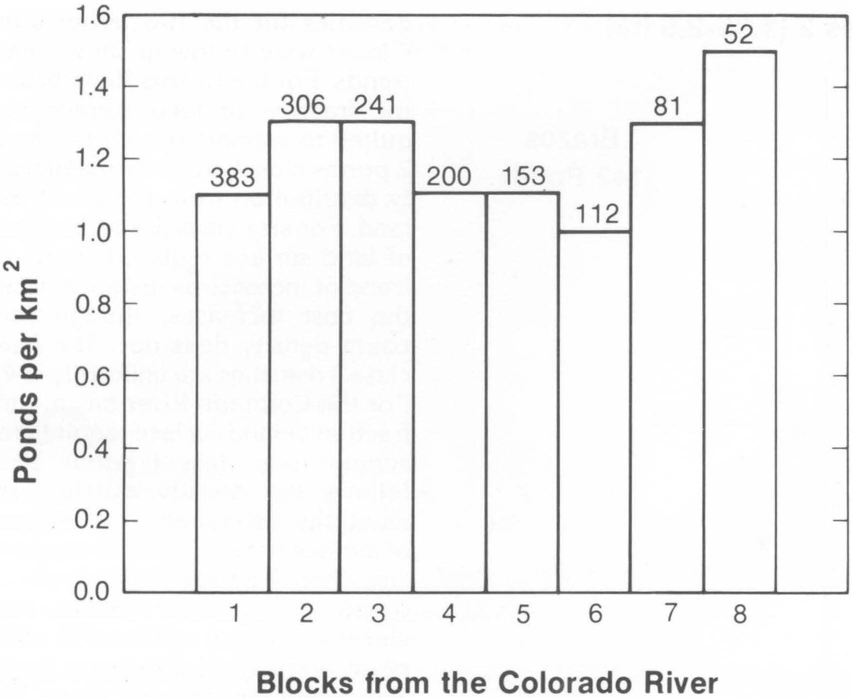

Figure 5. Pond density versus distance from the river for the Colorado River watershed. Numbers above bars are number of ponds.

TABLE 4. CONFIDENCE INTERVAL OF THE MEAN AT THE 95% CONFIDENCE LIMIT AND COEFFICIENTS OF VARIATION OF COUNTS OF ALL PONDS IN FRAMES WHERE ALL 100 BLOCKS ARE COUNTED

Frame	Mean Number per Block	Lower Limit	Upper Limit	C.V. %
1982	.432	.356	.507	88
2012	.572	.466	.678	93
2042	1.250	1.131	1.371	48
2072	1.684	1.488	1.880	59
2101	.412	.331	.493	99
2126	1.970	1.793	2.147	45

drawn from a normal distribution have skewness of 0 and kurtosis of 3; the values of these parameters for pond densities in each frame are given in Table 5.

These statistics indicate that the sampling distributions of the ponds are skewed to the left but show no regular trends with regard to kurtosis. Some caution must be used in performing parametric statistical tests since the counts of ponds in the blocks within the frames do not seem to be normally distributed, and it seems unlikely that any normalizing transformation would be uniformly appropriate.

Stepwise multiple regression analysis was used to examine the relationships between the various factors and the pond densities. The stepwise regression procedure was set up to sequentially report the best models for up to six parameters. It should be noted that the data set treated here is fairly large (72 frames). When interpreting the significance of any regression based on a large data set, a highly significant F statistic may be obtained even though the correlation coefficient may remain small. The small correlation coefficient indicates that only a small fraction of the variability of the dependent variable is explained; the significant F statistic simply indicates that spurious correlations are unlikely and even a small correlation probably indicates a real relationship.

The stepwise models used the following factors as independent variables: (1) rainfall; (2) runnoff; (3) fraction of land in irrigated acreage, (4) slope, (5) soil types, (6) geologic types, (7) cattle density, (8) rural population density of county; (9) density of habitations in frame, and (10) distance from the coast. The dependent variable was density of ponds in a frame of both the Colorado and Brazos River basins. The regression was carried out using the maximum R-square as the criterion for inclusion of a variable in the model. Table 6 defines the variables used in the analysis, and Table 7 shows the model selected at each step of the regression procedure. The regression for all ponds of less than 11.3 ha (Table 7) was significant at each step, but the coefficient of determination (R-square) ranged between only 0.12 and 0.37. Since the independent variables, cattle density, and rainfall for example, are not independent of each other, they tend to contribute some of the same information to the model. Thus, as more variables are added to the model, the significance of a particular factor may decline as the information it contains becomes redundant. If this occurs, then the factor may be dropped from the model, as it was when cattle density was replaced by runoff in step 5 of the regression.

It is informative to compare the probabilities of occurrence of greater F for each of the variables in the six variable model in order to evaluate the relative contribution of each to the prediction of the number of ponds in a frame: The smaller the probability, the less likely it is for the relationship to have occurred by chance, and the greater the predictive value of the variable. In this case, the factor which contributed most to variability of total pond density appears to be the slope factor, which is simply the difference between

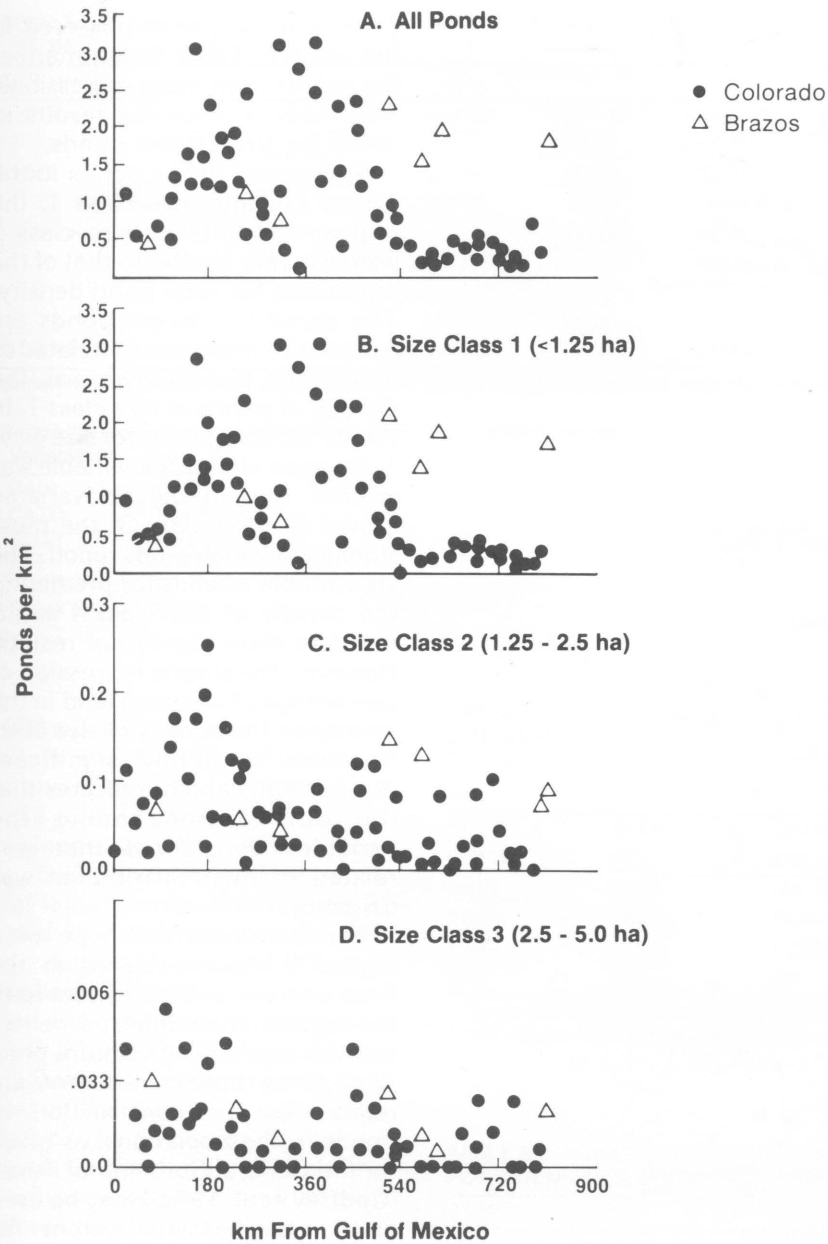

Figure 6. Pond density versus distance from the Gulf of Mexico by pond size, for the Colorado and Brazos River watersheds.

TABLE 5. SKEWNESS AND KURTOSIS OF THE DISTRIBUTIONS OF COUNTS IN FRAMES WHEN ALL 100 BLOCKS ARE COUNTED

Frame	Skewness	Kurtosis
1982	0.89	0.59
2012	1.28	1.39
2042	0.43	-0.40
2072	0.7	0.83
2102	2.10	7.13
2126	0.26	0.36

the minimum and the maximum altitudes in the county, and is a gross measure of topographic relief. The next most important variable in the regression model is population density in the county of the frame. The contributions of all variables to the regression were significant at the $\alpha = 0.05$ level, which indicates that each of the factors included in the model has a significant influence on the number of ponds constructed, and should be retained.

It is important to remember that in a multiple regression model such as the one developed here, the effect of each variable can be thought of as being independent of the others. That is, the effect due to a factor such as population density is equivalent to the contribution which would be obtained if the population density were changed while cattle density was held constant. Thus, the importance of the slope factor may reflect the difficulty of constructing ponds in areas where there are no valleys that can be dammed to form the lake basins, independent of any relation to population density. The high level of significance of population density itself probably reflects a situation in which a high population density is associated with small individual land holdings, where each landowner constructs a pond of his own to gain access to water for agricultural, recreational, and aesthetic purposes. The best single variable model had cattle density as its independent variable, and while the regression was significant, only 12 percent of the variability in pond density was explained. Cattle density was relatively unimportant in the six variable model, indicating that it is related to the other factors in the model in much the same way as pond density.

Different sized ponds tend to be built for different purposes. Small ponds are adequate for cattle watering, but ponds which are to be used as a source of irrigation water must have larger volumes. Thus, we decided to carry out the stepwise regression on the density of each of the different size

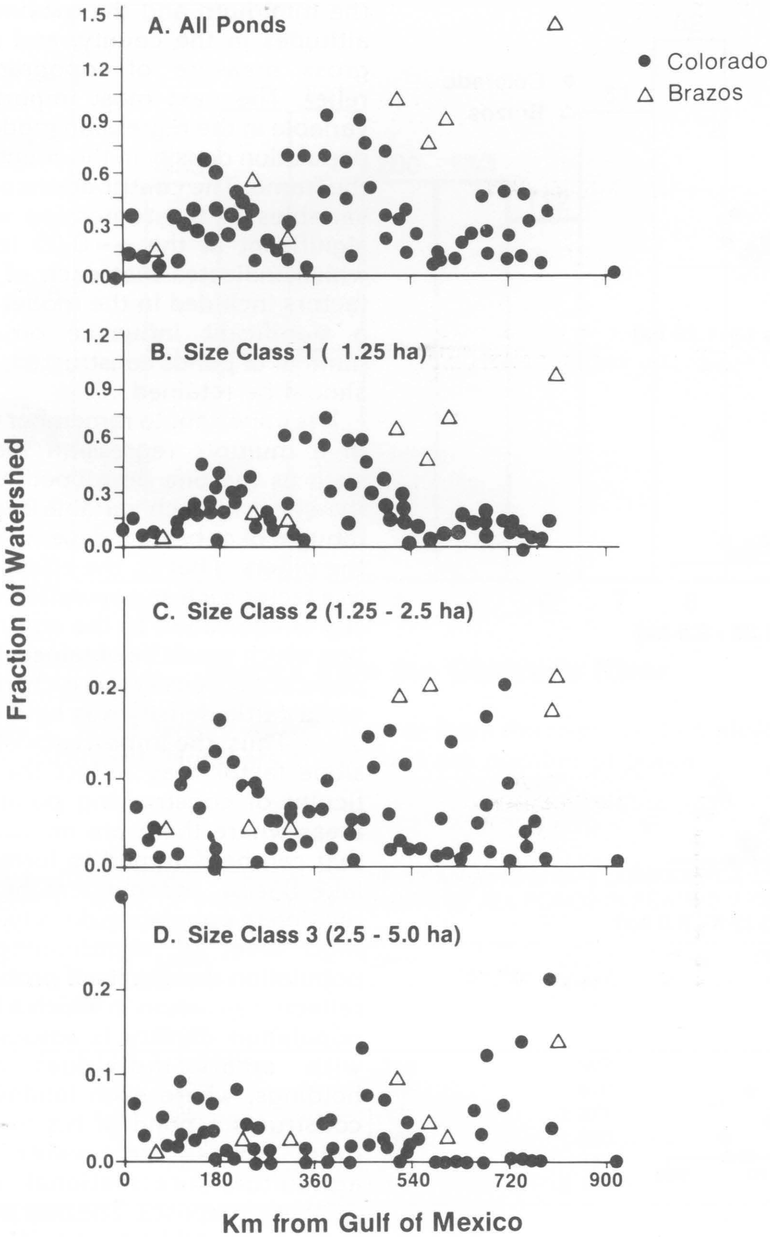

Figure 7. Fraction of the watershed in pond watersheds, by pond size, for the Colorado and Brazos River watersheds.

TABLE 6. VARIABLES USED IN THE STEPWISE REGRESSION ANALYSIS

Variable	Meaning
CATD	Density of cattle in dominant county of frame[1]
DK	Density of geologic types per unit area
DIS	Distance of frame from coast
DN	Density of soil types per unit area
FRMX	Density of habitations observed in frame
IRR	Percent of irrigated land in dominant county of frame[1]
POPD	Rural population density of dominant county in frame[2]
RAIN	Rainfall in dominant county of frame[3]
RUN	Runoff in dominant county of frame[4]
SLOP	Difference between maximum and minimum altitude in dominant county[3]

[1]TCLR (1976). [3]Pass (1980).
[2]USBC (1971). [4]USGS (1966).

classes of the ponds observed in the survey. Table 8 summarizes the results from these regressions, and Table 9 gives the results in detail for size class 1 ponds.

Since most of the ponds in the survey fall into size class 1, the regression model of size class 1 ponds is very similar to that of the regression for total pond density. The density of larger ponds appears to be more closely related to hydrologic factors than was the density of ponds of size class 1. In the six variable model for size class 1, the most significant variable was rainfall, and in the six variable model for size class 3, the most significant variable was runoff. The six variable models for predicting the density of size class 4 and 5 failed to show significant results. However, the simple regression of percentage of irrigated land in the county on the density of size class 5 ponds is highly significant ($P = 0.0065$), which indicates that the only factor among the variables considered that was related to their distribution was irrigation.

The dominant soil type of a region is closely related to the local climate, and influences both the regional hydrologic properties and the regional agriculture practices. Since these same factors are related to the construction of ponds, soil associations, as given on the General Soil Map of Texas (Godfrey et al. 1973), may be used as a classification system for predicting some aspects of the distribution of ponds. Table 10 gives the soil associations which were present in the area encompassed by the aerial survey, and the density of each size class of ponds in each of the soil associations. Sixteen of the 66 Texas soil associations were represented in the sample. It should be noted that the scale of the soils map used did not permit the identification of the many small scale inclusions of other soil types within the soil associations. Subject to the caveat mentioned, the data suggest that there may be considerable differences between pond densities for the soil associations, ranging from a mean density of

TABLE 7. VARIABLE SELECTION DURING STEPWISE REGRESSION OF FRAMEWISE POND DENSITIES FOR PONDS LESS THAN 11.25 HA

STEP	1	2	3	4	5	5	5	6	6
	Intercept	Intercept	Intercept	Intercept	Intercept	Intercept	Intercept	Intercept	Intercept
	CATD*	CATD	CATD	CATD	CATD	RAIN	RAIN	RAIN	RAIN
MODEL		SLOP	SLOP	SLOP	SLOP	CATD	RUN	RUN	CATD
			FRMX	IRR	IRR	SLOP	SLOP	SLOP	SLOP
				FRMX	POPD	POPD	POPD	IRR	IRR
					FRMX	FRMX	FRMX	POPD	POPD
								FRMX	FRMX
R^2	0.125	0.206	0.262	0.296	0.313	0.321	0.324	0.352	0.372
PROB > F	0.0026	0.0004	0.0002	0.0001	0.0002	0.0001	0.0001	0.0001	0.0001

*Underlined variables were significant at $\alpha = 20.05$. Doubly underlined variables are significant at $\alpha = 0.001$.

Probability of F values of parameters of best six-variable model

Variable	Prob > F
RAIN	0.0179
CATD	0.0206
SLOP	0.0002
IRR	0.0271
POPD	0.0133
FRMX	0.0191

3.028 ± 0.197 ponds (all sizes) per km^2 in the Castell - Ponotoc - Ligon Soil Association to 0.172 ± 0.123 ponds (all sizes) per km^2 in the Amarillo - Acuff - Mansker Soil Association. The density of larger ponds (size classes 2, 3, and 4) were highest in the Lufkin - Axtell - Tabor and Wilson - Crockett - Burleson Soil Associations and lowest in the Amarillo - Acuff - Mansker Soil Association.

Differences between pond densities in the land use regions defined by the General Soil Map of Texas (Godfrey et al. 1973) in the overflight area were smaller than differences between pond densities in the soil associations. Table 11 gives the densities of ponds in each land use region and includes data from 10 of the 15 Texas land use categories. Note that the standard deviations of pond densities in land use regions are larger than those of the soil associations, indicating that the latter is more homogeneous and is probably more suitable as a unit for classification. We also attempted to use geologic substrate as a classification variable, but the complexity of the map gave data which could not be interpreted.

Since many ponds are built for agricultural purposes, we also compared the densities of ponds in the different agricultural regions

TABLE 8. RELATIVE IMPORTANCE OF FACTORS IN PREDICTING POND DENSITY BY SIZE CLASS

	POND SIZE CLASS				
ALL	1	2	3	4	5
SLOP	SLOP	RAIN	RAIN	NS**	NS
POPD	POPD	DIS	DN		
RAIN	RAIN	CATD	DK		
FRMX	FRMX	RUN	POPD		
CATD	CATD	FRMX	FRMX		
IRR	IRR	DK	IRR		

*Underlined variables were significant at $\alpha = 0.05$.
**NS means that the regression was not significant at $\alpha = 0.05$.

TABLE 9. VARIABLE SELECTION DURING STEPWISE REGRESSION OF FRAMEWISE POND DENSITIES FOR PONDS LESS THAN 1.25 HA

STEP	1	2	3	4	5	5	6
	Intercept	Intercept	Intercept	Intercept	Intercept	Intercept	Intercept
	CATD*	CATD	CATD	CATD	CATD	RAIN	RAIN
MODEL		SLOP	SLOP	SLOP	SLOP	CATD	CATD
			FRMX	IRR	IRR	SLOP	SLOP
				FRMX	POPD	POPD	IRR
					FRMX	FRMX	POPD
							PRMX
R^2	0.115	0.211	0.270	0.294	0.315	0.336	0.375
PROB > F	0.0040	0.0004	0.0001	0.0001	0.0002	0.0002	0.0001

*Underlined variables were significant at $\alpha = 0.05$. Doubly underlined variables are significant at $\alpha = 0.001$.

Probability of F values of parameters of best six-variable model

Variable	Prob > F
RAIN	0.0161
CATD	0.0242
SLOP	0.0001
IRR	0.0498
POPD	0.0097
FRMX	0.0177

TABLE 10. POND DENSITY (PONDS/km^2 ± 1 STANDARD DEVIATION) BY POND SIZE AND SOIL TYPE

Soil Association	Frames	< 1.25 ha	1.25-2.5 ha	2.5-5.1 ha	5.1-11.25 ha	All Sizes
Lake Charles-Edna-Bernard	5	0.596 ± 0.201	0.050 ± 0.041	0.014 ± 0.018	0.007 ± 0.009	0.671 ± 0.265
Miller-Norwood-Pledger	3	0.827 ± 0.346	0.084 ± 0.049	0.034 ± 0.022	0.002 ± 0.004	0.959 ± 0.367
Katy-Hockley-Clodine	2	0.865 ± 0.376	0.092 ± 0.014	0.015 ± 0.003	0.000 ± 0.000	0.972 ± 0.395
Wilson-Crockett-Burleson	3	1.941 ± 0.416	0.138 ± 0.028	0.027 ± 0.020	0.006 ± 0.000	2.112 ± 0.374
Burleson Heiden-Crockett	4	1.944 ± 0.831	0.153 ± 0.076	0.028 ± 0.011	0.002 ± 0.008	2.045 ± 0.934
Lufkin-Axtell-Tabor	4	1.499 ± 0.348	0.153 ± 0.088	0.028 ± 0.017	0.002 ± 0.003	1.687 ± 0.443
Castell-Pontotoc-Ligon	3	2.932 ± 0.176	0.075 ± 0.016	0.012 ± 0.007	0.002 ± 0.004	3.028 ± 0.0197
Truce-Owens-Waurika	4	1.965 ± 0.460	0.057 ± 0.025	0.003 ± 0.004	0.004 ± 0.004	2.039 ± 0.473
Abilene-Tillman-Vernon	9	0.312 ± 0.084	0.037 ± 0.037	0.007 ± 0.009	0.002 ± 0.003	0.359 ± 0.103
Rowena-Sagerton-Mereta	6	0.490 ± 0.335	0.029 ± 0.031	0.008 ± 0.009	0	0.526 ± 0.358
Tarrant-Kavett-Rowena	4	1.590 ± 0.501	0.096 ± 0.037	0.021 ± 0.018	0.012 ± 0.006	1.724 ± 0.497
Tarrant-Brackett-Denton	5	0.843 ± 0.345	0.044 ± 0.029	0.003 ± 0.004	0	0.893 ± 0.345
Tarrant-Kavett-Tobosa	5	0.477 ± 0.313	0.015 ± 0.016	0.001 ± 0.003	0	0.493 ± 0.319
Tarrant-Brackett-Speck	3	0.677 ± 0.291	0.037 ± 0.022	0.000 ± 0.000	0	0.704 ± 0.295
Amarillo-Acuff-Mansker	2	0.120 ± 0.123	0.013 ± 0.009	0.013 ± 0.018	0.010 ± 0.014	0.172 ± 0.059
Patricia-Brownfield-Tivoli	3	0.153 ± 0.101	0.033 ± 0.039	0.002 ± 0.004	0.005 ± 0.009	0.395 ± 0.293

TABLE 11. POND DENSITY (PONDS/km^2 ± 1 STANDARD DEVIATION) BY SIZE CLASS AND LAND USE REGION

Land Use Region	Frames	< 1.25 ha	1.25-2.5 ha	2.5-5.1 ha	5.1-11.25 ha	All Sizes
Coastal Prairie	9	0.996 ± 0.794	0.088 ± 0.049	0.023 ± 0.019	0.004 ± 0.005	1.088 ± 0.844
Claypan Area	4	1.547 ± 0.290	0.102 ± 0.051	0.021 ± 0.020	0.001 ± 0.003	1.675 ± 0.298
Blackland Prairie	10	1.159 ± 0.583	0.090 ± 0.080	0.011 ± 0.013	0.003 ± 0.005	1.266 ± 0.648
Grand Prairie	6	1.466 ± 0.986	0.048 ± 0.022	0.004 ± 0.004	0.000 ± 0.000	1.527 ± 1.005
North Central Prairies	4	1.785 ± 0.294	0.123 ± 0.025	0.018 ± 0.011	0.003 ± 0.004	1.195 ± 0.298
Central Basin	2	1.851 ± 1.244	0.048 ± 0.026	0.003 ± 0.005	0	1.902 ± 1.274
Edwards Plateau	11	1.145 ± 0.992	0.038 ± 0.036	0.008 ± 0.014	0.005 ± 0.005	1.197 ± 1.031
Rolling Plains	13	0.458 ± 0.349	0.047 ± 0.040	0.010 ± 0.010	0.003 ± 0.007	0.522 ± 0.369
High Plains	8	0.395 ± 0.541	0.030 ± 0.035	0.005 ± 0.008	0.003 ± 0.005	0.507 ± 0.566
Bottom Lands	3	0.681 ± 0.232	0.060 ± 0.047	0.023 ± 0.019	0.010 ± 0.011	0.781 ± 0.306

covered by the survey (Table 12). While differences between agricultural regions are smaller in general than those between soil associations, the range of densities is considerable, varying between 0.207 ± .120 ponds per hectare in the Edwards Plateau large ranch cattle-sheep-and-goats region to 1.851 ± 1.244 in the Edwards Plateau Central basin cattle-and-goats region. It is somewhat sur-

TABLE 12. POND DENSITY (PONDS/km^2 ± 1 STANDARD DEVIATION) BY POND SIZE AND AGRICULTURAL REGION

Agricultural Region	Frames	‹ 1.25 ha	1.25-2.5 ha	2.5-5.1 ha	5.1-11.25 ha	All Sizes
Southern High Plains (farming, cotton, grains, sorghum, cattle)	8	0.395 ± 0.541	0.300 ± 0.035	0.005 ± 0.008	0.003 ± 0.005	0.507 ± 0.566
Rolling Plains and Prairies (cotton, grains, sorghum, wheat, livestock)	12	0.465 ± 0.307	0.046 ± 0.036	0.009 ± 0.009	0.003 ± 0.006	0.526 ± 0.310
Rolling Plains and Prairies (small grains and livestock)	5	1.473 ± 0.538	0.107 ± 0.041	0.015 ± 0.010	0.005 ± 0.008	1.605 ± 0.566
Edwards Plateau (large ranches, cattle, sheep, goats)	4	0.197 ± 0.111	0.005 ± 0.007	0.004 ± 0.004	0.002 ± 0.004	0.207 ± 0.120
Edwards Plateau (small ranches, cattle, sheep, goats)	6	1.170 ± 1.020	0.049 ± 0.032	0.011 ± 0.018	0.006 ± 0.006	1.767 ± 1.059
Edwards Plateau Central Basin (cattle, goats)	2	1.851 ± 1.244	0.048 ± 0.026	0.003 ± 0.005	0.000 ± 0.000	1.902 ± 1.274
Grand Prairie (livestock, small grains, cotton)	6	1.466 ± 0.946	0.048 ± 0.022	0.004 ± 0.004	0.000 ± 0.000	1.527 ± 1.005
Blackland Prairie (cotton, livestock)	5	1.034 ± 0.714	0.063 ± 0.049	0.006 ± 0.008	0.004 ± 0.006	1.110 ± 0.748
Blackland Prairie (dairy products, cattle, cotton)	4	1.431 ± 0.378	0.133 ± 0.109	0.017 ± 0.017	0.002 ± 0.003	1.588 ± 0.500
Post Oak (cotton, livestock, poultry)	9	1.423 ± 0.696	0.095 ± 0.051	0.021 ± 0.015	0.003 ± 0.005	1.546 ± 0.746
Coastal Prairie (cotton, rice, cattle)	8	0.602 ± 0.191	0.071 ± 0.042	0.023 ± 0.021	0.006 ± 0.007	0.710 ± 0.252

prising that the lowest and highest densities of ponds should be in agricultural regions that seem so similar, but the differences in pond density are probably due to the variability of the geologic substrate of the Edwards Plateau rather than differences in agricultural practices. The standard deviations of pond densities in the agricultural regions are nearly as large, or are larger, than the mean densities, indicating that agricultural regions do not form homogeneous groups with respect to pond density.

Data on pond densities arranged by county are given in Table 13.

CONCLUSIONS

It is possible to inventory farm ponds from NASA color infrared photography and classify them by size by using a stereo-microscope on the light table. A frame from high altitude photography covers considerable area, which makes determining the relationship of pond densities to land use or soil factors difficult since most photographic frames will include two or more classification categories for geology, soil association, or land use. There was no significant change in pond density when the river was in the sample block (2.2 km^2), indicating that if there were any change in density near the river it occurred in a very narrow band. Many types of data on criteria which might be

TABLE 13. POND DENSITY (PONDS/km^2 $\pm$ 1 STANDARD DEVIATION) BY POND SIZE AND COUNTY

County	Frames	× 1.25 ha	1.25-2.5 ha	2.5-5.1 ha	5.1-11.25 ha	All Sizes
Bastrop	3	1.673 ± 0.177	0.115 ± 0.054	0.021 ± 0.024	0.002 ± 0.003	1.815 ± 0.123
Borden	3	0.197 ± 0.143	0.056 ± 0.043	0.013 ± 0.013	0.009 ± 0.010	0.287 ± 0.147
Brazos	1	1.70	0.062	0.022	0.000	1.254
Brown	1	1.762	0.123	0.030	0.006	1.93
Burnet	4	1.32 ± 1.174	0.056 ± 0.020	0.002 ± 0.004	0.00 ± 0.00	1.388 ± 1.197
Coke	3	0.226 ± 0.087	0.010 ± 0.005	0.002 ± 0.004	0.002 ± 0.004	0.240 ± 0.100
Coleman	2	0.996 ± 0.370	0.084 ± 0.056	0.014 ± 0.011	0.010 ± 0.014	1.107 ± 0.433
Colorado	5	1.412 ± 0.882	0.114 ± 0.060	0.022 ± 0.013	0.003 ± 0.006	1.556 ± 0.942
Concho	2	0.838 ± 0.402	0.052 ± 0.057	0.006 ± .0004	0.003 ± 0.005	0.900 ± 0.465
Dawson	2	0.144 ± 0.088	0.015 ± 0.011	0.00 ± 0.00	0.007 ± 0.010	0.170 ± 0.062
Falls	1	0.694	0.050	0.011	0.006	0.761
Fayette	4	1.43 ± 0.378	0.133 ± 0.109	0.017 ± 0.017	0.002 ± 0.003	1.588 ± 0.500
Fort Bend	1	0.392	0.073 ±	0.034	0.006	0.509
Hays	1	0.744	0.063 ±	0.00	0.00	0.807
Howard	3	0.261 ± 0.118	0.014 ± 0.019	0.002 ± 0.004	0.00 ± 0.00	0.277 ± 0.135
Lampasas	1	1.27	0.019	0.006	0.00	1.296
Llano	2	1.851 ± 1.244	0.048 ± 0.026	0.003 ± 0.005	0.00 ± 0.00	1.902 ± 1.274
Lynn	2	1.851 ± 1.244	0.048 ± 0.026	0.003 ± 0.005	0.00 ± 0.00	0.529 ± 0.251
Matagorda	3	0.681 ± 0.232	0.060 ± 0.047	0.023 ± 0.019	0.010 ± 0.011	0.781 ± 0.306
McCulloch	2	1.325 ± 1.263	0.022 ± 0.031	0.022 ± 0.031	0.007 ± 0.010	1.377 ± 1.336
Mills	1	2.242	0.045	0.006	0.00	2.312
Mitchell	3	0.379 ± 0.051	0.041 ± 0.044	0.013 ± 0.013	0.00 ± 0.00	0.436 ± 0.048
Nolan	1	0.201	0.032	0.00	0.00	0.233
Palo Pinto	1	2.104	0.146	0.028	0.006	2.284
Runnels	3	0.657 ± 0.256	0.041 ± 0.038	0.006 ± 0.007	0.00 ± 0.00	0.703 ± 0.264
San Saba	3	2.265 ± 0.853	0.063 ± 0.032	0.007 ± 0.012	0.007 ± 0.004	2.347 ± 0.890
Sterling	1	0.227	0.00	0.00	0.00	0.227
Terrell	1	1.713	0.090	0.022	0.006	1.831
Tom Green	1	0.060	0.00	0.007	0.00	0.066
Travis	5	1.034 ± 0.714	0.063 ± 0.049	0.006 ± 0.008	0.004 ± 0.006	1.110 ± 0.748
Wharton	4	0.595 ± 0.167	0.079 ± 0.050	0.020 ± 0.027	0.004 ± 0.004	0.707 ± 0.260
Young	2	1.636 ± 0.334	0.111 ± 0.033	0.009 ± 0.003	0.00 ± 0.00	1.763 ± 0.293

related to pond density are maintained on a county basis, and are confounded by the lack of coincidence between photographic frame boundaries and county boundaries. The county data are suggestive, however, and can be useful as a guide to further research.

In the area photographed, over 90 percent of the ponds were smaller than 1.25 ha, and the percentages by pond size were nearly the same in the Brazos and Colorado River watersheds. Mean pond densities were similar for the Brazos and Colorado River watersheds except for the smallest size group (< 1.25 ha). In this size group the density of pond counts in the Brazos River watershed (1.7 ponds/per km^2) was nearly twice that of the Colorado (0.97 ponds per km^2). However, the area covered by photography in the Brazos River watershed was much smaller, and did not include the upper part of the basin, which would be expected to have very low pond densities. In an earlier unpublished study where all of the ponds in Brazos County were counted, the reported density was 0.927 ponds/km^2, which is similar to the density observed in the Colorado River basin. The Colorado and Brazos River watersheds differed in the distribution of pond densities along their watersheds from the Gulf of Mexico to upstream reaches. Pond densities were low near the Gulf for both watersheds. Pond densities increased for the Brazos River with distance from the Gulf. For the Colorado River the densities were very erratic in the central part of the watershed, with the highest densities found in the study located there, along with many frames of very low density. This variability coincides with the southern Edwards Plateau region. The upper Colorado watershed, on the Texas High Plains, had very low pond densities. The pond density differences are consistent with climatic and soil conditions in the watersheds. Total ponds 1.25 ha and smaller are estimated to be 102,000 for the Colorado River basin and 191,000 for the Brazos River basin.

In a 10 factor stepwise regression analysis, the factor of the best six variable model which contributed the most to pond density was slope (a gross measure of relief obtained by subtracting the lowest elevation in the county from the highest). Population density was the second most important contributor, and rainfall third.

Estimates were made of the amount of watershed required to supply water to maintain the observed pond surface area in the photographic frames. Using the simplifying assumption that the watersheds were hydrologically independent, we calculate that in 28 percent of the frames over half of the available watershed would be required to maintain the ponds. Because the assumption of independence of watersheds fails in some frames with a high pond count densities, the calculated requirement may exceed 100 percent of the land surface area in these frames.

It is obvious that published numbers for the number of ponds in Texas are much too low. We estimate 293,000 ponds 1.25 ha and smaller in the Brazos and Colorado River basins alone, as compared to SCS estimates of 299,000 ponds for the entire state. Inventory studies must be done in the other major watersheds before satisfactory statewide totals can be calculated, but some idea of the order of magnitude of the number can be estimated from our data.

If the area of the Rio Grande River basin is excluded, since it contains very few ponds, and the average pond density from this study (1.335 ponds/km^2) is applied to the remainder of the area of the state, it is estimated that there are approximately 782,000 ponds 1.25 ha or smaller, and approximately 842,000 ponds of all sizes in the state.

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APPENDIX

Example calculation of watershed area required to support ponds in the study area.

Data from observation 66 are used in the following example. The approximate size of watershed required for each acre foot of pond water varies as a function of distance from the coast (see page 11, TSPE 1974). An approximation of the relationship was developed using a polynomial regression which gave

(1) $\frac{A}{V} = 9.62 + (1.232 \times 10^{-3})m + (1.148 \times 10^{-4})m^2$

where

A = acres of watershed to support pond

M = Miles from coast

V = volume of pond in acre-feet

Observation 66 was 505 miles inland. Thus

(2) $\frac{A}{V} = 9.62 + (1.232 \times 10^{-3})(505) + (1.248 \times 10^{-4})(505)^2 = 39.5 \frac{\text{acres}}{\text{acre/foot}}$

converting to ha/m^3, and calling the result R we have

(3) $R = 0.01296 \frac{\text{ha}}{\text{m}^3}$

The volumes of ponds in each size class were estimated using the following areas and depths

According to Wetzel (1983), the mean depth of lakes tends to be about one-half of the maximum depth. Thus, we can estimate volume of a pond in cubic meters as

(4) V = [hectares area] × [.5 × max. depth m] × [10,000 m^2]

For size class 1 ponds, this volume (V_1) amounts to

(5) $V_1 = [0.600] \times [0.5 \times 1.5) \times (10{,}000] = 4{,}500$ m^3 per pond

Observation 66 has a density (D) of size class 1 ponds of 0.01713 ponds/ha. The total volume density V_1(tot) of size class 1 ponds in the frame is

(6) $V_1(\text{tot}) = V_1 \times D = 4{,}500 \times 0.01713 = 77.005$ m^3

Finally we calculate the proportion of the watershed area (P_w) required to support this volume of water,

(7) $P_w = V_1(\text{tot}) \times R$
$= 77.085 \times 0.01296 = 0.9990$ ha required/ha available

Since V_1(tot) is based on the number of ponds per hectare, we see that potentially, 99.9 percent of the watershed in the hectare may be devoted to supporting size class 1 ponds.