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A MODEL FOR FLOODPLAIN MANAGEMENT IN URBANIZING AREAS

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ABSTRACT

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A target land use pattern found using a dynamic programming model is shown to be a useful reference for comparing the success of floodplain management policies. At least in the test case, there is interdependence in the land use allocation for floodplain management--that is, a good solution includes some reduction of current land use in the floodplain and some provision of detention storage.

For the test case, current floodplain management policies are not sufficient; some of the existing floodplain use should be removed. Although specific land use patterns are in part sensitive to potential error in land value data and to inaccuracy in the routing model, the general conclusion that some existing use must be removed is stable within the range of likely error. Trend surface analysis is shown to be a potentially useful way of generating bid price data for use in land use allocation models. Sensitivity analysis of the dynamic programming model with respect to routing of hydrographs is conducted through simulation based on expected distributions of error.

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PREFACE

This report describes the results of work over a period of four years to develop and test a model that treats floodplain management as a problem of allocating land uses to parcels both in the floodplain and in the rest of the watershed. The basic dynamic programming model is described in an earlier research report (Hopkins et al., 1976). Chapter 1 of this report briefly reviews the model and describes its test application to analyzing policies for the Hickory Creek watershed in Will County Illinois. Chapter 2 describes the procedures used for developing land use value data and the relative senstivity of the model to potential errors in this data. Trend surface analysis is shown to be a potentially useful tool for generating such data. Chapter 3 describes the simple routing procedure used to handle hydrologic relationships. The routing procedures are compared to other more complex routing procedures, and the sensitivity of results from the land use allocation model to inaccuracy in the routing model is analyzed.

In the test application to Hickory Creek, the model suggests policy choices for managing the watershed. These policy choices are largely insensitive to the expected error in the land value data and in the routing procedure.

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Several staff members at the Illinois State Water Survey provided assistance in using the HEC-1 and HEC-2 computer programs. The Survey also provided some of the hydrologic data used in the study.

Several persons on the staffs of the County Assessors' offices and the County Clerks' offices of Cook and Will Counties aided us in obtaining the tax assessment data used in generating land values. Discussions with David Berry were helpful in the initial formulation of the land value estimation approach.

LIST OF FIGURES

CHAPTER 1 FLOODPLAIN MANAGEMENT POLICIES FOR URBANIZING WATERSHEDS

1.1 Problem

Urban development affects flood damages in two ways. First, new development changes the pattern of stormwater runoff and therefore the timing, intensity, and duration of flooding. For example, the increase in the amount of impervious surface generally associated with urban development tends to increase the peak flow from a watershed. Second, new development, in areas subject to flooding, changes the set of land uses subjected to damage. Generally, development in flood-prone areas results in an increase in the amount of damages that will result from storms in given intensities.

1.1.1 Current Policies

Current practices in flood control policy attempt to deal with the two effects of urban development on flood damages. Ordinances and regulations that attempt to control the amount of stormwater runoff generated by new development may take the form of zoning for low densities or limiting the amount of allowable runoff. Runoff limitations, such as those adopted by the Metropolitan Sanitary District of Greater Chicago (MSD), are examples of the latter. The MSD regulation requires developers to provide stormwater detention such that the maximum discharge rate from the 100-year frequency storm is no higher than the peak discharge rate from a three-year storm on the undeveloped site (Metropolitan Sanitary District).

Another group of flood control measures attempts to restrict development in flood prone areas, frequently through zoning and often in response to requirements that make the availability of federally subsidized flood insurance conditional upon the adoption of such measures.

where $f_N(X_N)$ is the function yielding the highest aggregate bid price for each final outflow level. D_n is the set of possible uses for reach n; X_n is the set of possible input water flows for reach n. r_n is the return function for each reach, which in this case can be expressed as

$$r_n = v_{nj}a_n \quad -c^k_{jn} \; d^k_n \tag{1.3}$$

where

v_{jn} = economic rent per acre of use j in reach n

a_n = number of acres in reach n

c^k_{jn} = present worth of flood damage per acres for use j in reach n at depth k

d^k_n = acres flooded to average depth k in reach n.

t_n is the transformation function that takes the input flow and decision for stage n and generates the output flow from stage n, which is also the input flow to stage n+1. In this case, the transformation function is a very simple routing model, which is described below. The problem can be solved using the usual recursion equations of dynamic programming, which simply describe mathematically the search process outlined above. (See for example, Nemhauser, 1966.)

This basic formulation was extended to handle branching stream networks and to make possible the assignment of a land use to the floodplain area that is different from the use assigned to the remainder of the subbasin. These extensions are described in Hopkins et al. (1978). In order to run the dynamic programming model, it was desirable to develop a simple and very efficient routing model to combine hydrographs within the dynamic program.

The "triangle" routing method was devised to fill this need (Hopkins et al, 1978). This routing model is evaluated and compared to others in Chapter 3. As with most optimization algorithms, the results of the dynamic program should be viewed as approximate, and more complex simulation models should be used to check results if the land use pattern chosen by the dynamic program is to be implemented directly.

The previously reported model was extended in two ways for the present application. First, the triangle routing method was modified to handle the trapezoidal form of hydrographs resulting from land uses incorporating detention storage. Second, the method of computing damages was altered to take into account the expected damages over all storms rather than simply dealing with a 100-year design storm.

1.2.2 Routing Detention Basin Hydrographs

The previously reported model used a triangular routing procedure to translate and combine individual hydrographs from each of the subbasins in the watershed. However, for this study, additional land uses, representing development complying with the MSD runoff requirements, have been added to the model. These new land uses are restricted to a relatively low peak runoff but must still discharge the same volume of runoff as the same land use developed without the restrictions. This change must be achieved through some form of detention which results in a reduction in hydrograph peak flow and a corresponding elongation. The resulting hydrographs are approximately trapezoidal, and triangular hydrographs would not provide a good approximation of the time and duration of the peak flow.

Therefore, a slightly more complex routing method was developed that could accept trapezoidal hydrographs, and combine two trapezoids, two triangles, or one of each. The new procedure preserves most of logic of the previous one, the major difference being the method of representing the

the 10-year and the 100-year floods. Because the elevation of the 10-year flood is not generated by the dynamic programming model, it was assumed that the differences between the 100-year and 10-year flood elevations remain constant for each subbasin no matter what the allocation of land uses. The values for these differences in elevation were determined by two runs of the HEC-2 Water Surface Profile program (U.S. Army, 1973b) using discharge values generated by the HEC-1 Flood-Hydrograph Package (U.S. Army, 1973a) for runoff from the 100-year and 10-year storms given existing land use patterns. For those subbasins for which the lack of survey data prevented the running of HEC-2, the difference between the 10- and 100-year flood elevations was assumed to be the same as nearby subbasins of similar characteristics. Thus, given an elevation for the 100-year flood, such as that generated by the dynamic programming model, it is possible to estimate the present worth of expected damages for all storms using the flood insurance rate data.

This procedure has several limitations. First, the assumption that the differences between the 10-year and 100-year flood depths are constant is used because there is no basis for predicting even the direction of change. Although at least two attempts have been made to estimate the effect of urbanization on the difference between small and large storms, neither is applicable to the present case. The results reported by Barnard (1978) apply to a much smaller watershed, and those of Doehring and Smith (1978) apply to an unusual New England drainage pattern. This assumption also leads to the underestimation of damages when land uses with detention are assigned to a subbasin because then both the 100-year, 10-year, and all intermediate storms should be restricted to the same amount of discharge. Therefore, the difference between elevations of the two floods should become zero, rather than remain constant. The extensive empirical work that would be required to incorporate variable differences between the 10- and 100-year storm cannot be justified for this model. Lastly, this procedure estimates only the damages occurring within the 100-year floodplain. Other damages accruing to land uses outside this floodplain during storms of lesser frequency are not estimated.

1.2.4 Data and Assumptions

The Hickory Creek watershed in Will County, Illinois, was chosen for the demonstration because of its size, the expectation that it would undergo substantial development in its upper reaches in the near future, the existing and increasing flood damage problems already occurring in its lower reaches, and the availability of land use and hydrologic data. The watershed encompasses an area of 109.8 square miles. It was divided into 67 subbasins and associated reaches, which are the stages of the dynamic programming model. (See Figure 1.2.)

Six general land use categories plus four additional uses, which are equivalent to the first four except that they incorporate detention sufficient to meet the requirements of the MSD, were identified. These 10 uses are listed in Table 1.1. Hydrographs for each land use on each subbasin were generated using the Clark method (Clark, 1945) as programmed in the HEC-1 Flood Hydrograph Package (U.S. Army, 1973a). The computation of depth for given flows was based on the assumptions of uniform flow within the channel. The area flooded for a given flow was then determined from the cross sections and topographic maps.

Greenberg et al. (1974) have discussed the problems of obtaining economic rent data by alternative approaches, such as used by Day and Weisz (1976) and Arvanitidis et al. (1972). The economic rent data, that is bid prices for each use in each subbasin, were obtained using trend surface

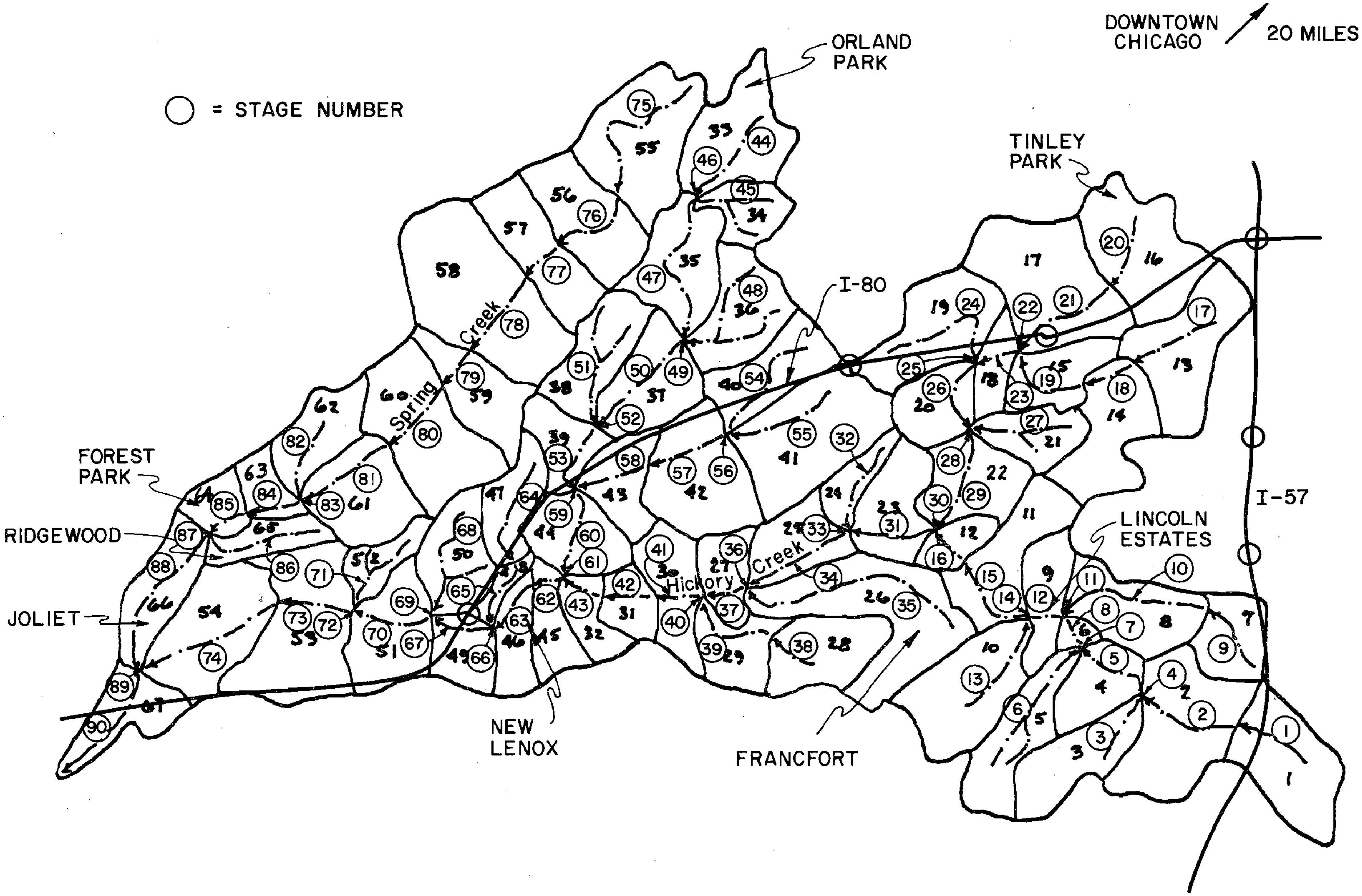


Figure 1.2 Hickory Creek Watershed Showing Stage and Subbasin Numbering

Table 1.1 Land Use Categories

Catagory Number	Description
1	Urban 1: 0.2 dwelling units per acre
2	Urban 2: 1.0 dwelling units per acre
3	Urban 3: 2.75 dwelling units per acre
4	Urban 4: greater than 6 dwelling units per acre &/or industrial use
5	Urban 1 with detention
6	Urban 2 with detention
7	Urban 3 with detention
8	Urban 4 with detention
9	Agriculture
10	Recreation

analysis as described in Chapter 2. Land use conversion costs were included by subtracting demolition costs for the existing use from the bid price for each other use for each parcel. These costs were estimated from building volume, area of paving, and dollar costs from a contractors estimating handbook (Godfrey, 1978). The analysis below, therefore, takes into account the current land use pattern; it is not simply an ideal pattern for undeveloped land.

The easiest, most effective way of adapting the dynamic programming model to the purposes of this study was to include a set of land uses representing development complying with specific runoff restrictions. The land uses were described on the assumption that if detention facilities were included in a new development, the detention would be constructed to comply with the specifications required by the Metropolitan Sanitary District. Furthermore, data were derived as if an entire subbasin would be developed by a single developer so that the runoff restrictions would only have to be met at the base of the subbasin. The effects of this assumption are not entirely clear, but the hydrograph peak produced in this manner is probably always greater than or equal to the hydrograph peak that would result if each subbasin could be divided into a series of smaller developments, each with development individually required to comply with the runoff restrictions. Thus, in one sense, the hydrographs used in this study represent the maximum possible discharge that could result from the application of these requirements to a given subbasin.

Assuming that losses of water through seepage for a land use developed with detention are not significantly greater than for the same land use without detention, then the area under the trapezoidal hydrograph must equal the area under the equivalent triangular hydrograph. The new trapezoidal hydrographs have the same ascending slopes as the equivalent triangular hydrographs because developers would always release the maximum amount allowable since the storage of any additional runoff would represent an unwanted and unnecessary cost to the developer. The slope of the descending portion of the trapezoidal hydrograph was assumed to be equal to the ascending slope. Given these assumptions about 1) the value of the peak flow for a given sabbasin, 2) the area under the trapezoidal hydrograph, and 3) the ascending and descending slopes of the trapezoidal hydrograph, it is possible to devise a hydrograph for each of the new land uses, in each of the subbasins, from the triangular hydrograph for each of thoses uses developed without the detention requirements.

The economic rent values of the land uses complying with the runoff requirements are equal to the values of these land uses developed in a conventional manner minus the costs of complying with the runoff requirements. The costs of compliance are primarily the costs incurred by the developer to construct and operate the detention facility. There may at the same time be certain benefits, mostly savings in the costs of other facilities, such as storm sewers, due to this decision to provide detention. For this analysis only cost estimates were made, assuming the benefits to the developer of compliance to be minimal.

The two primary costs of a detention basin are construction and land costs. Construction costs are best determined by examining the costs of comparable projects. Cost data for seven detention basin projects in suburban Cook County Illinois (Poertner, 1974) under climate and site characteristics similar to the study area were averaged to obtain a 1977 price of $6,100 per acre-foot of storage capacity. Land costs vary depending on the particular land use with which the detention facility is located. These costs are the opportunity costs of the land occupied by the detention basin, which therefore cannot be developed into the corresponding land use. The amount of land consumed by the detention basin can be estimated by examining the same seven detention projects, which yields an average of 14.1 acres of land per 100 acre-ft of storage.

From the set of trapezoidal hydrographs derived earlier, it was possible to determine the volume of storage required for each of the new land uses in each of the subbasins. Then, using the figures shown above, the costs of complying with the runoff requirements were calculated and subtracted from the normal land value to determine the economic rent in each subbasin of each of the land uses with detention.

1.3 Evaluating Policies

It is now possible to evaluate alternative policies. First, the dynamic programming model was used to find a "good" target land use pattern. Then the results from alternative policies were predicted and compared to this plan. Six policies were evaluated as summarized in Table 1.2. The policies are explained in this section and compared in section 4.

Table 1.2 Comparison of Policies*

	Total Economic Rent in 10^6\$	Discharge (1000 cfs)
Dynamic Programming Model	853 (618)	19.84 (18.43)
Policies		
1. Detention without Prediction	735 (564)	20.77 (20.89)
2. Detention with Prediction	774 (568)	20.77 (20.89)
3. Floodplain Regulation	3,023 (473)	34.63 (22.25)
4. Both Regulations	192 (536)	20.77 (20.89)
5. No Regulations without Prediction	720 (576)	34.63 (22.25)
6. No Regulations with Prediction	741 (577)	34.63 (22.25)

*Numbers in parentheses refer to an earlier experiment that is discussed in section 5.

1.3.1 Dynamic Programming Solution

First, the dynamic programming model was used to find a good target land use pattern. The dynamic program was run with a discrete interval of 1,000 cubic feet per second for hydrograph peaks and one hour for times of peaks. Test runs indicated that solutions remained stable for more narrowly defined intervals. The resulting target pattern is shown in Figure 1.3 and the aggregate economic rent is given in Table 1.2. This pattern is hereafter referred to as optimal for simplicity, but is, of course, optimal only in the restricted sense of the particular mode. (See for example, Hopkins, 1977.)

1.3.2 Detention Regulation

The detention requirements of the Metropolitan Sanitary District of Greater Chicago were analyzed in conjunction with two possible assumptions about the reactions of floodplain landowners. The regulation requires that the 100-year peak flow for new development be less than or equal to the peak for the three year storm given existing land conditions. The data described above were used to determine the land use with the highest economic rent for each subbasin given the requirements of the detention ordinance. If this land use was a new use in a subbasin it was assumed to be developed under the restrictions of the ordinance. The model was also run under the assumption that detention would be required even for existing uses, but this requirement increased total rent only $10 million.

There are at least two possible assumptions about floodplain land development. First, one could assume that floodplain owners would take into account only expected flooding from the existing land use pattern. This assumption is <u>not</u> equivalent to assuming that floodplain owners maintain their current uses. It is possible that current floodplain land uses are not appropriate even for current flood conditions; persons tend to underestimate expected flood damages. This issue is discussed in section 4 below. For this case, the total flood pattern resulting from the existing land uses is used to determine expected damages for each use if located in the floodplain of each subbasin. Then, the use with the highest bid net of these expected damages given current land uses upstream was assumed to develop on that flood plain segment. This situation, detention regulations and assumed constancy of expected flood damages, constitutes Policy 1. The land use pattern is shown in Figure 1.4 and the aggregate economic rent in Table 1.2.

An alternative assumption is that the floodplain landowners are aware of the detention regulation and its potential benefit to them. If the land use pattern that is likely to occur upstream given the ordinance and the resulting flooding pattern are predicted, then the floodplain landowners could be expected to respond to this information in making their land use decisions. This combination of the detention regulation and prediction and dissemination of its effect on flood damages constitutes Policy 2. For this case the floodplain land uses were determined by choosing the use with the highest bid net of expected damages. These expected damages were derived from the flood pattern resulting from the non-floodplain land uses in each subbasin that are allowed by the detention ordinance and that have the highest economic rent in that subbasin. The results are shown in Figure 1.5 and Table 1.2.

1.3.3 Floodplain Regulation

Policy 3 consists of a regulation that prohibits any new development in the 100-year floodplain. This policy is meant to represent the kind of requirements mandated by the federal flood insurance program. Even though in most cases some forms of development with special construction details to prevent flood damages would be allowed under such ordinances, the policy here assumes no new development. Each floodplain segment was assigned to the highest bidder from among the existing use, recreation, or agriculture. The predicted land use pattern for the non-floodplain areas consisted of the highest bidding uses for each subbasin. The resulting pattern and aggregate economic rent are shown in Figure 1.6 and Table 1.2, respectively.

The assumptions in this calculation are not strictly equivalent to current ordinances. In the model the floodplain regulations apply to the 100-year floodplain resulting from the future land use pattern rather than the floodplain resulting from the existing pattern as is usually the case in such ordinances. The major failing of the floodplain regulations, as discussed in section 4 below, is that they do not require the removal of existing urban uses from the floodplain. These existing uses would occur throughout the larger, future floodplain because they are the existing uses. This imperfect representation does not affect the implications of the analysis because the total damage to floodplain uses computed by the model will be the same as would result from typical ordinances.

1.3.4 Both Regulations

Policy 4 comprises implementation of both detention regulation and floodplain regulation. The predicted non-floodplain uses are the uses yielding the highest economic rent from among the uses complying with the detention ordinance. The floodplain uses are the highest bidder of the existing use, recreation, or agriculture. The results are shown in Figure 1.7 and Table 1.2. Again, the 100-year floodplain is that of the predicted land use pattern, not the current pattern.

1.3.5 No Regulations

Policy 5 assumes there are no regulations. Non-floodplain uses are predicted to be the highest-bidding use. Floodplain uses are predicted to be the highest bidding uses net of expected flood damages derived from the 100-year storm for the existing land use pattern. Again, this is not equivalent to maintaining current floodplain land uses. In addition to assuming no regulations, Policy 6 also assumes that the floodplain land users choose by considering the expected flood damages that would result from the predicted land use pattern. These two cases are analogous to the two possibilities associated with detention regulations. The results for these policies are shown in Table 1.2 and mapped in Figures 1.8 and 1.9.

1.4 Comparison and Interpretation of Policies

The results described here are not intended to be conclusive for application to the real situation at Hickory Creek. Although real data have been used, the necessary field checking and consideration of issues outside the scope of the model have not been undertaken. These results are intended to illustrate the potential of this type of analysis and to give some indication of policy choices that would be worth further consideration.

1.4.1 Results

The results from the dynamic programming model and the six policy options are displayed in Table 1.2, which shows the aggregate economic rents and the peak discharges at the base of the watershed. The dynamic programming model yielded the highest aggregate economic rent because it is designed to maximize economic rent. In this case it also yields a low discharge. The final discharge from the watershed is not constrained or valued within the model so it would not be necessarily low. A low discharge is, however,

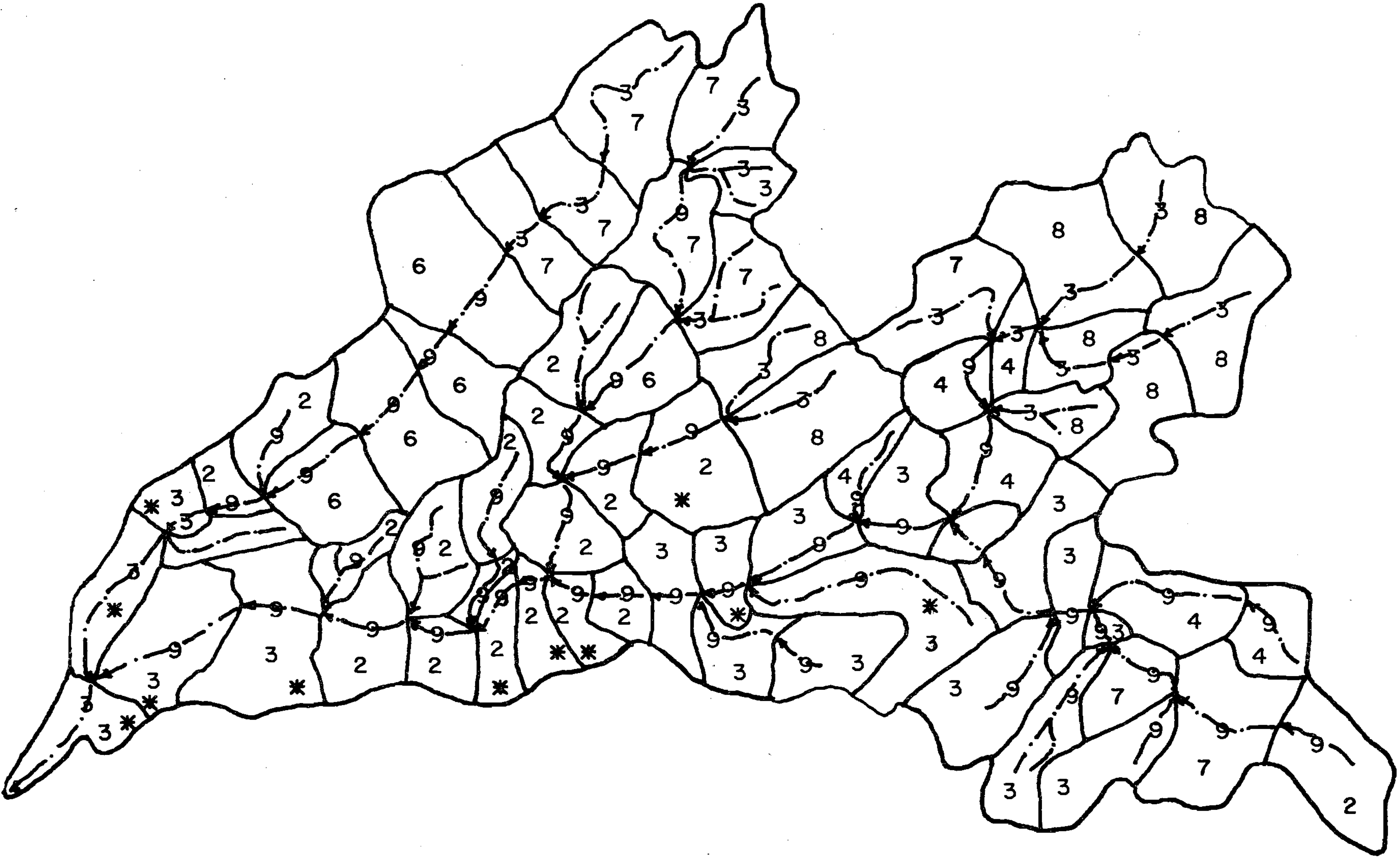


Figure 1.3 Land Use Pattern Dynamic Programming Solution

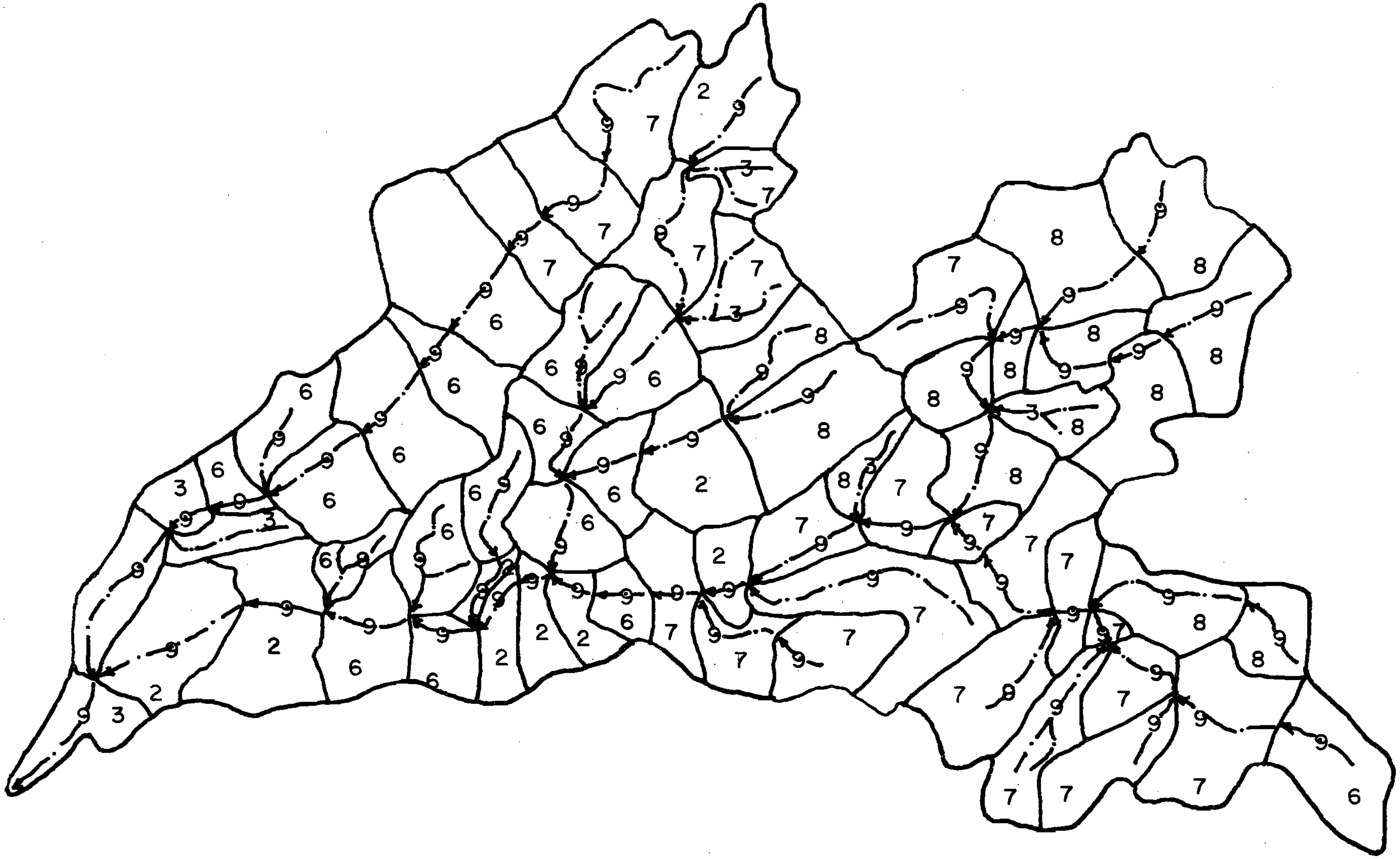


Figure 1.4 Land Use Pattern Using Detention Storage without Prediction

Figure 1.5. Land Use Pattern Using Detention Storage with Prediction

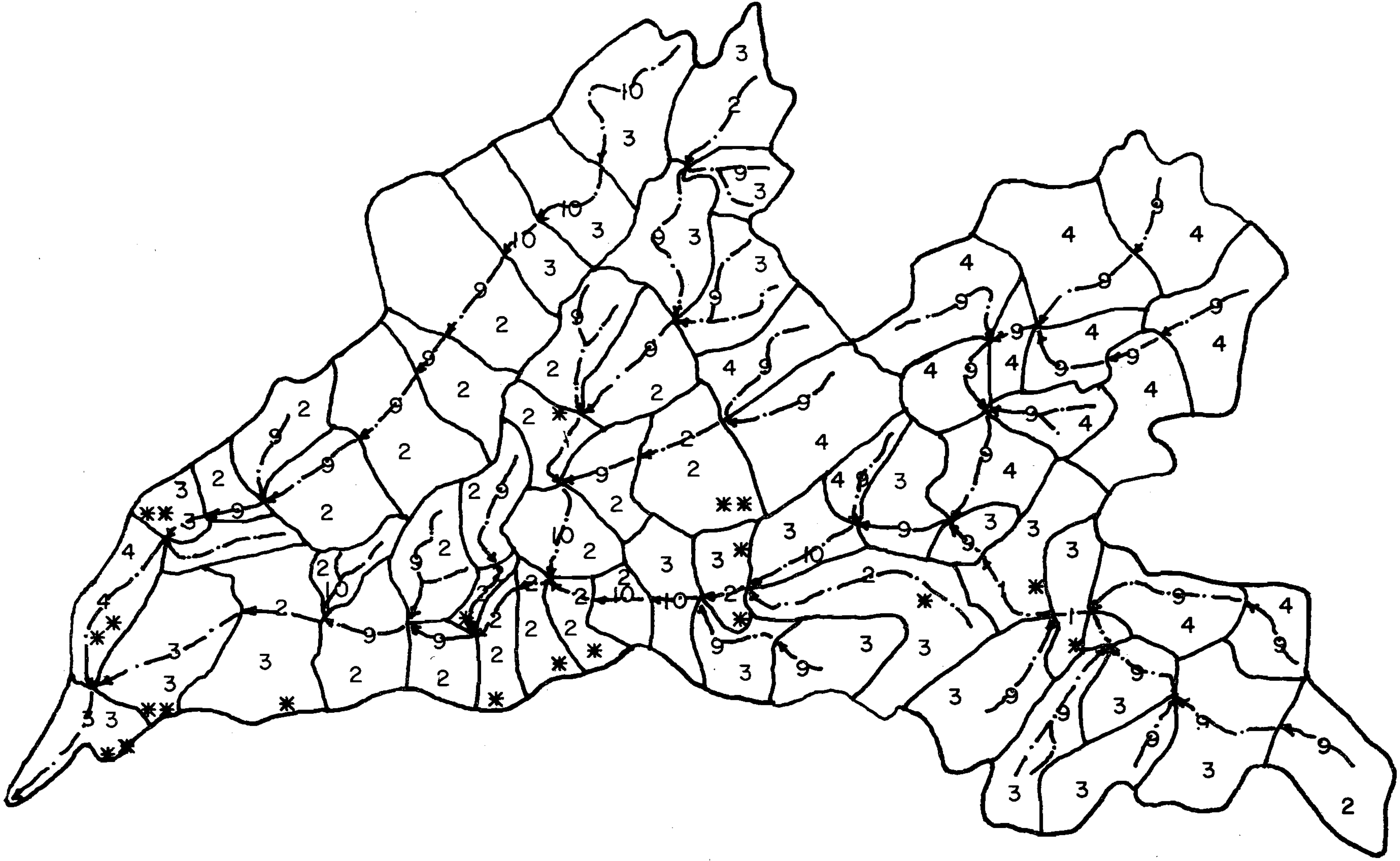


Figure 1.6 Land Use Pattern with Floodplain Regulation

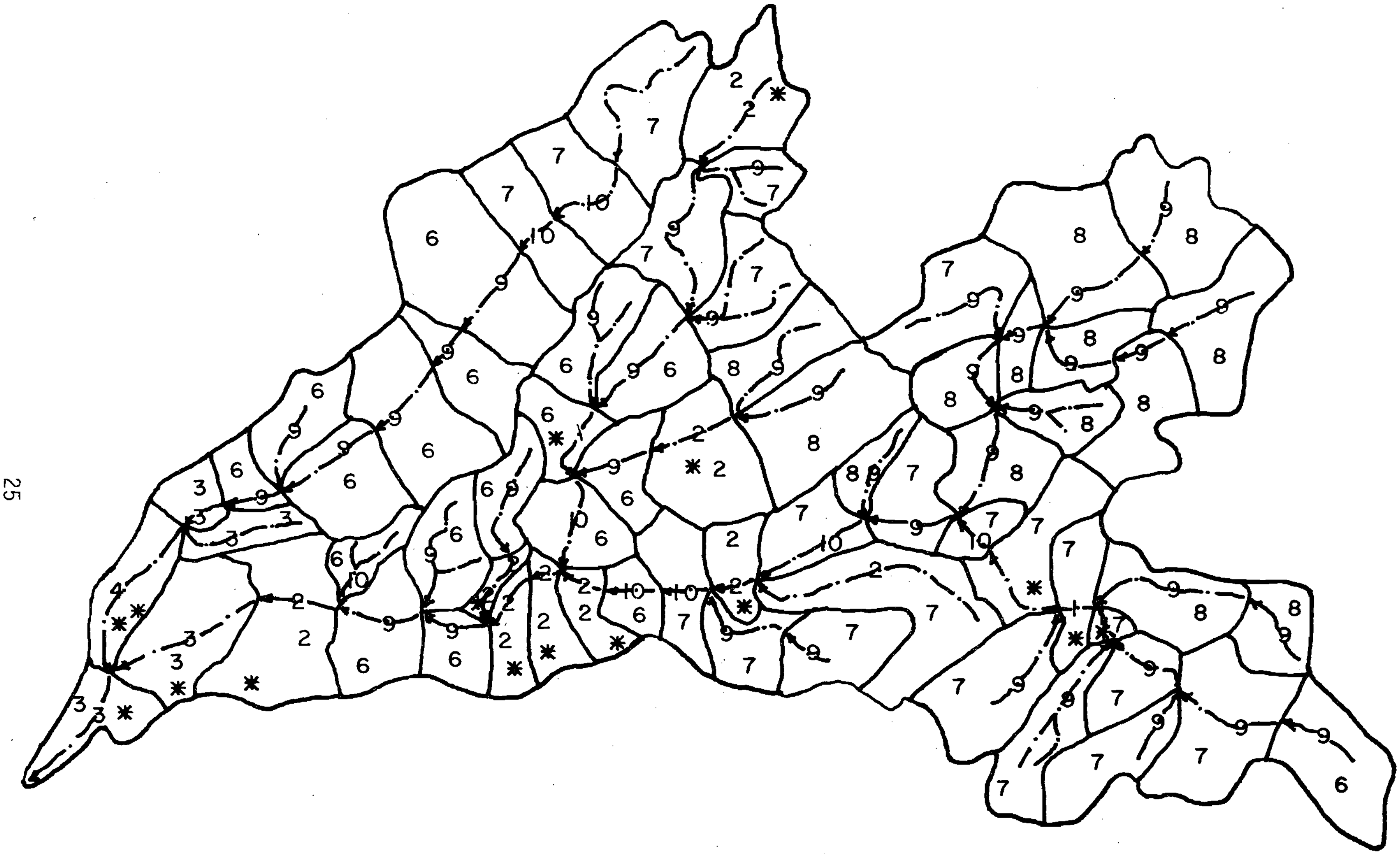


Figure 1.7 Land Use Pattern with Detention Storage and Floodplain Regulation

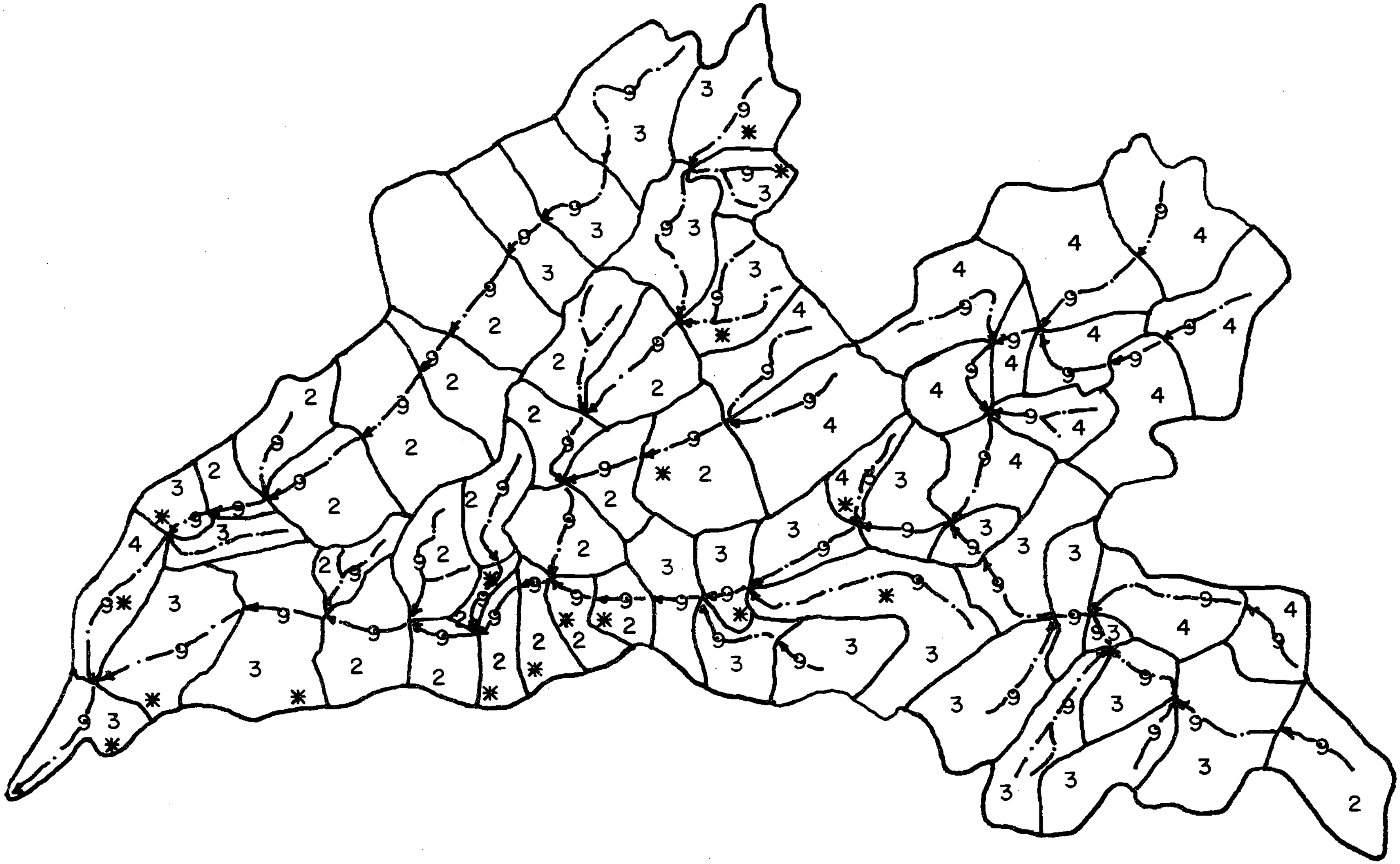


Figure 1.8 Land Use Pattern without Prediction: No Detention or Floodplain Regulation

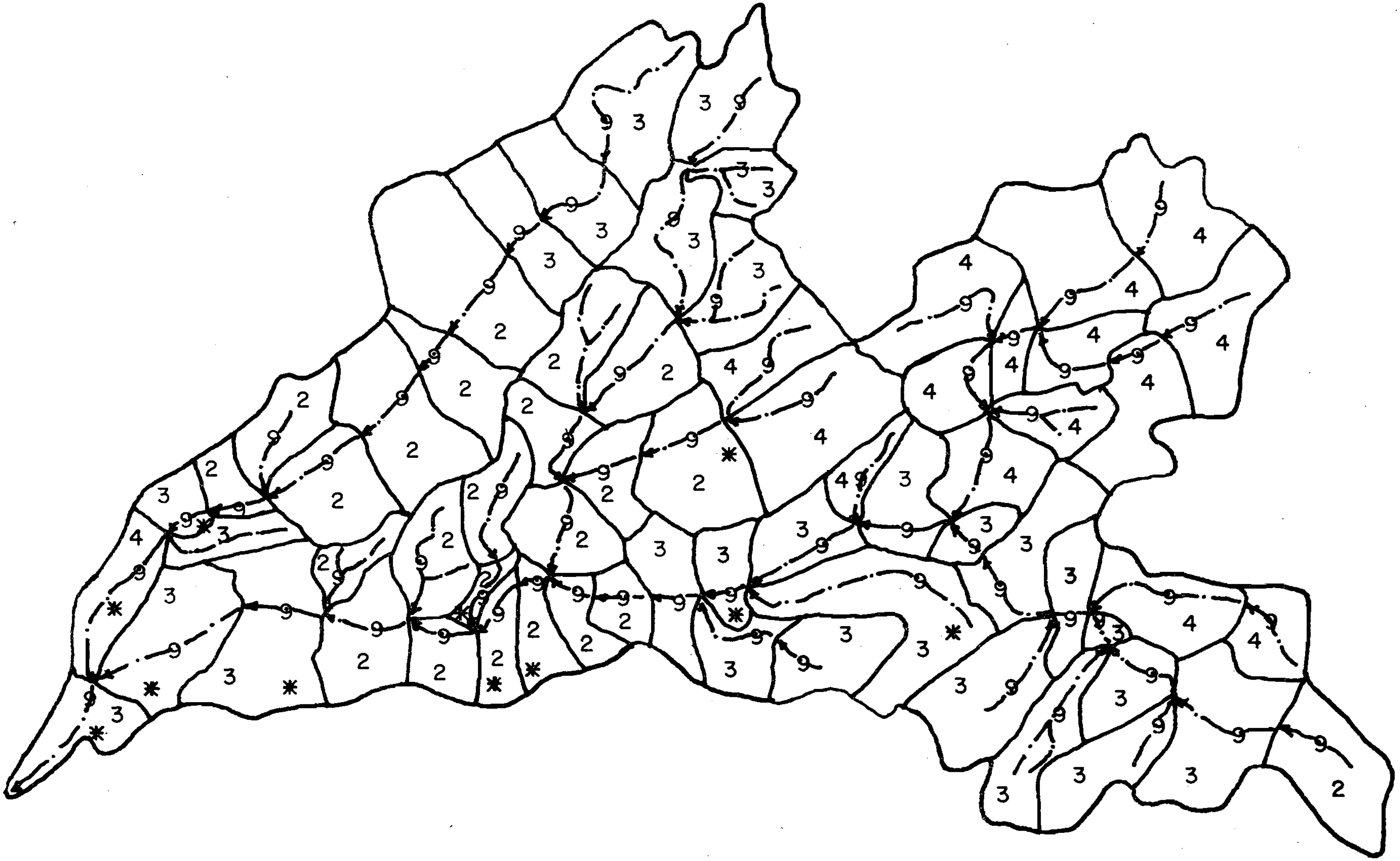


Figure 1.9 Land Use Pattern with Prediction: No Detention or Floodplain Regulation

desirable in the larger context because it affects flooding in the larger riverbasin of which the Hickory Creek Watershed is a part. The pattern of land uses as shown in Figure 1.3 illustrates the complexity of interdependence in the problem. Some, but not all, subbasins are assigned detention (i.e., uses 5 through 8) and some floodplain segments are assigned recreation or agriculture rather than a higher bidding use that would sustain flood damage. From the point of view of the model, agriculture (9) and recreation (10) are distinguishable only by runoff rates. In the model, floodplain land uses do not affect runoff. Therefore, recreation and agriculture are indistinguishable as floodplain uses. Given the overall intensity of development, assignments use 9 or 10 to the floodplain are presumed to be recreation.

The detention regulation policy resulted in a lower aggregate economic rent than the dynamic programming allocation. Comparison of the land use pattern (Figure 1.4) with that from the dynamic programming model shows that there is unnecessary (i.e. costs greater than benefits) investment in detention in the southeastern part of the watershed (7 or 8 instead of 3 or 4) and along the mainstem (6 instead of 2). There is also unnecessary restriction of floodplain development in and around Joliet. The result from Policy 1 was slightly improved by Policy 2 in which floodplain landowners were assumed to respond to the predicted expected damages. It was therefore possible to develop floodplain land more intensely. The predicted runoff would be less than that from existing development because the MSD regulations specify discharge levels below those for an undeveloped site. Therefore, the floodplain uses in the upper reaches of the watershed and in Joliet shift from recreation in Urban 3.

Floodplain development regulations were the least effective policy as evaluated in this experiment. Although this result could occur because the elimination of all future floodplain development is overly restrictive, the opposite is true for the present case. The floodplain development restrictions do not require removal of existing floodplain development. In the Hickory Creek watershed, with Joliet already in existence at the base and new development occurring upstream, the model predicts tremendous damages to existing uses, particularly along the mainstem and in Joliet. The very large negative aggregate economic rent shown in Table 1.2 results primarily from expected damages of 2 billion dollars to the city of Joliet. The asterisks in Figure 1.6 indicate subbasins in which the economic rent in the floodplain becomes negative. Although this damage estimate may be excessive, the policy implication holds up to sensitivity analysis as discussed in section 5.

The resulting economic rent from implementing both the detention and floodplain development regulations showed Policy 4 to be worse than implementing only the detention regulation, but better than the floodplain regulation. The improvement results from much reduced flows, but the existing uses allowed to remain in the floodplains still sustain large damages.

Policy 5, no regulations without prediction, yields a better result than either floodplain regulation or both regulations. The floodplain uses with Policy 5 are those that would have the highest economic rent net of flood damages given existing uses, and these are lower intensities of development than exist now in certain key subbasins, particularly near Joliet. Policy 6, no regulations but with prediction of the increased flows from new development, yields a slightly better result by the removal of urban land uses from a few more floodplain segments. At least three cases where Urban 3 in the floodplain is replaced (9) can be found by comparing Figures 1.8 and 1.9 for subbasins with asterisks in Figure 1.8.

1.4.2 Implications

These results show that for the Hickory Creek watershed, as modeled in this project, floodplain regulations that do not eliminate existing urban uses from floodplains would be very ineffective as floodplain management policies. It is possible that extensive floodproofing or channel improvements, rather than the removal of existing urban uses, would be effective. The choice among density reduction, floodproofing, and channel improvements, or combinations thereof, could be considered using the same model. Additional data would be required on the costs, damage reduction, and hydrologic effects of floodproofing and channel improvement.

The major reason that floodplain regulations are ineffective, either alone or in combination with detention, is that they do not remove existing uses. If all urban uses were removed from the floodplain, the aggregate bid price for the watershed would be predicted to be $740 million. This value is close to the value for no regulations with prediction because in that case most urban use was removed from the floodplain in expectation of future flood damages.

The combination of both regulations, which is most closely analogous to policies currently being encouraged, is much better than floodplain regulations alone but still worse than all other policies. Additional improvement can only be gained by removing existing uses from the floodplain. Indeed, removal of almost all urban uses is sufficient to render detention largely unnecessary. This result can be observed by comparing Policy 1, in which almost no floodplain development occurs and there is detention, with Policy 6, in which there is a similar amount of floodplain development but no detention. As shown in Table 1.2, there is little difference in total value; indeed, with detention is slightly less, indicating no additional benefit from detention. However, the "no regulations" of Policy 6 implies recreation or agriculture in all the floodplain areas, which might exceed the reasonableness of the assumption of horizontal demand. (See Hopkins, 1978.) That is, there would be insufficient demand for that quantity of recreational open space to support the assumed land purchase price. Similarly, it is doubtful whether agricultural use can be sustained in the face of complete encirclement by urban development.

Finally, the Policy 6 implies extensive floodproofing or channel improvement at least and, by literal interpretation of the model, removal of much of the east side of Joliet. The anomaly here is that even though bid rents for individuals might be negative when expected flood damages are taken into account, these expectations are probabilistic and generally not properly considered by individual landowners. Several studies have shown that persons do not respond to probabilistic hazards in accord with expected values. (See for example White, 1961, 1964; James et al., 1971.) It is therefore likely that persons would remain in the floodplain even in the face of these negative bid prices. In this case this "no regulations" policy would require forced or compensated removal of urban uses from the floodplain.

The most tenable policy would most likely be Policy 2, detention with prediction. This policy yields the highest aggregate economic rent other than that from the optimization model, has a low total discharge, and requires the least displacement of existing uses from the floodplain. It does, however, require reduction in density (Joliet) or removal (for example, along the main stem) of some existing floodplain uses. It, therefore, cannot be considered equivalent to current floodplain policies that allow existing floodplain uses to remain. It is possible, as mentioned above, that floodproofing or channel improvement could be undertaken rather than removal or density reductions.

The model indicates a negative economic rent for Urban 3 in Joliet, even with detention. This choice means that shifting from the existing Urban 4 to Urban 3 is less costly than shifting to recreation or agriculture. Apparently the additional demolition costs as represented in the model are large enough to compensate for the higher expected damages. One might argue that if the economic rent is negative, then the land use would not locate there. This conclusion ignores the transition from existing uses. Given that the area is currently developed it is less bad to decrease the density than it is to maintain the present density or to remove the buildings.

Additional structural measures might be worthwhile to reduce flood damages to existing property in Joliet. Large detention structures on the main stems of Hickory or Spring Creek have not been considered in this study, but have been elsewhere (Department of Transporation, 1972, 1973). These studies also propose channel improvements in Joliet to protect existing development from flooding expected given the current pattern of land use in the watershed. If the results from our model are correct, such structural measures may be justified even with stormwater detention. This question could be explored by incorporating the structural measures as alternative "land uses" in the model.

The dynamic programming model yields the highest total economic rent, about 80 million dollars higher than Policy 2, detention with prediction. Extensive error analysis would be required to show conclusively that this difference is significant. Given that there is no established policy for achieving the "optimal" solution, it would also be necessary to explore the costs of carrying out policies that might achieve it. The major conceptual difficulty with direct implementation of the optimal pattern is that it could be argued to require unequal treatment of equals. That is, some persons would be required to leave the floodplain, but not others in apparently similar circumstances, and some would be required to provide detention, but not others. This characteristic would make use of the police power extremely questionable. Greater financial resources would be required if compensation were necessary. This discussion assumes that persons would be unwilling to leave the floodplain even though in expected value terms it is in their own best interest.

Given that the optimal solution has an allocation of land use to subbasins that is similar to the allocation from Policy 2, detention with prediction, the optimal solution could be used as a guide in implementing Policy 2. In general, the optimal solution requires detention in fewer subbasins and the removal or restriction of floodplain development in fewer subbasins. Therefore, priorities for floodplain purchase or floodproofing and for detention could be determined. These priorities would be of importance if financial resources were limited and compensation were required.

The comparisons above for the most part address only allocative or efficiency questions. There is also the distributive question--which individual or which group gains or loses. For example, the cost of providing detention would be borne largely by suburban newcomers in order to protect the property of current urban residents. The east side of Joliet is the "wrong side of town" so that in the present case, this question raises all the familiar issues of income distribution and race. It should also be remembered that additional runoff from the newly developed suburban areas is the cause of much of the predicted damage to Joliet. Barnard (1978) found a similar situation in Iowa City. There is no simple answer to responsibility as pointed out by Coase (1960) and resolved conceptually for the efficiency criterion but not for the equity criterion by Baumol (1972). In the present case there are also several governmental jurisdictions involved to further complicate the issue. (See Hartigan and Bonucelli, 1977.)

1.5 Sensitivity of Implications to Models and Data

Management conclusions drawn from modeling efforts of this kind must be considered carefully in light of limitations of the models, which of course only approximate reality, and in light of error in the data. There are many possible approaches to sensitivity analysis. In the present case, five sources of possible confirmation are considered.

In the development of the present model, an early version was used to address the same question (Hopkins et al., 1978). This early version used the same basic framework, but the watershed was divided into 42 subbasins instead of 67, a completely different computer code was used, and most of the data were different. For example, the economic rent data used in the early study were based on roughly calculated transportation cost differentials, and the data of the present study were derived through trend surface analysis of assessed value data as described in Chapter 2. To a great degree, these two sets of runs can be considered replications of the same experiment.

The results from these two sets of runs are compared in Table 1.2 in which the results from the early run are given in parenthesis. The relative order of preference among policies is the same for both cases. The aggregate economic rents are generally higher for the second experiment because the relative economic rents yielded much higher levels of expected urban development. The greater area of impervious surface yielded larger outflows, especially for the case without detention. As indicated above, the larger negative value for the floodplain restrictions policy in the later set of runs results primarily from losses in Joliet. The Joliet subbasin is also predicted to have negative economic rent in the earlier runs, but not large enough to make the total economic rent for the watershed negative. This analysis suggests that the constant relative preference among policies was due, at least in part, to the same general relationships. This comparison is confirming evidence that the general preference among alternative policies holds up under a wide range of potential data error.

It is more difficult to use this replication to determine the sensitivity of the optimal solution from the dynamic programming model itself. The economic rent data in the early runs implied a much lower level of urban density throughout the watershed with a greater difference between the intensity of Joliet and the intensities elsewhere in the watershed. One interpretation would be that the two runs refer to different times in the future. Some similarities do arise, however. Both runs choose nonurban uses for the floodplains along the mainstem of Hickory Creek and along most of Spring Creek, except in Joliet. Both runs locate detention on some but not all upstream subbasins and none along the mainstem of Hickory Creek. In general, it would not be possible to use this comparison as sufficient confirmation of the details of either dynamic programming solution because the land value data is dissimilar. The early run locates a great deal of nonurban use, where the later run locates urban uses. Because there is no detention option for the nonurban uses, there is no basis for comparing the locations for which detention is chosen in the two runs where one run chooses urban and the other nonurban.

A second form of confirmation for the general preference among policy alternatives comes from the studies conducted by the Department of Transporation (1972, 1973) of the State of Illinois. These studies were concerned primarily with structural measures to protect existing land use. Almost all the damage of concern was in Joliet, with minor amounts in New Lenox and Lincoln Estates. These are the same areas that our model predicts as problem areas. The Department of Transporation studies of structural measures indicated that there would still be substantial damages in Joliet, even with large detention reservoirs on Hickory Creek and Spring Creek. Retaining walls and other channel improvements were recommended to protect existing development from flood flows expected given existing development in the rest of the watershed. The present model also predicts substantial damages to existing uses from expected flows given the existing development. The structural alternatives studies thus confirm the general conclusions of the present model that special protection is required for Joliet even with upstream detention. In comparison to the Department of Transportation studies, the present model, however, is able to consider a wider range of detention and land use patterns as well as considering future growth. Structural measures could also be included in the model if they were defined as land use types, such as a floodplain land use with or without retaining walls. Such a use would simply have a different construction cost and a different damage function from the same use without retaining walls.

The sensitivity of the dynamic programming solution to potential error in the routing of hydrographs and to potential error in relative bid prices for land are reported in Chapters 2 and 3. These analyses apply only to the dynamic programming solution itself because the above comparisons suggest that the choice among alternative policies is robust with respect to both data error and model formulation. However, if the detailed implications of the dynamic programming solution, such as detention in a specific watershed, were to be implemented, then the sensitivity of that particular decision would have to be explored. The analyses, in the following chapters, indicate that most, but not all, of the preferences for detention in particular subbasins or for nonurban use in floodplains in particular subbasins are stable with respect to variations in economic rent data or error in the routing model. Where changes were observed, they could often be separated into tradeoffs between detention and floodplain use among adjacent subbasins on one major tributary. Other differences in land use patterns consisted primarily of changes from one density level to the next lower or higher level. Such shifts had little effect on runoff and therefore were unimportant in determining floodplain uses that would be compatible with use in the remainder of the watershed. In general, some of the subbasin level decisions were sensitive to likely ranges of data error and should be examined in detail using more elaborate routing models, such as the Muskingum method, and field confirmation of economic rent data.

Finally, the sensitivity to error in the estimated flood damages or in the choice of discount rate was considered. These two types of errors are equivalent because the only cost for which the present worth must be calculated is flood damages. The transformation of annual damages over a given time period (in this case 100 years) into present value consists only of multiplication by a coefficient (see equation 1.4). Therefore, sensitivity tests based on changing the discount rate (i.e. changing the coefficient) can also be interpreted as changing the annual damages and keeping the discount rate constant. Discount rates of 10 percent and 3 percent were chosen to compare to the above runs, which used a 5 percent discount rate. The 10 percent rate can also be thought of as approximately halving the annual damages (.504 to be exact) and retaining a 5 percent discount rate. The 3 percent rate is approximately equivalent to increasing damages by 50 percent (1.592 to be exact)

These two runs are compared to the standard run in Table 1.3. There is little change in the total economic rent for the watershed. The outflow for the 3 percent run is increased primarily because damages are increased sufficiently to make urban uses unprofitable in the floodplain near Joliet. Therefore, the outflow can be even higher because there is no urban use to be damaged. The close similarity of total rents suggests that the relative preference among policies would not be altered by likely ranges of error in the damage data.

These sensitivity runs with respect to damage data can also be compared with respect to the resulting land use pattern. The non-floodplain land uses were the same for all three runs in 91 percent of the subbasins; the floodplain uses were the same in 78 percent of the subbasins. The changes that did occur were directly predictable in all but a couple of cases. As damages increased, there were more subbasins with nonurban uses in floodplains and more with detention. These results indicate that a sufficient portion of the dynamic programming solution is stable to be useful for choosing subbasins of higher priority for detention or floodplain restriction as in the implementation strategy suggested above.

Table 1.3 Sensitivity with Respect to Damage Estimates

	Total Economic Rent in $1,000,000	Discharge in 1000 cfs
3% discount rate	852	26.06
5% discount rate	853	19.84
10% discount rate	863	19.84

1.6 Conclusions

The modeling approach developed here provides useful insights by demonstrating the interdependence arising among land uses in floodplain and non-floodplain parcels in the Hickory Creek Watershed. Although the results reported here should not be construed as being directly applicable to the real situation, they do provide a useful basis for further consideration of alternative policies. Floodproofing, channel improvement, or removal of urban uses from some floodplain areas will almost certainly be required in an effective policy if the watershed becomes largely urbanized. The choice among these three options could be incorporated into the model within its current structure. Even with detention in accordance with the MSD ordinance, existing land uses in the floodplain should be modified. Policies that simply restrict further floodplain development will not be of much use because the floodplain is already developed beyond densities appropriate for expected runoff.

The target solution found using the dynamic programming model is a useful reference for comparing the success of alternative policies. More importantly, the model solution should prove useful in guiding the implementation of one or more of the traditional policies by indicating priority areas for detention or for modification of floodplain land uses. The optimization model also shows that, at least in this case, there is interdependence in land use allocation for floodplain managment. A good solution includes some reduction of current land uses in the floodplain and some provision of detention. This means that determination of good solutions through land use allocation models that take account of this interdependence may be worthwhile, especially if policy instruments can be developed so that such targets can be achieved without great investment of resources in the process of implementation.

CHAPTER 2 ESTIMATING BID PRICES FOR LAND USING TREND SURFACE ANALYSIS

2.1 The Bid Price Objective for Land Use Allocation

One approach to choosing target land use plans is to maximize the aggregate bid price for land. (E.g., see Alonso, 1964; Herbert and Stevens, 1960; Lind, 1973.) The bid price (or bid rent) is the amount an individual or firm would be willing to pay for a particular site to use it for a particular purpose. The resulting allocation will yield the maximum utility (or productivity) attainable from the land given conditions on the model. It is, however, difficult to obtain valid bid price data for a given land use problem. The primary purpose of this chapter is to report an experiment with trend surface analysis as an operational means for obtaining bid price data for use in a land use allocation model. The basic idea is to derive a bid price surface for each use, i.e., a description of the spatial variation in bid price as if it were the topography of the region, presented, for example, as a contour map. The model for which this data was developed must be described briefly first to establish the assumptions on which the data should be developed. Then the procedure and results for trend surface analysis of assessed value data to generate bid price surfaces are presented.

2.1.1 A Land Use Allocation Model for Floodplain Management

The problem is to find efficient allocations of land uses to land parcels. It is assumed that new development in the watershed affects the rate of runoff and therefore the peak flows of floods. It is also assumed that the damage within the floodplain is a function of the land use located there and the level of peak flows. This relationship between land uses on the floodplain and land uses in the rest of the watershed is the familiar externality problem. Baumol's (1972) result that an optimal allocation will not result from incremental adjustments, even with externality taxes, has been shown in a previous paper (Hopkins et al.,1976) to apply to this case; a target allocation should be chosen. Therefore, a dynamic programming model was devised to allocate land uses so as to maximize aggregate bid price throughout the watershed with bid prices in the floodplain being net of expected damages caused by the runoff resulting from the land uses located in the remainder of the watershed (Hopkins et al., 1978).

The model allocates discrete land use density classes, which implies a fixed ratio of capital to land within a land use class regardless of bid price for land. However, the use of a range of land use density classes is equivalent to an activity analysis approach in which continuous variation in the ratio of capital to land is approximated by discrete classes. Each density class has a separate bid price surface so the discrete classes approximate a continuous model.

The model assumes a horizontal demand curve for each land use class for the given pattern of prices. Therefore, bid price remains constant regardless of the amount of any land use class located. This assumption implies that the commodity, in this case land, is being sold in a market of which the study area is a sufficiently small subarea that it does not affect price or supply. (See, e.g., Greenberg et al., 1974.) The land use allocation model has been developed for the 100 square mile Hickory Creek watershed on the fringe of metropolitan Chicago. The study region is argued to be a sufficiently small portion of the total fringe area that the horizontal demand assumption constitutes an operationally useful approximation. Land uses could find alternative locations outside the study area. There would also be sufficient total demand in the metropolitan area that bidders for any one land use class could fill the entire study region without changing their willingness to pay. This approach is analogous to Wheaton's (1974a) concept of an open city--utility levels given and population determined by the model. Such an assumption might not be satisfactory for certain land uses, such as recreation, but value of recreation land was not estimated by this technique.

The horizontal demand assumption is important because it makes the floodplain externality problem feasible to solve through dynamic programming. Without it, additional state variables would be required to represent aggregate quantities of each land use; such additional state variables would render the problem too large to be solved practically.

2.1.2 Current Land Values as Estimators of Bid Price

The use of current land price data to estimate bid prices for particular land uses requires assumptions about consumers' surplus, population growth, externalities, and capitalization of future expectations. If the implications of these assumptions are understood and kept in mind, bid price data estimated in this way can be adequate for policy analysis using land use allocation models.

The model allocates uses to land so as to maximize the sum of the bid prices. This objective is a valid economic efficiency measure because the bid prices are equivalent to willingness to pay. The bid prices used in the model are thus not equivalent to resulting land prices unless the market structure is such that there is no consumers' surplus. To use current land price data to estimate bid price requires either the addition of consumers' surplus, somehow measured and obtained separately, or the assertion that consumers' surplus is everywhere zero in the existing land use pattern from which land price data are taken.

For the present situation it is plausible to argue that consumers' surplus in the existing land use patterns is likely to be very small. The theoretical requirement for consumers' surplus to be zero is that for every bidder who does win land there be at least one potential land bidder who does not win land and who has a utility function identical to that of the winner. In this way there would always be another bidder waiting in the wings to outbid any land bidder who did not bid his full willingness to pay. Given that the study region is a sector of the metropolitan fringe in Chicago, it is reasonable to argue that this requirement is approximately met. There are, for example, plenty of residents of any one type buying land in other sectors of the metropolitan fringe who would shift to the Hickory Creek sector if bidders for similar types of residential developments there did not bid their full willingness to pay. Current land values are, therefore, accepted as reasonable estimators of willingness to pay, at least for the broad land use classes and level of spatial precision of the present study.

The assumption of horizontal demand curves and the estimation of regional bid price trends for particular land use classes from existing land prices require assumptions with respect to population growth. In an urban fringe, there are many areas of noncontinuous growth. When a trend surface is estimated, parcels that have not yet been developed will be estimated to have bid prices for a particular density similar to the bid prices of the already developed parcels of that density. This interpolation effect is desirable for the present purpose. The implied assumption of sufficient population growth to fill in existing areas that have development potential, but are not currently in that land use, is based on the expectation of major increases in developed area over the next fifty years. This population growth is also consistent with the assumption of a horizontal demand curve for each land use class.

The use of current prices implies that the forms and the relative levels among bid price surfaces at the present will be preserved in the future. If there were a limited supply of land, one would expect the bid price surface for higher density uses to rise relative to lower density uses as population increased. That is, the bid price surface for higher density use would have to rise so that the increased population could successfully compete for sites. Similarly, if demand were not horizontal for each land use class, there would be relative shifts in the heights of bid price surfaces to equilibrate supply and demand for different land use classes. The horizontal demand curve assumption thus obviates the need for a general equilibrium model that would otherwise be required. (See for example Wheaton, 1974a.) The use of trend surface analysis in the present context will smooth current land prices and therefore yield less sharply peaked bid price surfaces than are currently revealed at the localized level. This smoothing is consistent with the shift during urban fringe development from scattered small towns to relatively homogeneous surburban development. Therefore, the forms of the bid price surfaces derived through trend surface analysis do not take current forms into the future unchanged. Although the smoothing is not measured, the change is at least in the right direction.

The bid price surfaces derived from current prices also imply that external effects, other than the flooding effect that is included in the model, remain constant. The bid prices incorporate external effects from the existing land use pattern, but not from the future land use pattern. This limitation is acceptable if the basic structure of the study area is already established. In the Hickory Creek watershed, the major nodes of external effect--for example, industry on the south and east sides of Joliet and along the Des Plaines River, interstate highway interchanges, and major commercial nodes--are generally in place. If something analogous to Hoyt's (1939) sectoral theory of growth is an appropriate conceptual model, then the future bid prices for particular land use classes will evolve spatially from current patterns. With these assumptions, relative regional bid price trends will tend to be constant with respect to external effects. Future development of a major new industrial or commercial node, such as a regional airport, would of course invalidate this assumption.

The use of current land values to estimate bid prices for particular uses requires that these land values represent the present worth of the stream of future benefits for the current use and not for some future use. For example, if one were trying to estimate the bid price surface for low density residential parcels from land values for existing low density parcels, the current land values of these parcels must not represent value for potential redevelopment at higher densities. For this reason, assessed land values have a potential advantage over data from current sales transactions. Assessed land value, separated from assessed value of improvements, tends to underestimate the value of a parcel of land that is currently developed but that could be redeveloped at a higher density use. There is no easy way to confirm this assertion; it was pointed out by a county assessor and supported by observation of the data. This assessment pattern means that assessed land values for improved properties do not represent value for a future use, but for the present use. There is one obvious exception, agricultural land. One could surmise that because agricultural land has no obsolete improvements to hamper redevelopment and no improvements to which to ascribe the apparent value, agricultural land is more likely to be assessed in part on development potential.

Sales transactions data, on the other hand, are more likely to reflect expected changes in land use, but these expectations are one likely cause of sales. Sales prices are frequently argued to have advantages over assessed values because the former result directly from market transactions. Keeping in mind that most sales rely on an appraisal to determine an appropriate price and an appraisal for approval of financing, it is not clear that there is a great difference between sales prices and assessed values in the aggregate.

finding data for a range of land use types in a mixture of urban and nonurban areas is likely to be prohibitive. There have been many regression studies of land or improvements value for appraisal purposes, but these are generally far too detailed in nature to make bid price estimates for future uses at the regional level.

Clonts (1970) predicted values of subdivided improved, subdivided unimproved, and rural lots with respect to value of improvements, distance to urban periphery, distance to highway, front feet, and size of parcel. Although he obtained very high R^2 values, most of the explanation resulted from variation in lot size. That is, the price of lots was strongly determined by their size. Clont's regressions for value per acre of agricultural land yielded an R^2 of .543. This latter figure is the more appropriate benchmark with which to compare the trend surface results presented below. Hushak (1975) predicted the price gradient for urban-rural fringe land with four different equations yielding R^2 values ranging from .477 to .710. Although Hushak's study yielded some useful rates of change that could be used in an estimation of site cost differentials, it predicted the equilibrium price gradient of the uses that did locate in each parcel, not the bid price curves for each individual land use in each parcel as required in land use allocation models.

2.3 Trend Surface Analysis of Assessed Value Data

Given the large study area and the relatively coarse system of subbasins (approximately two square miles) to which land uses were to be assigned by the model, fitting of trends to assessed value data appeared to be a possible alternative. Assessed value data in Illinois is conveniently referenced to a grid of quarter sections (160 acres) by the tax parcel numbering system. This reference system makes it possible to determine easily the mean assessed value of land per acre in any quarter section. By then determining the existing land use type of each quarter section, the study area can be divided into sets of quarter sections, one set for each current land use type. Trend surfaces can then be computed to interpolate the values for quarter sections in which a particular use does not currently occur. The quarter section data can then be aggregated to the subbasins for use in the land use allocation model.

The problem is to interpolate assessed land values as surrogates of bid price for a particular use over quarter sections in which that use does not currently occur. Other interpolation algorithms, such as an inverse weighted mean of a specified number of nearest neighbor points, might be considered. For example, the value for low density residential might be computed as the mean of the assessed land values in the nearest nine quarter sections that were currently low density residential, the value in each of the nine quarter sections being weighted inversely by its distance from the quarter section for which the value was being interpolated. An attraction of this approach is that there are no statistical assumptions required.

However, the difficulties that one would expect deductively rendered the inverse weighted mean approach inappropriate as confirmed by some informal trials. Consider the ubiquitous (in theory, not reality) monocentric urban form. For a given land use density class there would be data points, that is observations for a current land use, in one ring. The bid price at the center as interpolated for this use would be the inversely weighted mean of the values in the ring. The interpolated value at the center would, therefore, be exactly the same as the value in the ring because the observations are all equidistant from the center. However, theory indicates that the bid price for that use would increase toward the center. Therefore, the inverse weighted mean approach was rejected as being conceptually inappropriate.

Continuing the monocentric example, if the ring of a particular land use type is a finite width, as in the case of discrete land use classes, there would be a trend within that ring, which would be extrapolated. Given an appropriate function, this extrapolation would predict values at the center that would be higher than those in the ring in keeping with the predictions from location theory.

The use of trend surface analysis in this case serves two purposes. It predicts values at points for which there are no data, and it separates the regional trend from local effects that would not be preserved under relatively complete surburban development. This application is thus in the gray area between simple descriptive generalization and formal hypothesis testing. There is no theoretical basis for a firm hypothesis as to the functional form of the prediction equation. Nor is there any interest in proving that a particular form is a good one. However, in order to interpolate and to separate a regional trend, a functional form must be chosen. Different functions will interpolate different values and separate different regional trends. In the present application, the study area is a multinucleated urban fringe so that simple functions based on a radial distance from a center would not apply. The polar-coordinate Fourier series model proposed by Ricci et al. (1979) would not be appropriate here because it assumes a single node with respect to which land values vary in a predictable fashion. For want of an alternative function, the traditional polynomial surfaces used in most trend surface analyses were used.

There is some basis for choosing among polynomials of different degrees if one accepts the polynomial as an appropriate function. A polynomial of degree n will generate a surface with n-1 maxima or minima. One would expect a second degree polynomial with one maximum to give the best fit for data for a monocentric city. In the Hickory Creek watershed, the expected pattern of maxima is less obvious. (See Figure 2.1.) Initial expectations were that values would tend to increase toward Chicago and toward Joliet

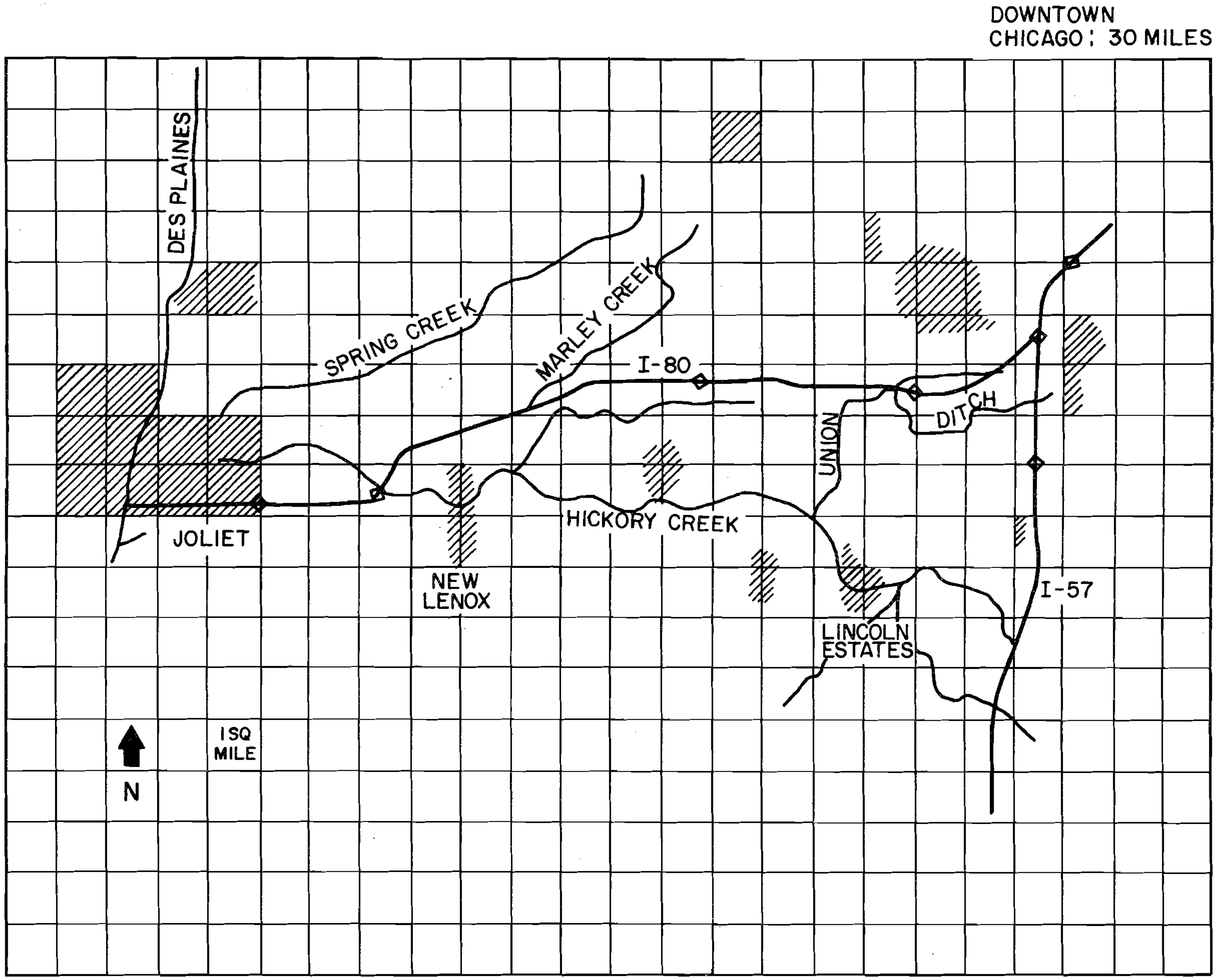


Figure 2.1 Map of Study Area

with up to three additional maxima depending on the particular land use density class. For higher density uses, one would expect a steeper bid price gradient around interchanges or towns. A peak in the bid price surface might, therefore, show up for higher density uses but not for lower density uses.

Because there was no basis for using strict hypothesis testing, the choice of the degree of polynomial for a particular use was based on four considerations. First, there was an appropriate degree based on the expected number of potential minima and maxima. Second, F tests of significance of the equation for a given degree and of the improvement of the degree over the next lower degree were computed. Third, the resulting spatial pattern was mapped and considered in light of sensible bid price patterns for the study area. Finally, the residuals for the chosen surfaces were plotted to determine informally whether there was spatial autocorrelation among residuals that would invalidate the interpretation of the bid price surfaces.

It is inherent in the proposed approach that data points will be frequent in some areas, where the land use currently exists, and sparse or nonexistent in others. Statistical theory indicates that the data points should be randomly chosen. However, in this case, as in many applications of trend surface, random sampling is impossible because the data set is given (the set of quarter sections currently in a given land use class) and is so small that sampling from it would eliminate too much of the information content.

It has been argued that data points that are clustered rather than random or uniform may lead to distortions of the surface as well as invalidity of tests of significance. There is disagreement as to whether outliers are given undue weight (Unwin, n.d.) or clusters are given undue weight (Davis, 1973). In either case, experiments by Doveton and Parsley (1970) show that as long as there are some data points in all parts of the study region, clustered data will not grossly distort the surface. This result is especially true for lower order surfaces with relatively little noise in the data. Since the results reported below have relatively poor fits and are of order three and above, an experiment was conducted for one of the land use classes to determine the effect of a less clustered pattern of data points. The details are reported below. In summary, there was little effect on the surface and there was little basis for choosing one modification of the data over another. For these reasons, the data were used in their original form.

Each data set includes a range of mean parcel sizes for quarter sections because the land use classes are discretely defined. Therefore, the polynomial trend equation was augmented by the parcel size variable to control for the variation in parcel size within each land use class. The bid price surfaces were then predicted using the mean parcel size of the land use class in the regression equation.

2.4 Procedure

The land use allocation model requires discrete land uses defined with respect to bid price, impervious surface, and susceptibility to flood damage (Hopkins et al. 1978). The six basic land use types, defined by their mean density, are listed in Table 2.1. The model allocates only one land use to each subbasin, and the subbasins are approximately two square miles. Therefore, these descriptors should be considered labels for general land use intensity classes rather than narrowly defined land use types. Schools and community shopping centers are included within the residential categories, for example. Urban 2, one dwelling unit (du) per acre, might result from a mix of higher and lower density in a subbasin. The problem of estimating recreation land value presents a special case that is not addressed here. Originally a fourth residential density class was considered, but it seldom occurred in the study region, and most cases were very close to the class boundary with Urban 3. Therefore, it was subsumed within the Urban 3 and Urban 4 land use classes.

Table 2.1

Land Use Categories

Category	Description
Urban 1	.2 dwelling units per acre
Urban 2	1 dwelling unit per acre
Urban 3	2.75 dwelling units per acre
Urban 4	Greater than 6 dwelling units per acre or industrial or commerical
Agriculture	
Recreation	

2.4.1 Data Preparation

For the portion of the watershed falling within Will County, Illinois, assessed values for land were obtained from computer files arranged by tax parcel numbers. The numbers are structured so that parcels can be readily classified by quarter section. From this file, the mean parcel size was computed for each quarter section by dividing the total area (usually 160 acres) by the number of parcels. Adjustments, some extensive and tedious, were made to correct the quarter section areas to account for parcels that overlapped into adjacent quarter sections and other such anomalies. These mean parcel size figures were then used to classify the quarter sections into the five land use classes (excluding recreation) by establishing class boundaries for each type. Again, extensive manual checking was undertaken to correct for anomalies. For example, large parcels could be apartment complexes, farms, or industrial sites. United States Geological Survey topographic maps, various local area maps, and air photos were used to reclassify quarter sections that had been misclassified. The mean assessed value of improvements was also computed for each quarter section as an aid in checking the classification.

The bid prices required for the model should be exclusive of flood damage. That is, the bid price should not be reduced by the present value of damages because this component of value is handled separately in the model. No explicit modification of the assessed value data was made to delete this component because floodplain areas were a small portion of any quarter section, floodplain effects would be localized and therefore separated from the regional trend by the analysis, and experience elsewhere suggested that landowners did not consider flood damages significantly in determining bid prices.

Next, the mean assessed value of land per acre was computed for each quarter section. First, acres in nontaxable parcels were subtracted from the total acres of the respective quarter sections. Then the mean was computed by dividing total value of assessed land in the quarter section by total taxable acres. Again, manual work was required because the parcel sizes for subdivided parcels were not given in the data file. Therefore, small nontaxable parcels were identified on maps, their areas estimated, and corrections made to the total of taxable acres. The assessed value data were then transformed to market value by using the standard multiplier for Will County.

The data for that portion of the watershed falling within Cook County were collected manually because computer tapes were not readily available and the number of quarter sections was relatively small. However, the basic procedure was equivalent. Transformation from assessed to market value took into account the variation in assessment ratios in the Cook County data for different land use types.

Finally, each quarter section was given matrix coordinates as a location reference. This step was simple in this study area where the township range system fits fairly closely to a regular grid. The minor anomalies in surveying and the Indian boundary (one of two in Illinois, but of course falling within the site) were ignored as having insignificant effect on spatial referencing at the coarseness with which the data were being developed and used.

2.4.2 Statistical Analysis

These steps resulted in five data sets, one for each land use class. Each data set consists of the matrix coordinates, the mean parcel size, and the mean value of land per acre for each quarter section that was in the particular land use class in 1977 when the tax assessment data were created. For any given land use class, an equation of the following general form (following Davis, 1973) could then be estimated by standard regression techniques.

$$y_i = a + b_0 s_i + b_1 x_1 + b_2 x_2 + b_3 x_1^2 + b_4 x_1 x_2 + b_5 x_2^2 + \ldots + (\gamma_i + \varepsilon_i) \qquad (2.1)$$

y_i = bid price per acre (land value) for use i

s_i = mean parcel size for quarter section for use i

$\left.\begin{array}{l} x_1 = \\ x_2 = \end{array}\right\}$ matrix coordinates of quarter section

γ_i = residual; i.e. local effects

ε_i = error of measurement

Equations for other degrees of polynomial include all the analogous powered and cross product terms of the two coordinate reference variables, x_1 and x_2.

First, each data set was fit to successively higher degree polynomials up to at least one degree greater than the degree expected to yield a sensible surface on the basis of general knowledge of land use patterns in the area. Three tests were conducted on the results for each land use class. (See Unwin.) An F test on the entire trend equation,

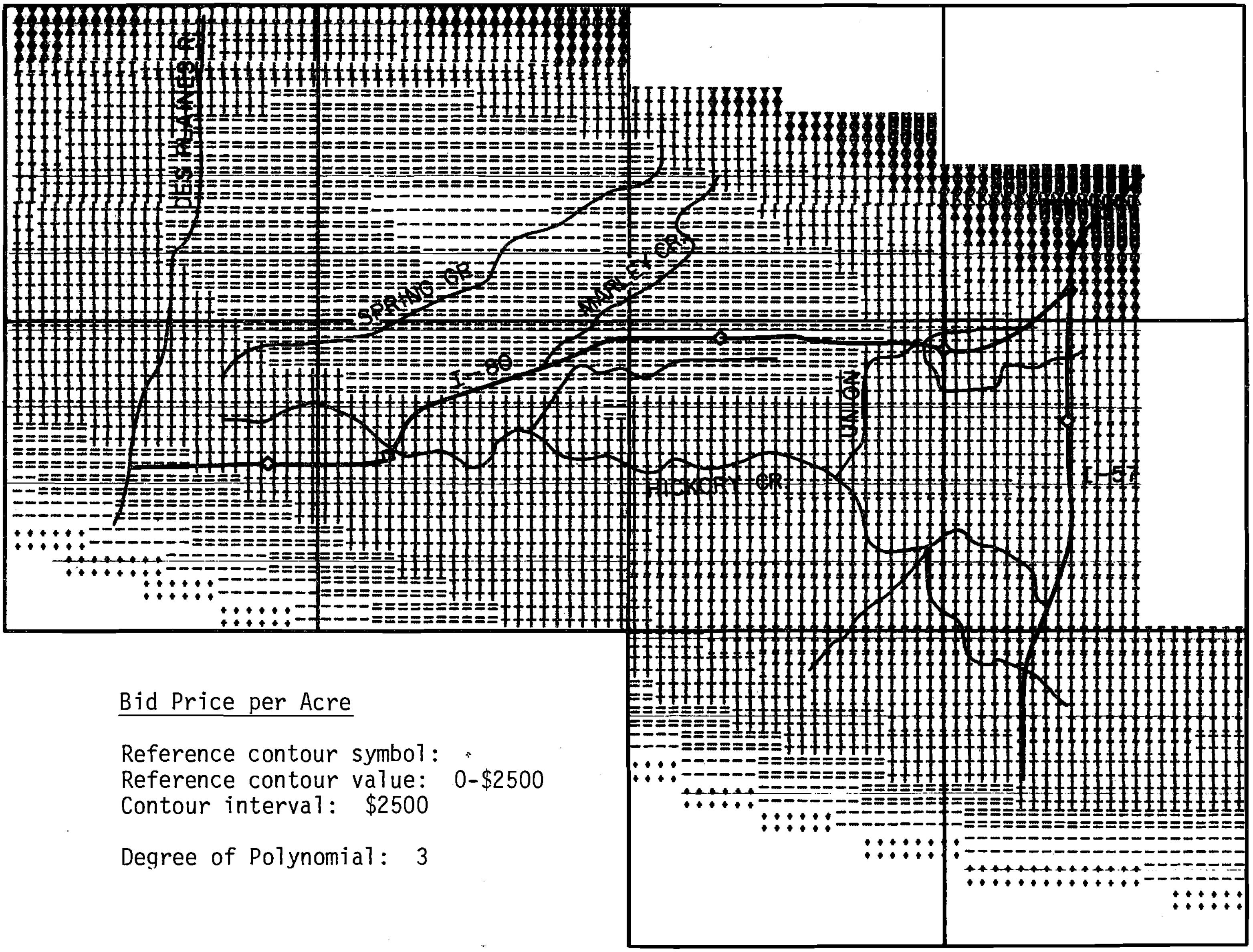
$$F = \frac{R^2/d_1}{(1-R^2)/d_2} \qquad (2.2)$$

where d_1 is degrees of freedom of the surface (number of coefficients in equation minus one), and d_2 is degrees of freedom of the residual (sample size = 1-d_1). F tests were also conducted to determine the significance of the improvement in explanation of an n degree surface over an n-1 surface. These F values were computed as:

$$F = \frac{(R_n^2 - R_{n-1}^2)/d_3}{(1-R_n^2)/d_2} \qquad (2.3)$$

where d_3 is degrees of freedom added from degree n-1 to degree n and d_2 is degrees of freedom of the residual. The results are shown in Table 2.2, lines 5 through 10. In general, the degree surface chosen for further study was the highest degree having a .05 significance of the improvement over the next lower degree. Each surface was also mapped. As shown in Figures 2.2 through 2.6. Each figure shows a contour map of bid price per acres for the particular land use. Price increases from light to dark symbols with the contour interval indicated on each figure. Blank areas have negative bid prices except as noted on the figures. For more detailed spatial reference to the watershed see Figure 2.1.

For Urban 3 (2.75 dwelling units), the improvement was not significant for any degree surface, although the overall F test indicated significance at the .01 level for the third and fourth degree surfaces. The fourth degree surface was chosen for further study on the basis of the spatial pattern as represented in map form. Theory would suggest local peaks in this surface at urban nodes, of which there were at least four. For agriculture, degree 2 was chosen, even though the improvement for degree three was significant at the .05 level. The degree 3 surface resulted in a nonsensical spatial pattern that could not be theoretically supported. The parcel size variable was not significant at .05 for the agriculture equation and was dropped from that equation.

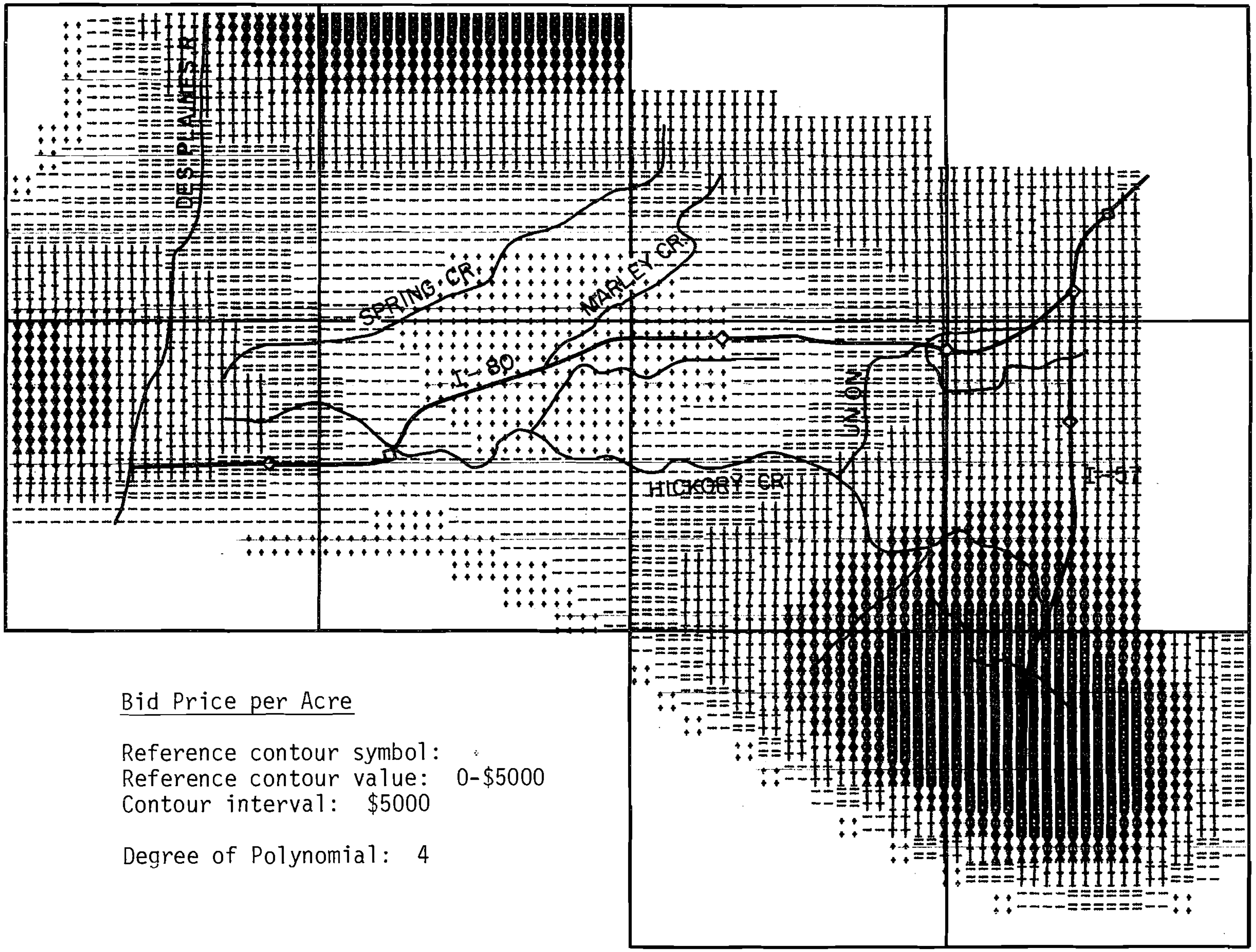


Bid Price per Acre

Reference contour symbol: ⋄
Reference contour value: 0-$2500
Contour interval: $2500

Degree of Polynomial: 3

Figure 2.3 Land Value Contours for Urban 2 Land Use

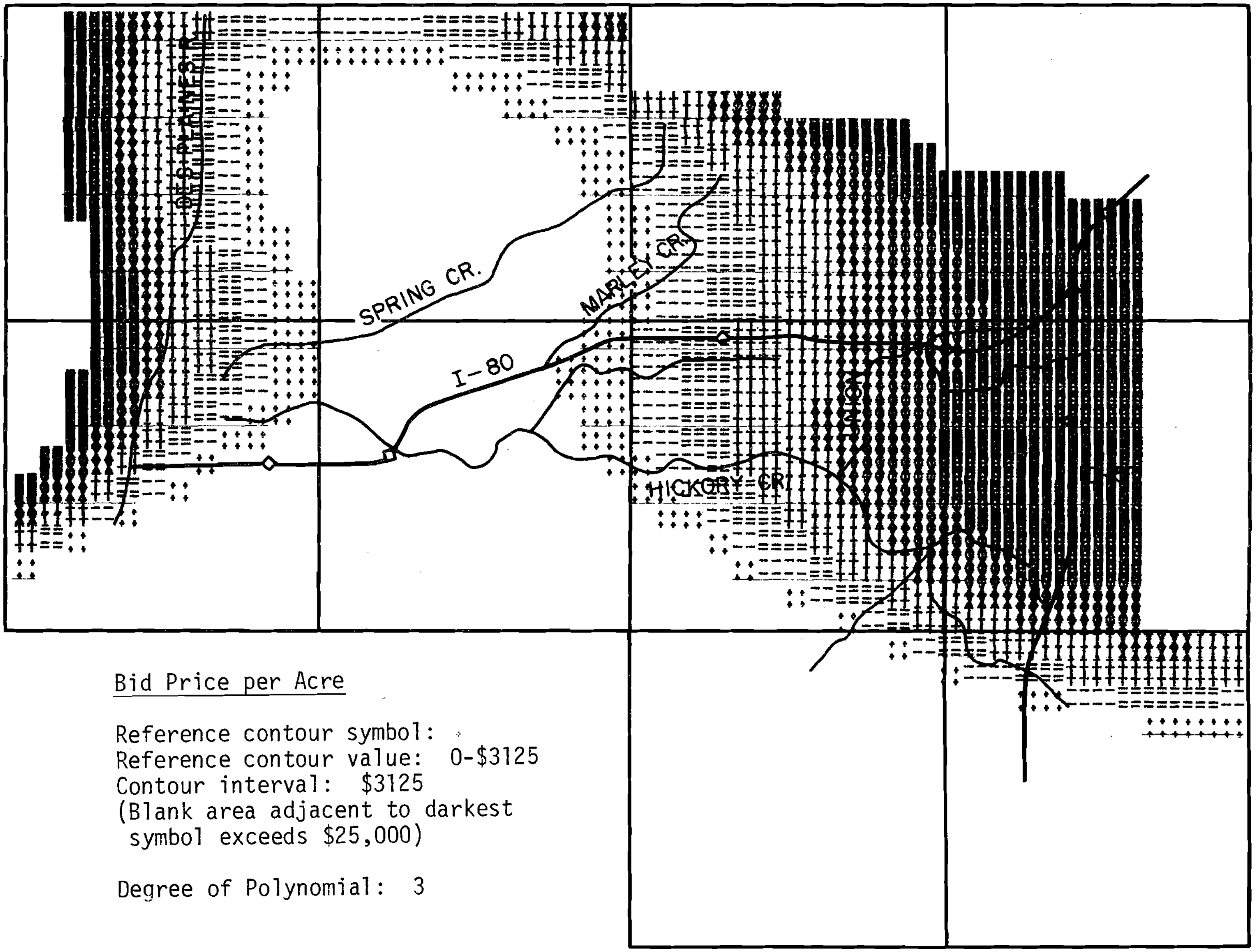


Bid Price per Acre

Reference contour symbol:
Reference contour value: 0-$5000
Contour interval: $5000

Degree of Polynomial: 4

Figure 2.4 Land Value Contours for Urban 3 Land Use

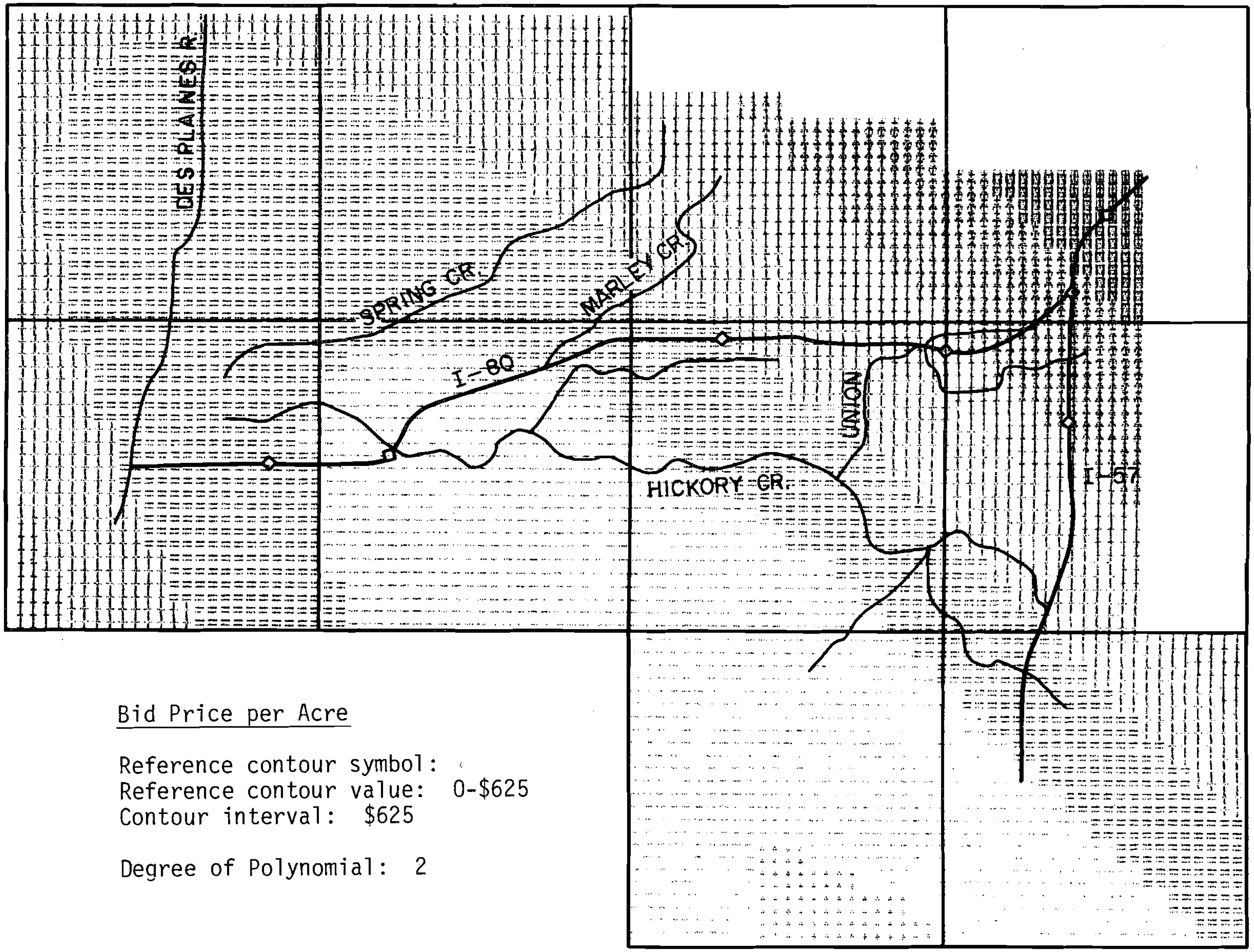


Bid Price per Acre

Reference contour symbol: +
Reference contour value: 0-$3125
Contour interval: $3125
(Blank area adjacent to darkest
symbol exceeds $25,000)

Degree of Polynomial: 3

Figure 2.5 Land Value Contours for Urban 4 Land Use

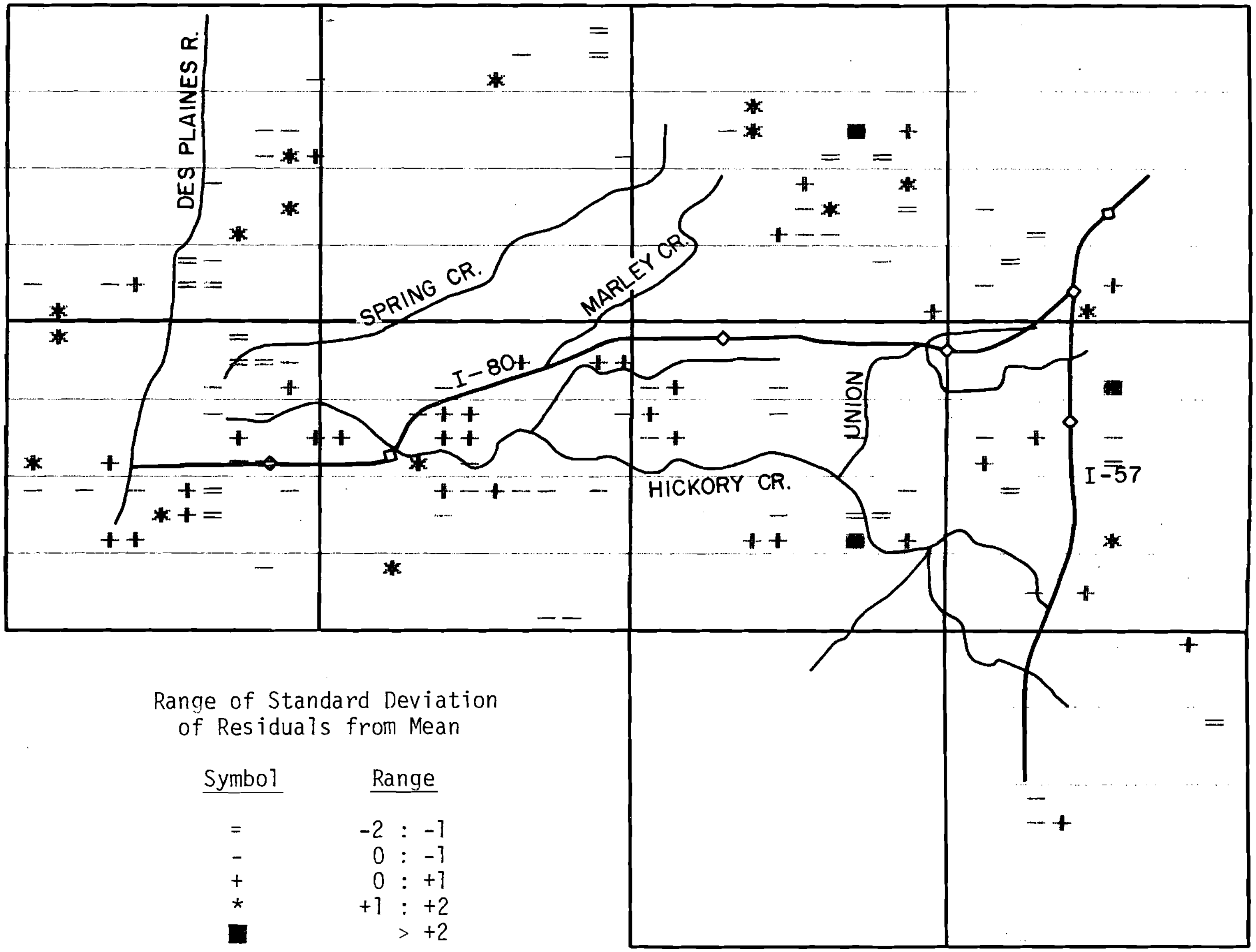


Bid Price per Acre

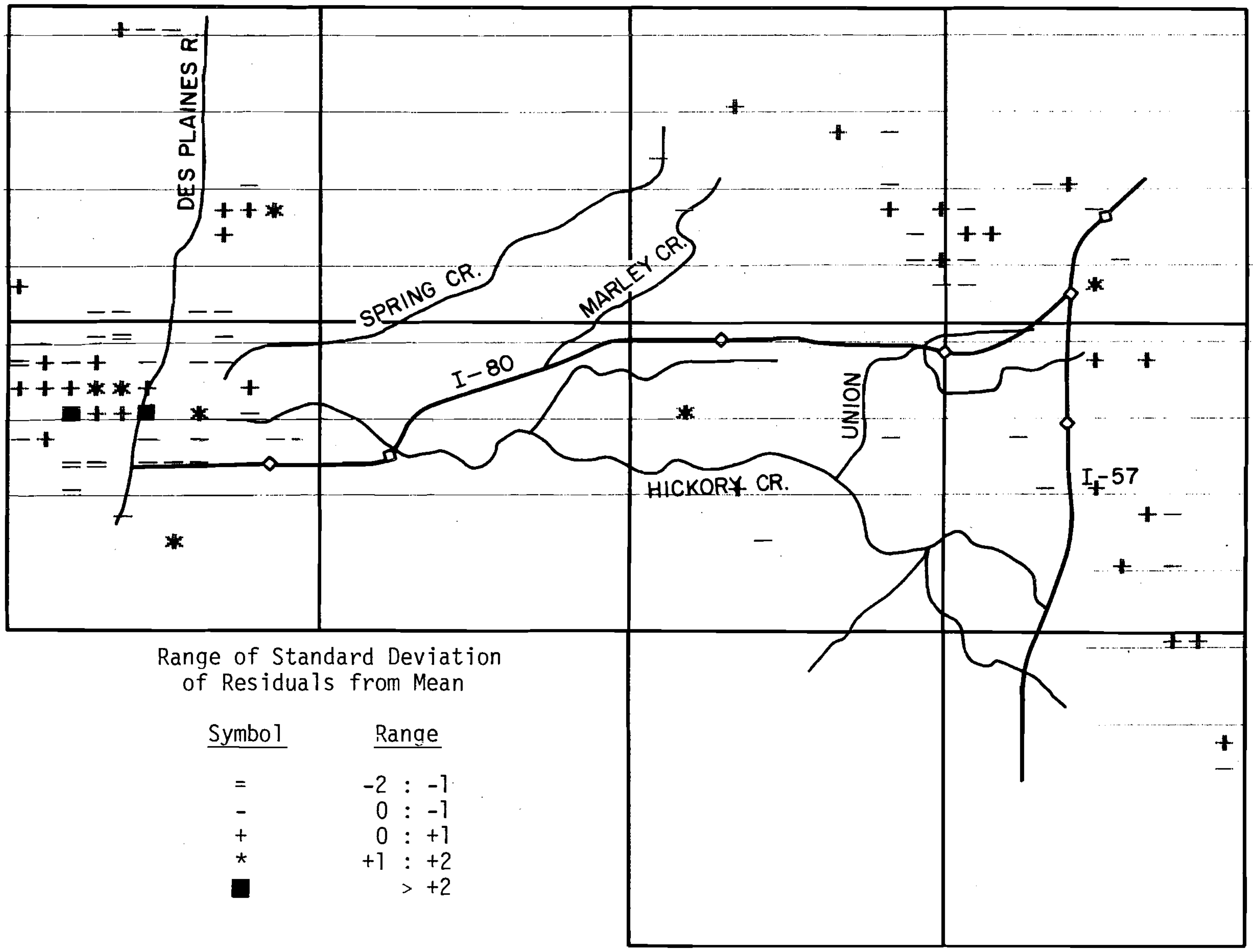
Reference contour symbol:
Reference contour value: 0-$625
Contour interval: $625

Degree of Polynomial: 2

Figure 2.6 Land Value Contours for Agriculture Land Use



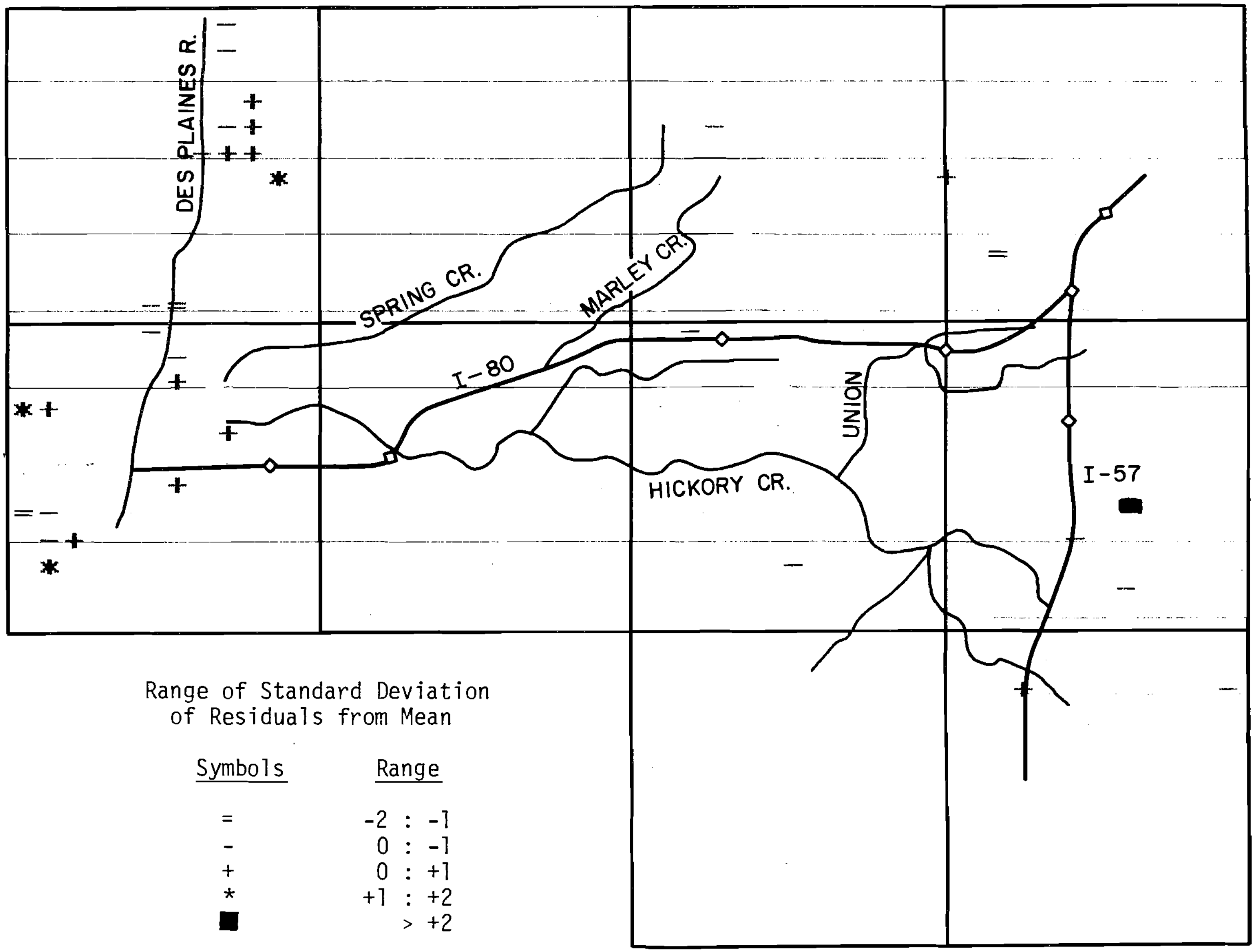
Figures 2.8 Residual Map for Urban 2 Land Use



Range of Standard Deviation of Residuals from Mean

Symbol	Range
=	-2 : -1
-	0 : -1
+	0 : +1
*	+1 : +2
■	> +2

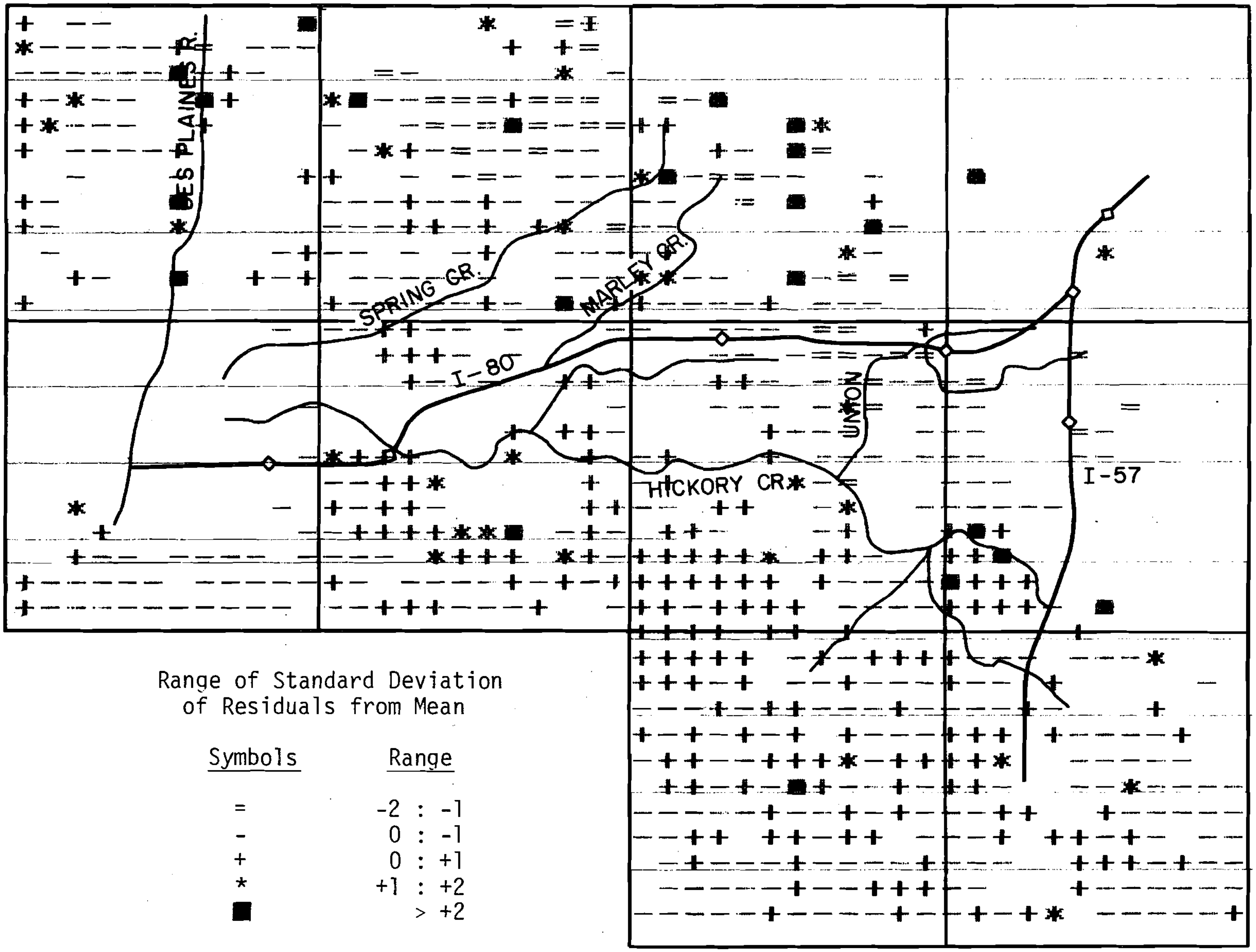
Figure 2.9 Residual Map for Urban 3 Land Use



Range of Standard Deviation
of Residuals from Mean

Symbols	Range
=	-2 : -1
-	0 : -1
+	0 : +1
*	+1 : +2
■	> +2

Figure 2.10 Residual Map for Urban 4 Land Use



Range of Standard Deviation
of Residuals from Mean

Symbols	Range
=	-2 : -1
-	0 : -1
+	0 : +1
*	+1 : +2
■	> +2

Figure 2.11 Residual Map for Agriculture Land Use

To explore the effect of the clustering, the Urban 2 (1 du/acre) data were modified by taking clusters of points, generally two or more contiguous sample points, and transforming them into one sample point. The location of the new sample point was the approximate centroid of the original points and the value was the mean of the values of the original points. Points that represented a particular homogeneous residential area that happened to be large enough to cover more than one quarter section were in particular transformed into a single point. The resulting pattern of sample points is shown in Figure 2.12. The polynomial regression was rerun and the results compared. Although the R^2 increased for the modified data set, this result is due in part to the decrease in variation resulting from the reduction from 127 to 67 sample points from taking the means of clustered points. The functional form and pattern was little changed as evidenced by comparison of the maps in Figures 2.3 and 2.13. There was no clear bias toward clustered or outlier sample points in the original data. The residuals for points in clusters both increased and decreased as did the residuals for outliers. Although there are minor differences between the two surfaces, there is little basis for accepting one over the over. Since there could be many modifications to lessen the clustering effect with little basis for choosing one over the other and because the general form of the surface changed very little, the original data were used.

2.4.4 Spatial Pattern of Bid Prices

Next, maps of the chosen surface were compared to maps of the n-1 and n+1 degree surfaces to determine whether a change would yield a more theoretically justifiable spatial pattern. Urban 1 (.2 du/acre) was increased to degree 3 from degree 2 and Urban 3 (2.75 du/acre) was increased from degree 4 to degree 5. For Urban 1 the change from second to third degree was significant at the .055 level,

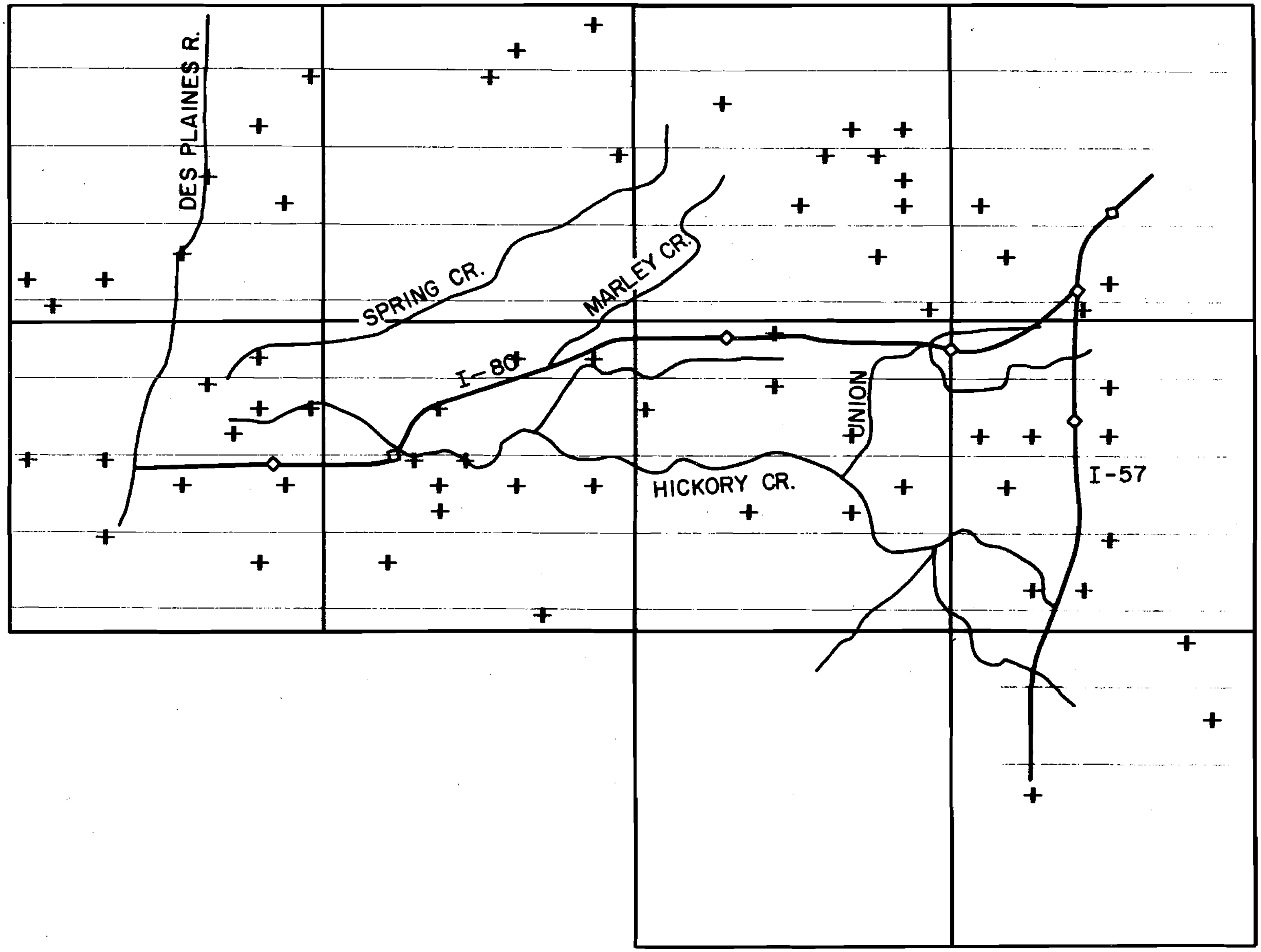
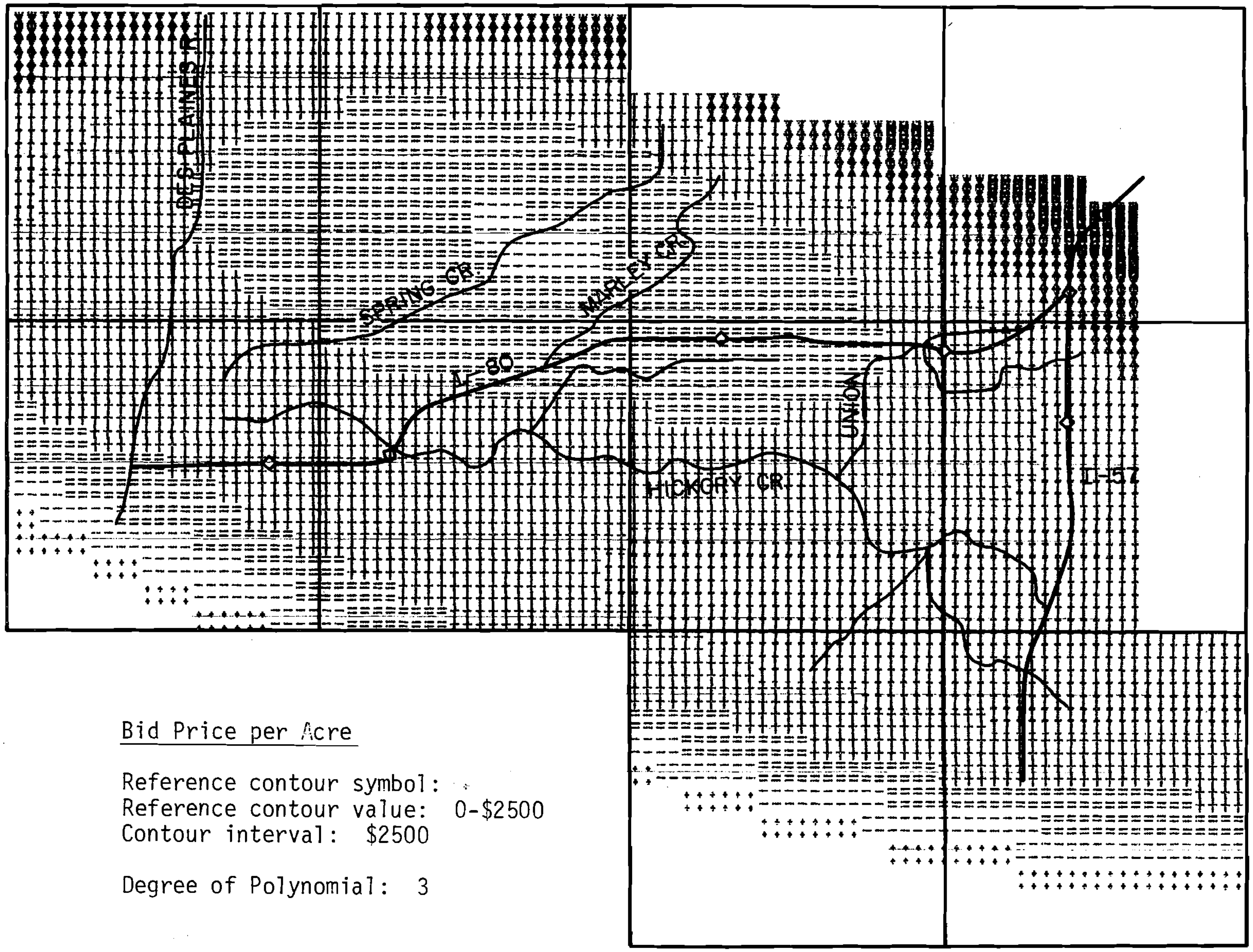


Figure 2.12 Homogeneous Residential Area Sample Point Pattern



Bid Price per Acre

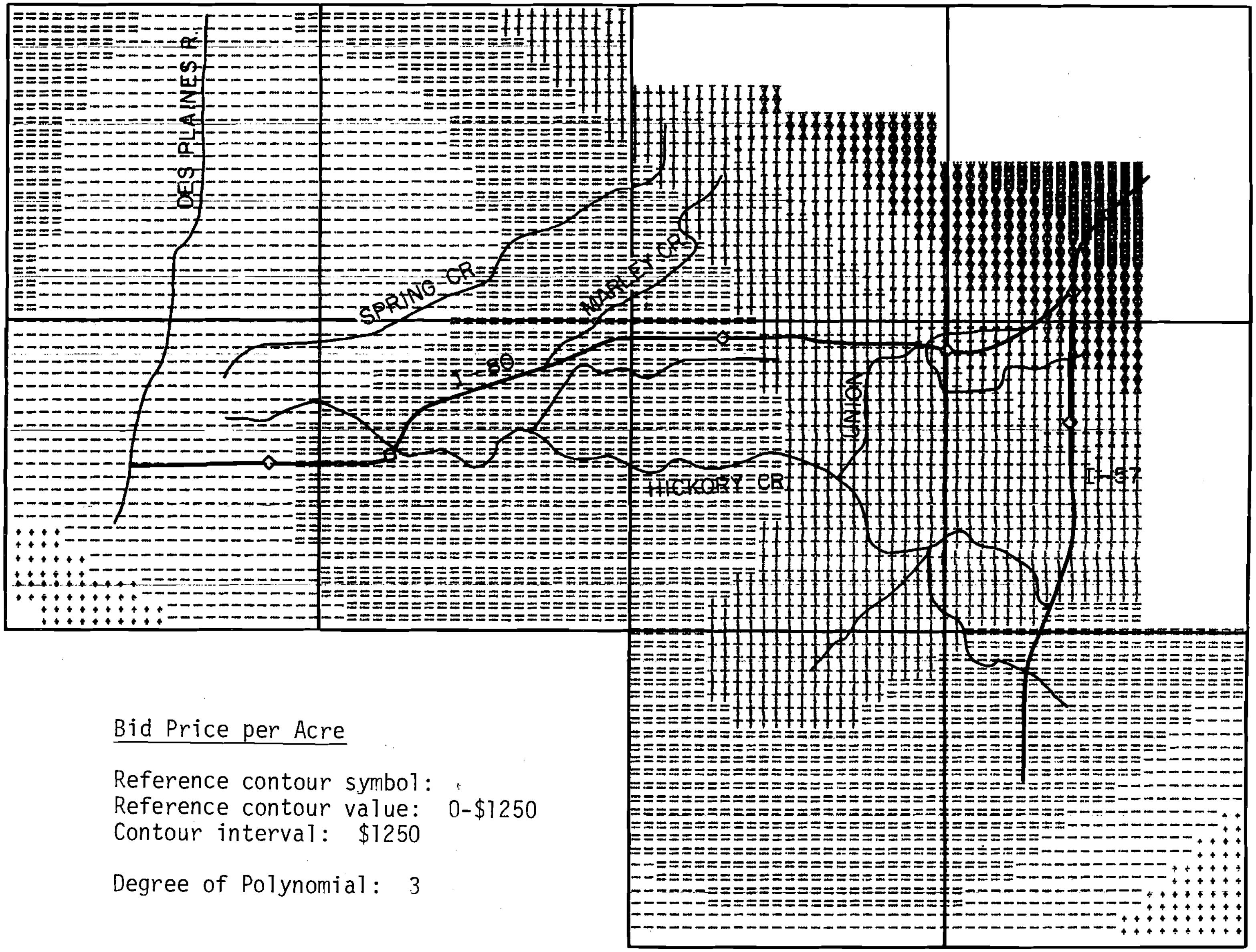
Reference contour symbol: +
Reference contour value: 0-$2500
Contour interval: $2500

Degree of Polynomial: 3

Figure 2.13 Land Value Contours for Urban 2 Land Use Using Unclustered Data which had just missed the earlier cutoff, and the resulting spatial pattern was preferred because of the finger of higher value toward the high amenity area and the fall-off in bid prices toward the southwest and southeast. (Compare Figures 2.2 and 2.14). The fifth degree spatial pattern made more sense for Urban 3 because the high value peak in the southeast shifts northwest, closer to the golf course and high environmental amenity area. Also, a ridge of higher value runs across to Joliet along U.S. 30. (Compare Figures 2.4 and 2.15.) Recall that there was no statistical evidence for the initial choice of the fourth degree except that it was among those significant at the .01 level. The change from fourth to fifth degree is also not significant at the .05 level, but the fifth degree equation is significant at the .01 level.

2.4.5 Spatial Pattern of Residuals

The residuals of predicted bid price versus observed bid price for each chosen surface are plotted in Figures 2.7 through 2.11. In most cases, there are no obvious spatial autocorrelations of residuals. Three or four contiguous residuals with the same sign were not considered a problem because they typically represent one homogeneous residential area that happens to be larger than 160 acres. These groups of residuals imply that land value is different from the regional trend and ascribable to local effects. For example, in Urban 1, there is a triplet of high positive residuals between 1 and 2 standard deviations from the predicted values just right of center of the map. (See Figure 2.7.) This cluster is a high cost housing subdivision located around a golf course. More problematic is the pattern of residuals just northwest of this triplet. There is first a cluster of negative residuals and then a cluster of positive residuals indicating that the trend surface is not picking up the pattern of spatial variation. The next higher degree surface was plotted but rejected because it did not resolve this anomaly and indicated an illogical increase in land values to the southwest.

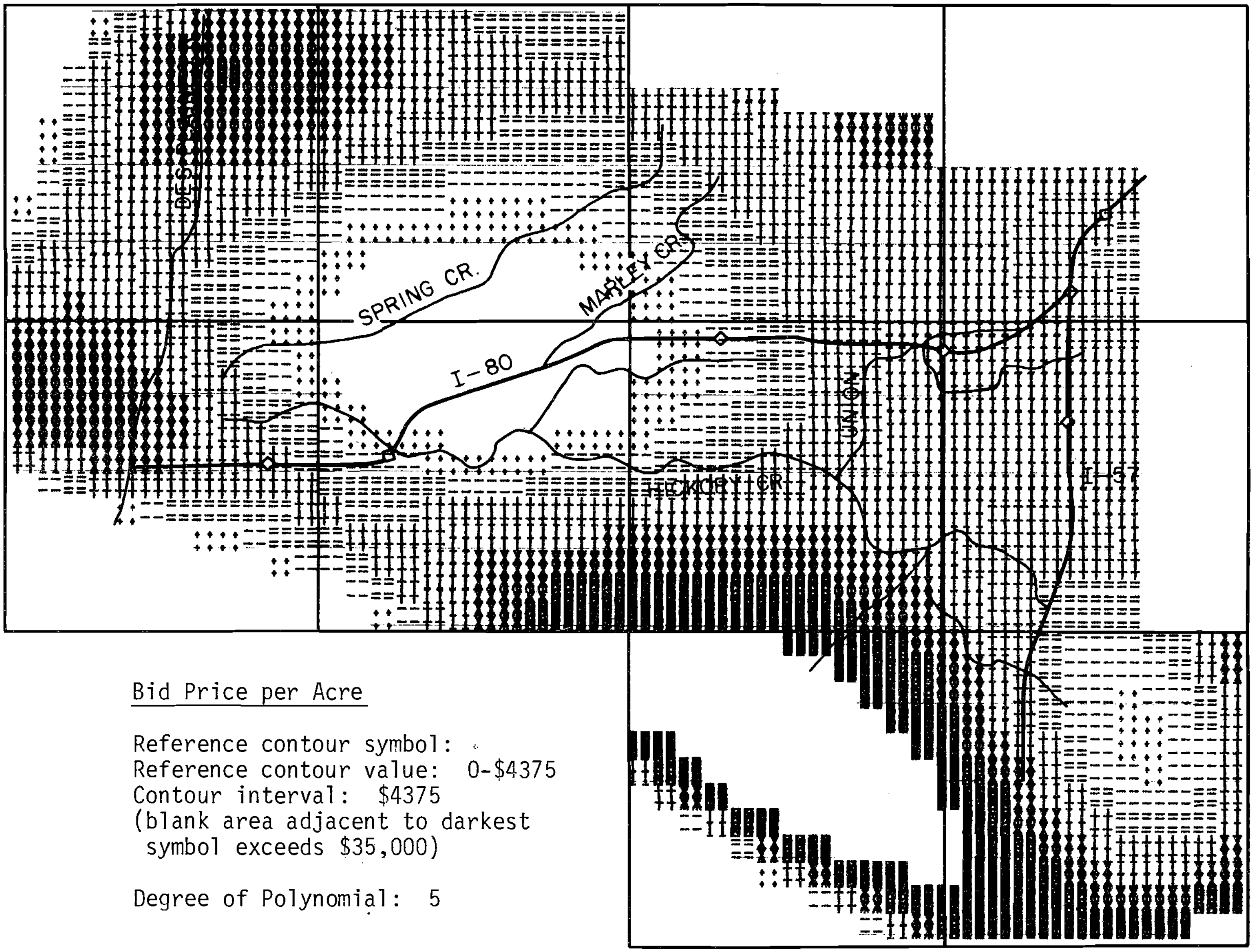


Bid Price per Acre

Reference contour symbol: ·
Reference contour value: 0-$1250
Contour interval: $1250

Degree of Polynomial: 3

Figure 2.14 Land Value Contours for Urban 1 Land Use



Bid Price per Acre

Reference contour symbol: ·
Reference contour value: 0-$4375
Contour interval: $4375
(blank area adjacent to darkest
 symbol exceeds $35,000)

Degree of Polynomial: 5

Figure 2.15 Land Value Contours for Urban 3 Land Use

There is also a problem in Urban 3 residuals at the west edge. (See Figure 2.9.) A cluster of positive residuals is surrounded by a cluster of negative residuals. This pattern indicates that the values on the north, east, and south sides of Joliet are being overestimated and the values in downtown and the west side are being underestimated. This result is not surprising numerically because there are few data points in the area east of Joliet and the west side of Joliet is at the edge of the study area. Surburban land values west of Joliet are high; it is the right side of town. The east side of Joliet is the wrong side of town. The underestimate of this difference is in part an edge effect and in part an example of the smoothing effect involved in identifying regional trends. The saving grace is that most of this area is outside the area for which subbasin values are actually computed for use in the model. This buffer area is included specifically so that such edge effects do not affect data values actually used in the model.

Finally the map of residuals for Urban 4 has three negative residuals in the center indicating that the surface is underestimating the value for such uses in this area. (See Figure 2.10.) These three sample points are relatively rural industries, which should, perhaps, be handled in a separate land use class. The definition used for Urban 4 is in retrospect ambiguous because it includes both densely developed urban land as well as industrial and commercial sites in a suburban setting. However, the resulting regional trend makes sense because it rises toward the interstates, Chicago, Joliet, and the Des Plaines River. If Urban 4 is considered the highest density urban use, as assumed in the runoff data, these three data points are perhaps misclassified.

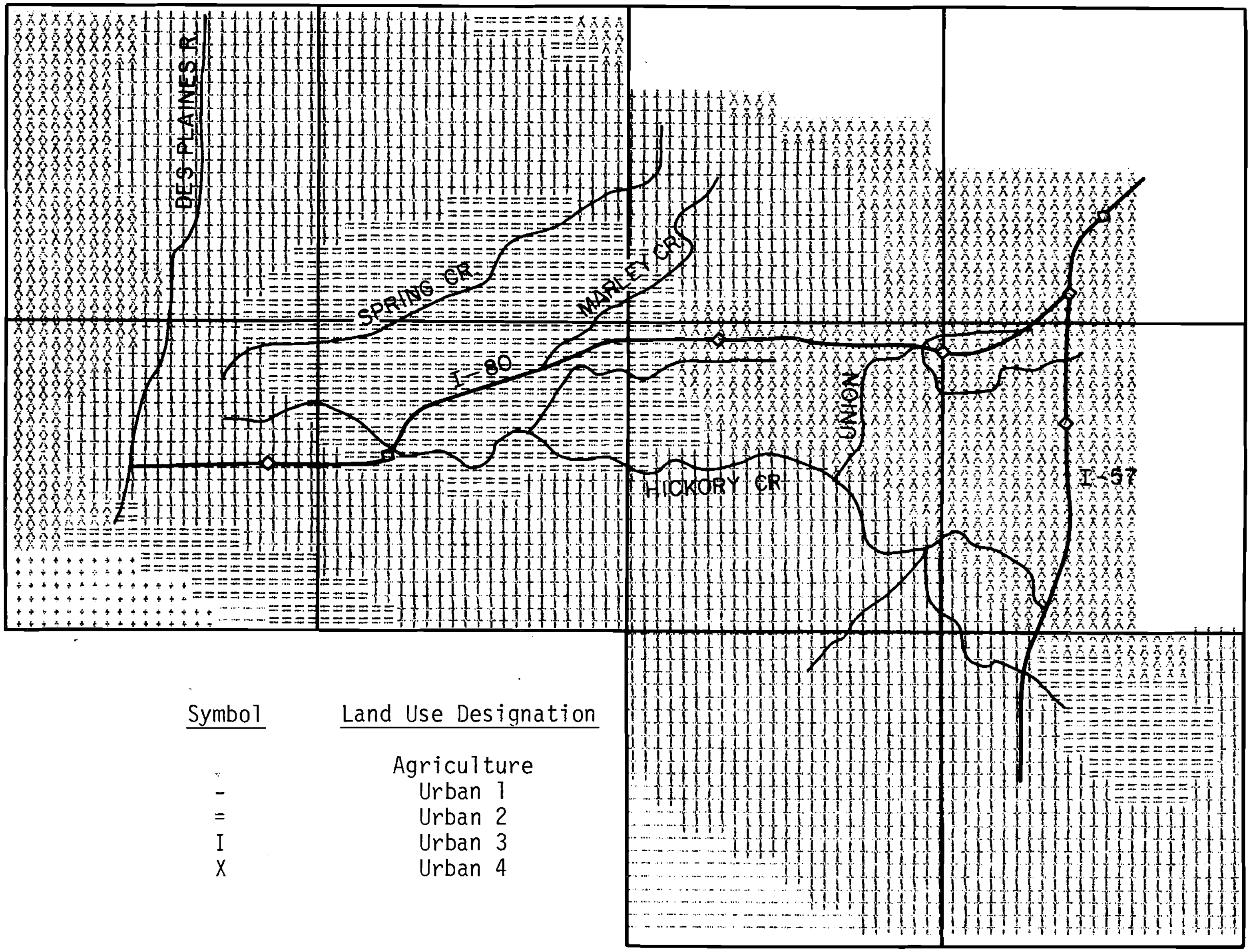
2.4.6 Data Gaps and the Implied Land Use Pattern

It is now possible to return to the question of the large gaps in the data, which are an inherent part of the approach. Recall that the basic premise is that the trends in the areas where a particular land use exists can be used to extrapolate bid prices in the intervening areas where other uses currently outbid the particular land use under consideration. The broad land use classes, implying large enough areas of a given use to indicate trends, are necessary to make this approach plausible. That there is a smoothing effect from this interpolation cannot be denied, but it has already been argued that some smoothing is acceptable as representing the value as infilling occurs among scattered uses on the urban fringe. There is no statistical means for determining whether the results, given these gaps, are acceptable.

One way to evaluate the results is to consider the pattern of land uses that is implied by assigning each quarter section to the highest bidding use. This pattern is shown in Figure 2.16. If one assumes that the varying densities of development are responding to the same nodes of higher value, for example, trip destinations, one would expect the highest valued and most dense uses to locate in the top portion of their range of bid prices in the study area and lower density uses to appear in successively lower parts of the range of their bid prices. That is, in compliance with the traditional land use theory, the highest density uses with the steepest bid price curves must locate closest to the nodal points or not at all.

This result is observable in Figure 2.16. Note that Urban 2 occurs in the center of the region. Comparison with Figure 2.3 shows that this area is in the lower portion of the range of bid prices for Urban 2. Urban 3 occurs in the areas that are in mid-range of its bid prices. The high value nodes are the interstates on the eastern side of the region, Joliet at the western side, and toward Chicago on the Northeast.

There are several anomalies in the pattern, at least some of which can be explained by considering the current pattern of transportation and land



Symbol	Land Use Designation
+	Agriculture
-	Urban 1
=	Urban 2
I	Urban 3
X	Urban 4

Figure 2.16 Implied Land Use Pattern

use as shown in Figure 2.1. The finger of Urban 4 coming from the east follows Interstate 80. The abrupt shift to Urban 2 coincides with the last interchange until southwest of New Providence, where the density increases again. The direct jump from Urban 4 to Urban 2 could be interpreted to mean that Urban 3 responds more to existing surburban centers than to the interstate, so that Urban 2 takes over once the interstate influence is eliminated. Such interpretations could only be validated by extensive investigation. The pocket of Urban 2 in the southeast corner also coincides with a gap in interstate exits and a shift of Interstate 57 to the west.

There are also some less satisfactory outcomes. The low density just south of Joliet is probably an underestimate, at least compared to estimates for other areas. Even though the south side of Joliet is not a desirable residential area, the density implied is too low. The Urban 4 at the west edge of the study region should probably more nearly coincide with the industrial areas along the Des Plaines River. Both these situations are of lesser concern because they are for the most part outside the Hickory Creek Watershed, being part of the buffer area added to avoid edge conditions. The relatively high density in the southeast part of the watershed is probably an overestimate, due in part to the extremely high residential values around a golf course. The area just east of Joliet is probably of too low a density as might be expected from the above discussion of residuals for Urban 3.

It is clearly difficult to argue convincingly, and impossible to argue statistically, that the large gaps inherent in this approach do not lead to spurious results. However, the bid price trends for individual land uses make sense, and the implied allocation makes sense at the regional level at which the data is to be used. The implied allocation is, in general, consonant with the Northeastern Illinois Planning Commission (1978) regional land use policy map, which is based largely on availability of municipal services.

The implied land use pattern is a massive increase in density for the watershed indicating that the smoothing effect of the trend surface is substantial. Whether the implied increase in population would occur within an appropriate time to be valid for the model is debatable. Current growth in the region is substantial. The general pattern is sensible, and two kinds of sensitivity checks could be used to determine how management conclusions would be affected. The slopes of the bid prices of higher density uses could be made steeper, or the absolute levels of the bid price surfaces of the high density uses could be lowered relative to those of lower density uses.

2.5 Comparison with Other Approaches and Sensitivity Analysis

The results reported are not supported sufficiently by traditional statistical criteria. There may be problems with the distribution of sample points; the coefficients of determination are less than .6; there is fuzziness in the choice of the degree of polynomial for some uses. However, there are really two appropriate questions: Is this approach sufficient for distinguishing among different land use allocations for regional watershed management purposes? Is it better than alternative approaches?

2.5.1 Comparison with Other Approaches

Consider the second question first. The alternative of estimating differential costs has the disadvantage of requiring simplifying assumptions about tripmaking behavior, which are difficult to justify in a multinucleated region. It is also difficult to estimate social and environmental amenity costs without recourse to some form of bid price data. The estimation of differential costs is therefore inadequate by itself. The trend surface technique and the differential cost technique could be considered complementary in providing checks for each other. Variations represented in the trend surface should be explainable after the fact by some kind of cost differential. Similarly, the trend surface results could be used to identify elements that might be left out of an attempt at direct estimation of cost differentials.

The approach preferred by Greenberg et al (1974), regression of values against property characteristics, has not yet been shown operational for generating regional bid price surfaces. Early in the development of bid price data for the land use allocation model, regression on parcel characteristics was attempted. This effort was unsuccessful because, when extrapolated to the entire watershed, the equations predicted that commercial activity would everywhere outbid high density residential and high density residential would everywhere outbid low density. These are nonsensical results and indicate that the traditional regression approach suffers when challenged with generation of bid price surfaces at the regional level. Among the apparent problems were too few sample points, which in this case were based on sales transactions, and the difficulty of obtaining data for independent variables relevant at the regional level.

Few of the regressions reported in the literature were aimed specifically at generating regional bid price surfaces. Whether they could generate bid price surfaces that intersected to yield sensible land use allocations is still open to question. Most such studies generate detailed, localized appraisals or equilibrium urban price gradients. The R^2 values from the trend surface results are similar to those from regression studies that predicted value per acre for urban fringe lands as discussed above. Only studies that predicted primarily with income, race, or lot size yielded higher R^2 values.

For the trend surface analysis, the mean error of the residuals, expressed as a percent, ranged from 30 to 40 percent for Urban 1, 2, and 3, which is similar to the results obtained by Weisz and Day (1974). For Urban 4 (industrial/mixed use) the percent error was 148 percent because some very low valued parcels had very large absolute residuals. As pointed out above this land use class suffered from an ambiguous definition, which may explain the poor result. The means of the residuals were approximately 1,000, 2,500, 5,500, and 7,600 dollars per acres respectively for the four urban uses. These values must be interpreted carefully because there are two components to the residual: local effects not part of the regional trend and error of measurement. However, if some portion is attributed to local effects, these are not very large absolute errors. In summary, the trend surface analysis yields results, at least as good as any extant operational studies using regression on parcel characteristics.

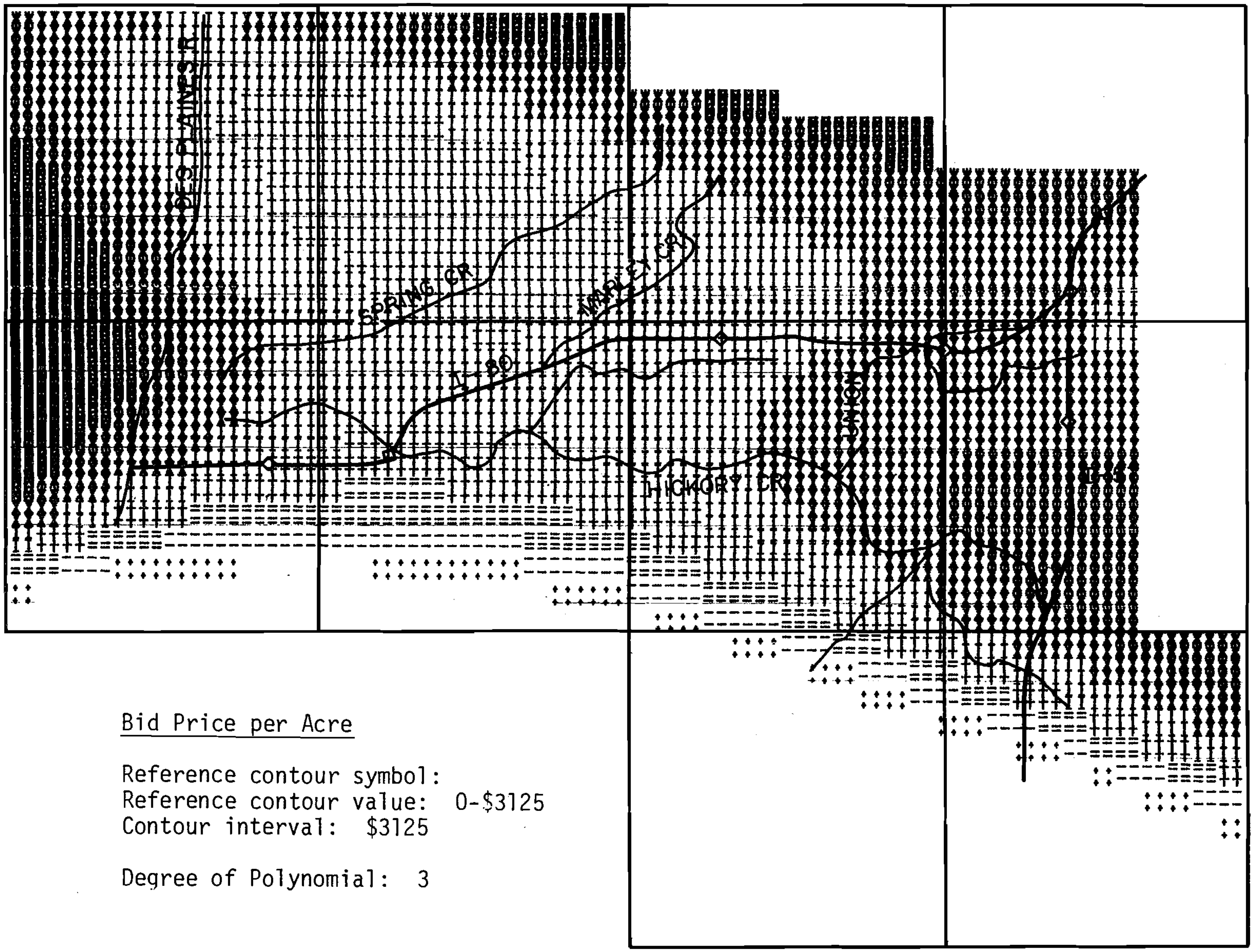
2.5.2 Adequacy of Results for Modeling Purposes

The second question is whether the trend surface approach yields data that are adequate for the intended modeling task. The best way to determine this is to conduct sensitivity analyses with the land use allocation model for which the data were generated. Theoretically, confidence surfaces could be generated for each of the trend surfaces (Krumbein, 1963) and used to determine error analysis parameters. Given that the present application is not a strict statistical application, less formal approaches are equally appropriate. Two types of sensitivity analyses of the bid price data were conducted. These analyses focused on Urban 3 because the basis for choice of the degree polynomial for Urban 3 was weak. It was also one of the most frequently located uses both on and off the floodplain in applications of the model. (See Chapter 1.) The data for Urban 1, for which the choice of the degree of polynomial was also relatively uncertain, was modified in conjunction with Urban 3 data in one test. This change had no effect on solutions primarily because Urban 1 was chosen very infrequently in the allocation model as the preferred land use for a subbasin. Systematic errors are considered rather than random errors because systematic differences in bid price patterns were deemed more likely to affect the overall land use pattern.

First, because the bid price data implied that Urban 3 would be the highest bidding use in Joliet, but the existing land use in Joliet was considered to be Urban 4, the value for Urban 4 in Joliet was raised to 45,000 dollars per acre. This value approximates the mean of raw data values of two quarter sections closest to Joliet. When the land use allocation model is run with this modified data, the only effect is to shift the land use in the Joliet subbasin from Urban 3 to Urban 4. The aggregate value of the watershed increased slightly because of this new bid price value. Other than the precise density in Joliet, the pattern of land uses including provision of detention is unchanged. The potential inaccuracy from the failure of the trend surface analysis to identify a possible sharp peak in bid prices near downtown Joliet does not, therefore, alter the policy implications of the dynamic programming model for land use allocation. (See Chapter 1.)

The second type of analysis was to use the bid price data for Urban 3 from the third and fourth degree polynomials because these were rejected in favor of the fifth degree on relatively uncertain grounds. The fourth degree surface was different within the watershed boundaries primarily in that the locations of maxima shifted. (Compare Figures 2.4 and 2.15.) The third degree surface was different in that values rose to the west and northeast with no local maxima. (Compare Figures 2.4, 2.15, and 2.17.) These patterns therefore represented systematically different bid price patterns. The bid price for Joliet was set at $45,000 per acre for both these runs. In the fourth degree surface run, the degree surface for Urban 1 was also changed from degree three to degree two, but this change had no discernable effect on the solution.

Among the three runs, 81 percent of the floodplain land uses were identical, including both urban and nonurban uses. That is, if the model were used to determine priorities in implementation of a plan as discussed in



Bid Price per Acre

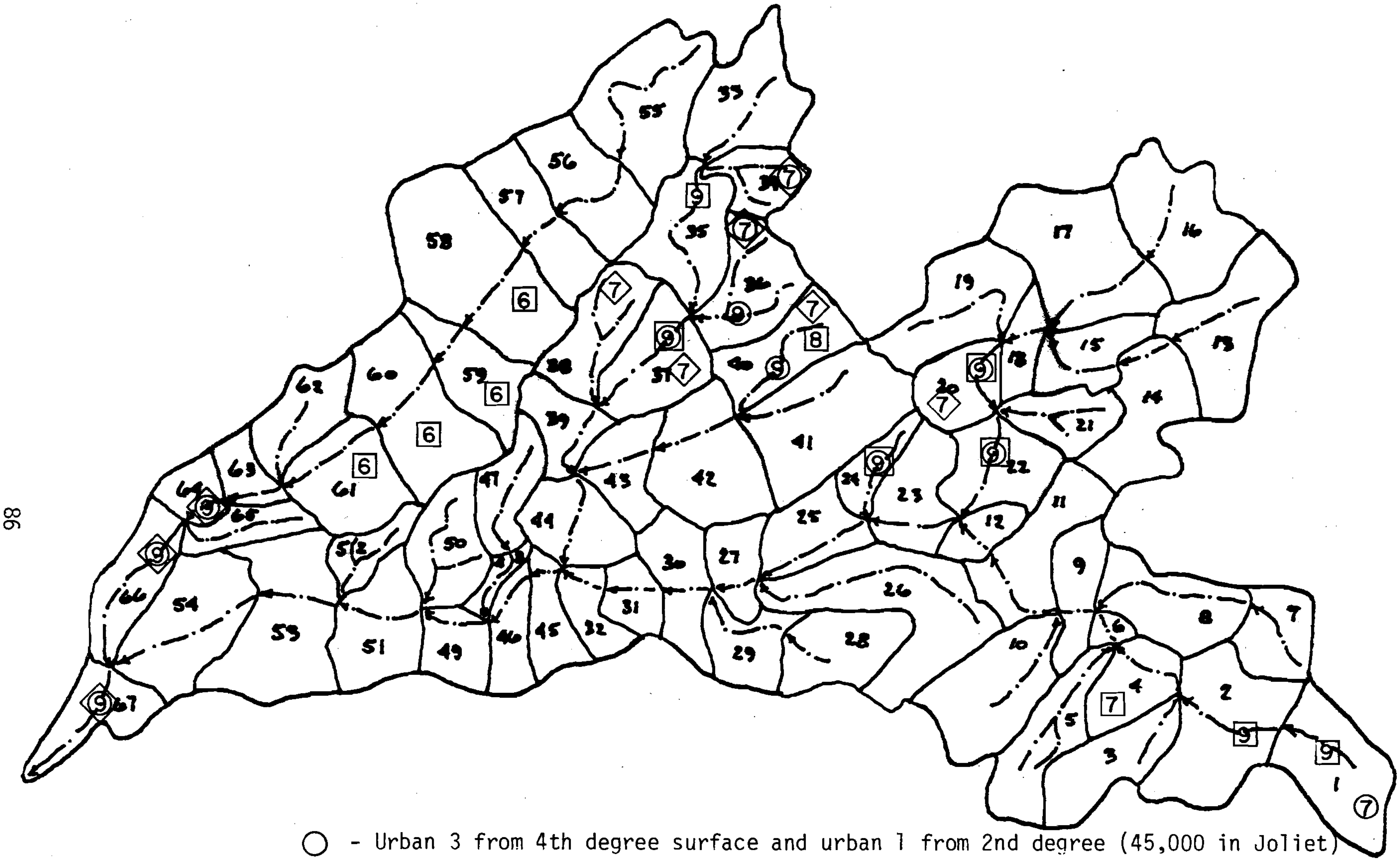
Reference contour symbol:
Reference contour value: 0-$3125
Contour interval: $3125

Degree of Polynomial: 3

Figure 2.17 Land Value Contours for Urban 3 Land Use

Chapter 1, most of the crucial floodplain decisions were stable with respect to these bid price changes. Only 41 percent of the non-floodplain uses were the same for all three runs. However, this set did include both detention and nondetention uses so that some implementation decisions could still be based on these model results as discussed below. Almost all the remaining non-floodplain land uses were different by just one density class. Such marginal differences in land density have little effect on runoff as evidenced by the high congruence of floodplain land uses. Therefore, controlling these subbasins only to the level of uncertainty implied by this variation in land use density would be sufficient to determine an appropriate set of floodplain uses. The data is adequate for this task.

The subbasins with detention versus no detention or urban versus nonurban floodplain uses are the most important differences among the three runs. These cases are shown in Figure 2.18 by indicating subbasins that required detention or nonurban floodplain uses in at least one but not all three runs. The run based on the fifth degree surface requires detention in four subbasins along Spring Creek, allowing urban uses in the floodplains in the lowest two subbasins on Spring Creek and the lowest subbasin of Hickory Creek. In contrast, the other two runs do not choose detention for the former subbasins and restrict the floodplains of the latter three downstream subbasins to nonurban use. Inspection of the data suggests that this shift occurs because the value of Urban 3 upstream is higher and the value of Urban 3 downstream is lower in the latter runs. There are very similar shifts among nonurban uses on the floodplains and upstream detention among adjacent subbasins in the headwaters of Marley Creek, Union Ditch, and Hickory Creek. Although these shifts represent a small portion of the total number of land use decisions, they do indicate that the model implications are sensitive to the postulated range of error in the bid price data.



○ - Urban 3 from 4th degree surface and urban 1 from 2nd degree (45,000 in Joliet)

◇ - Urban 3 from 3rd degree surface and urban 1 from 3rd degree (45,000 in Joliet)

□ - Urban 3 from 5th degree surface and urban 1 from 3rd degree

Figure 2.18 Differences among Dynamic Programming Solutions with Variation in Land Value Data

Based on these sensitivity analyses, the bid price data generated through trend surface techniques are adequate to determine choices among general policy approaches. The data are also adequate to determine some, but not all, land use choices at the subbasin level. Therefore, in any application, sensitivity analysis should be conducted to determine for which subbasins the level of certainty in the data is inadequate to determine a particular landuse decision. The requirements of detention or of non-urban use in the floodplain are the most important distinctions that must be made; such sensitivity analyses should therefore focus on these choices.

2.6 Conclusions

The trend surface approach merits further testing. The results obtained in this experiment were at least as good as results obtained by other approaches. They were adequate for the choice of general policies, such as whether or not to require storm water detention or to restrict floodplain development. The data were not adequate to determine with certainty preferred land uses for all subbasins. However, in the most important cases, subproblems were distinguishable that involved only a few subbasins. These subproblems could be analyzed more thoroughly with respect to the effects of possible error in the bid price data.

Future experiments with this approach might use data for individual parcels rather than quarter sections in order to increase the number of points of data control for each land use class. This end might be accomplished with justifiable effort by still referencing the locations of these data points only to the nearest quarter section. One could then have several sample values for a particular quarter section even for the same use as well as sample values for more than one use from the same quarter section where mixed uses occur. This approach might, however, exacerbate the problem of smoothing between sample points by picking very high-valued, small parcels and extrapolating these values as regional trends. It would also be desirable to experiment with other functional forms for the trend surface equations.

CHAPTER 3 THE VALIDITY OF A SIMPLE HYDROGRAPH ROUTING PROCEDURE

3.1 Introduction

Several floodplain management models have been developed to screen for possible land use patterns that increase total land value (Arvanitidis et al., 1972; Day and Weisz, 1976; Bialas and Loucks, 1976). None of these models explicitly incorporates the routing of hydrographs into the search for alternatives. The first two identify good land use patterns for given flooding conditions. The third deals with flood displacement (a bathtub model of floodplain occupancy), but not with changes in runoff or routing of hydrographs. The dynamic programming model developed by the present authors (Hopkins et al., 1978) was designed to find a land use allocation that maximizes total land value over a watershed explicitly taking into account the change in flooding conditions that would occur with changes in land use. A flood routing procedure was required. This procedure had to be very efficient and therefore very simple because of the large number of routing computations required in the dynamic programming algorithm. It is important to determine whether TROUT, the simple routing procedure used, was sufficiently accurate for the modeling purposes at hand.

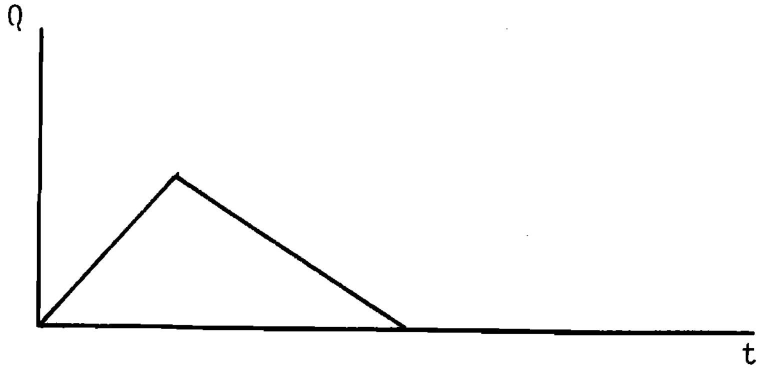
The land use allocation model is viewed as a screening model--a model to generate good solutions from which a preferred solution can be chosen through consideration of other criteria not in the model (Liebman, 1976). The land use patterns generated by the model would be evaluated using more complex hydrologic simulations, such as provided in the HEC-1 package (U.S. Army, 1973). The simple routing procedure must be sufficiently accurate to distinguish good land use allocations from bad ones, but not necessarily accurate enough to make a final choice among several very good solutions.

TROUT was evaluated in three different ways. It was used to predict gauged flows from given precipitation data for real events. TROUT was also compared with the Muskingum routing method to see how closely its predictions matched those of a more complex routing mode. Finally, estimates of the distribution of error in TROUT results compared to Muskingum results were used to determine the sensitivity of the solutions of the land use allocation model to such error in the routing procedure. The next section describes TROUT, and the succeeding sections describe each of the three types of comparisons.

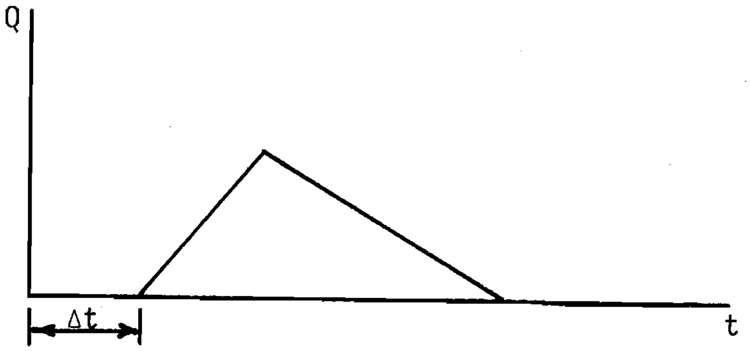
3.2 Triangular Hydrographs and Routing

A triangular hydrograph was chosen for the routing procedure because it can be described by a minimum number of data elements while at the same time retaining the essential characteristics of curvilinear hydrographs: the peak and its associated time, and the total volume of flow before and after the peak time.

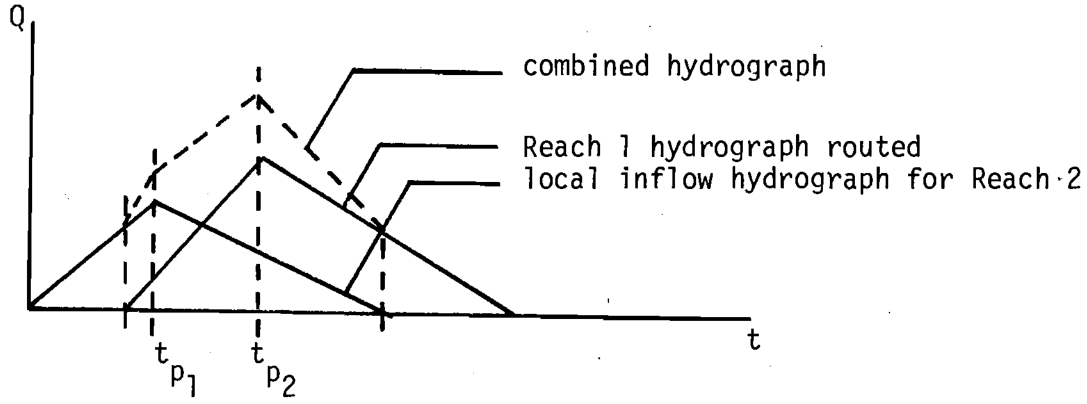
The first step in using the TROUT routing model is the generation of local inflow hydrographs for each of the subbasins. The Clark (1945) method as programmed in the HEC-1 package (U.S. Army, 1973) was used for this purpose. Each of these curvilinear hydrographs is then approximated by an equivalent triangular hydrograph. The peak flow and the time of its occurrence is maintained for the triangular hydrograph. The rising limb of the triangular hydrograph is determined by ensuring that the total volume of flow occurring before the peak flow for the curvilinear hydrograph is maintained for the triangular approximation. The recession limb of the triangular hydrograph is determined by ensuring that the total volume of flow occurring after the peak flow for the curvilinear hydrograph is maintained



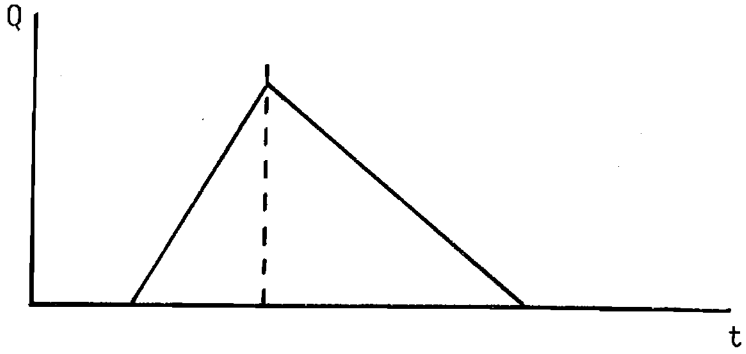
(a) Local inflow hydrograph for Reach 1 (channel hydrograph for Reach 2)



(b) Reach 1 hydrograph routed to downstream end of Reach 2



(c) Formation of combined hydrograph for Reach 2



(d) Combined triangular outflow hydrograph from Reach 2

Figure 3.1 Routing Procedure

for the triangular hydrograph. In this fashion, the total volume of flow associated with the curvilinear hydrograph is maintained in the triangular approximation.

The routing procedure begins at an extreme upstream subbasin where the local inflow hydrograph is taken as the channel hydrograph at the subbasin outlet. This channel hydrograph is then routed using a simple lagging procedure through the subbasin immediately downstream. The lag time, Δt as shown in Figure 3.1-b, is equal to the time of travel AMSKK, used in the Muskingum Routing scheme employed in HEC-1.

The routed channel hydrograph is then added to the local triangular inflow hydrograph for this subbasin at the downstream end of reach 2, maintaining a common time scale. The sum of these two triangular hydrographs is a hydrograph consisting of at most five linear segments as shown in Figure 3.1-c. It can be shown that the peak of this segmented hydrograph must occur at one of the two peak times, t_{p1} and t_{p2}, of the triangular hydrographs.

The segmented hydrograph is then in turn approximated by a triangular hydrograph whose peak and peak time are equal to the peak and peak time respectively of the segmented hydrograph as shown in Figure 3.1-c. The slope of the rising limb of the new combined triangular hydrograph is determined so that the volume of flow before the new peak time maintains the sum of inflow volumes after the new peak time. The new combined triangular hydrograph is then taken as the channel hydrograph at the upstream end of the next channel reach, and the process is repeated.

3.3 Comparison with Real Events

3.3.1 Test Watershed and Storms

The watershed chosen to evaluate TROUT as a useful routing model was the Hickory Creek watershed in northeastern Illinois. The Hickory Creek watershed encompasses an area of 109.8 square miles. For the purposes of the study, the watershed was broken down into 67 subbasins with sizes ranging from 241 acres to 2025 acres. Six storms between 1947 and 1976 were chosen for comparing the Muskingum method and TROUT. The six storms were chosen to get a wide range of final outflows, to have isolate hydrographs, to include a storm from nonwinter months, and meeting each of these criteria, to be the most recent storm of that magnitude. These bases for choice attempted to cover the range of possible flows considered in the model, to ease the identification of triangular hydrographs, to eliminate consideration of frozen ground, and to render the use of current land use valid in determining runoff. The July 13, 1957 storm runs were carried out on a different set of 42 subbasins used in an earlier study. This set of subbasins was used both for the Muskingum method and TROUT, so the within storm comparison is valid, but this storm was not used as part of the data for the error analysis described below because of this difference in subbasins.

The HEC-1 Flood Hydrograph package (U.S. Army, 1973) was used to generate the runoff hydrographs associated with each land use on each of the subbasins of the watershed. The precipitation data used as input to HEC-1 was taken from the precipitation records of the rain gauges surrounding the watershed (see Table 3.1). The curvilinear locally generated runoff hydrographs generated by HEC-1 were then reduced to the triangular form as described in section 2.1. The triangular hydrographs were then used as

Table 3.1 Storm Data

Storm Date	6/22/73	4/5/47	7/21/76	5/17/74	11/11/54	7/13/57
Total Depth (in.)	2.24	4.55	5.15	2.03	8.46	6.44
Duration (hrs)	36	44	10	27	35	15
Hour	Incremental Depth (in.)					
1	.03	.02	.06	.02	.04	.54
2	.08	0	0	.06	.01	.12
3	.09	0	1.0	.08	.18	.28
4	.03	0	.46	.01	.39	.02
5	.09	.03	.23	0	.31	0
6	.03	.01	1.84	.15	.32	0
7	0	.04	.26	0	.08	.23
8	.32	.02	.87	0	.65	0
9	.18	.01	.39	0	.54	0
10	.14	.02	.04	0	.68	0
11	.12	.11		0	1.11	2.37
12	.03	.01		0	.42	1.38
13	.01	.07		0	.49	.53
14	.01	.10		0	.21	.76
15	0	.03		0	.02	.21
16	.03	0		0	.10	
17	0	0		0	.00	
18	0	0		0	.20	
19	.02	.01		.76	.10	
20	.02	0		.70	.03	
21	0	0		.04	0	
22	0	0		0	.01	
23	0	0		0	.01	
24	0	0		.02	1.02	
25	0	0		.14	.22	
26	0	0		.01	.42	
27	.36	.21		.02	.44	
28	.06	1.18			.16	
29	.10	.15			.04	
30	.30	1.03			0	
31	.04	.46			.03	
32	.04	.14			.03	
33	.02	.19			.02	
34	.02	.22			.02	
35	.02	.08			.01	
36	.01	.06				
37		.02				
38		0				
39		0				
40		0				
41		0				
42		.24				
43		.11				
44		.02				

input to TROUT, which performs the routing computations through the system. For comparison, the curvilinear hydrographs generated by HEC-1 were routed through the river system using the Muskingum method as programmed in the HEC-1 package. The determination of flow depth for a given flow was based on the assumption of uniform flow within the channel. The details of the runoff hydrograph generation by HEC-1 and the development of the routing coefficients are discussed in Appendix A.

The gauging station on Hickory Creek, just downstream of the confluence of Spring Creek and Hickory Creek (see Figure 1.2), was used for comparisons of the real events and the predictions from TROUT and HEC-1. Because only one gauging station is available on Hickory Creek, the comparison of the routing models with the real events can only be performed at the downstream end of Hickory Creek. Upstream comparisons can only be made between the two routing models.

3.3.2 Comparison

Table 3.2 shows the peak flows and times of peak flows for each of the six storms as recorded at the gauging station and as predicted by TROUT and HEC-1. Figures 3.2 to 3.6 compare the outflow hydrographs at the gauging station for recorded hydrographs and the hydrographs predicted by TROUT and for HEC-1 for the five storms run with 67 subbasins. The differences between the peak flows recorded at the gauge and the peak flow generated by TROUT are within 20% of each other for four of the six storms. However, there is a significant difference between the recorded and predicted peak flows for the 1976 and 1973 storm.

3.3.3 Discussion

Assuming that the locally generated hydrographs produced by HEC-1 are reasonable representations of the actual runoff hydrographs from each

Table 3.2 Comparison of Hydrograph Peaks

DATE	GAUGING STATION Peak Flow	 Time of peak	HEC-1 Peak flow	 Time of Peak	TROUT Peak flow	 Time of Peak	$\frac{\text{Trout-HEC-1}}{\text{HEC-1}}$
	cfs	hour/date	cfs	hour/date		hour/date	
October 11, 1954	8,130	0200/11	9100	0700/10	9010	0800/10	-.9%
May 17, 1974	5,070	1445/17	4600	0300/17	4080	0400/17	-12.5%
July 21, 1976	3,580	0130/21	18,820	0230/21	18,130	2230/20	-3.7%
July 13, 1957*	15,200	1000/13	18,960	0230/13	16,660	0100.13	-12.2%
April 5, 1947	10,200	1100/5	11,600	0500/5	11,240	0500/5	-3.1%
April 22, 1973[D]	4,080	0600/22	620	0500/21	450	0400/21	-27.3%
			660	0030/22	520	2300/21	-22.1%

[D] Storm with 2 distinct peaks

*Run with watershed divided into 42 subbasins.

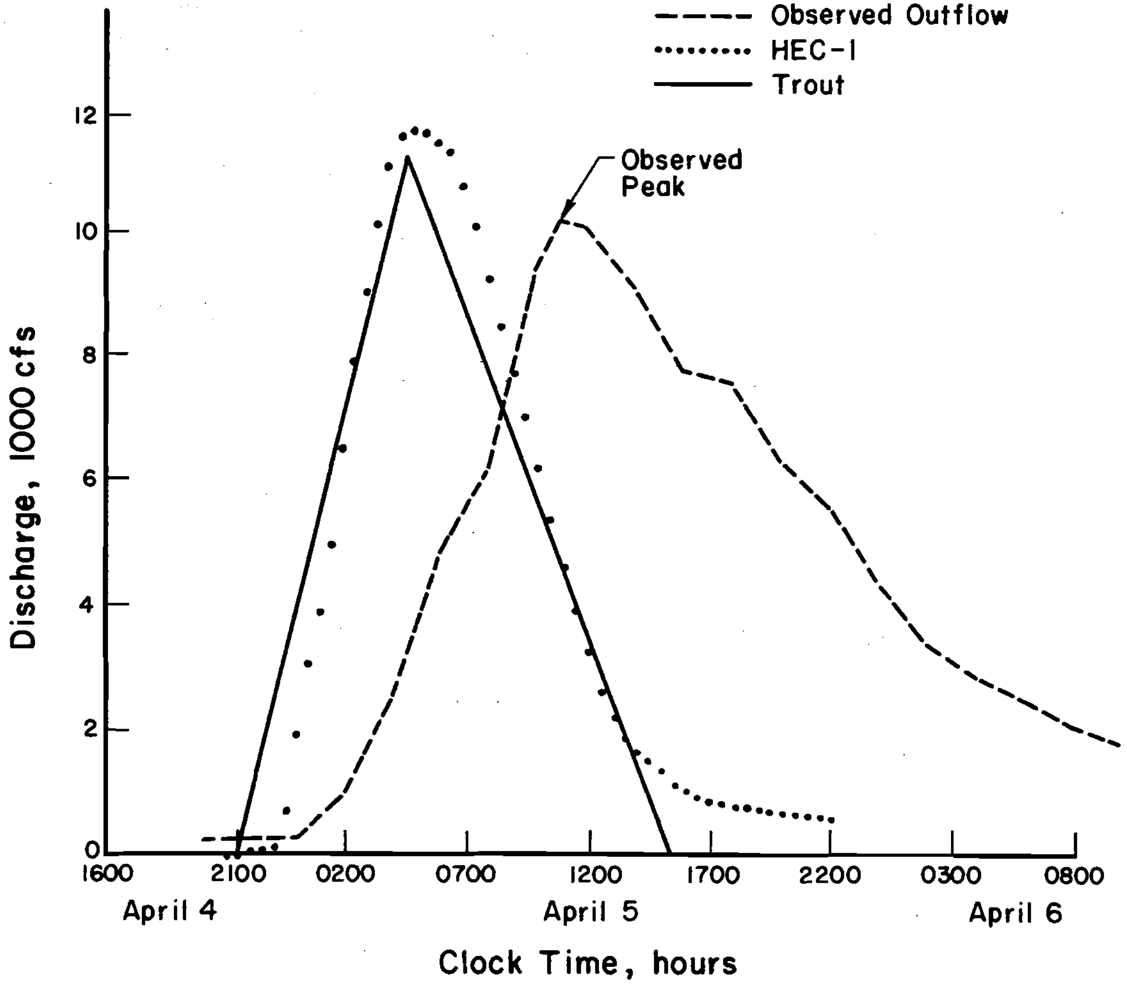


Figure 3.2 Outflow Hydrographs for April 5, 1947

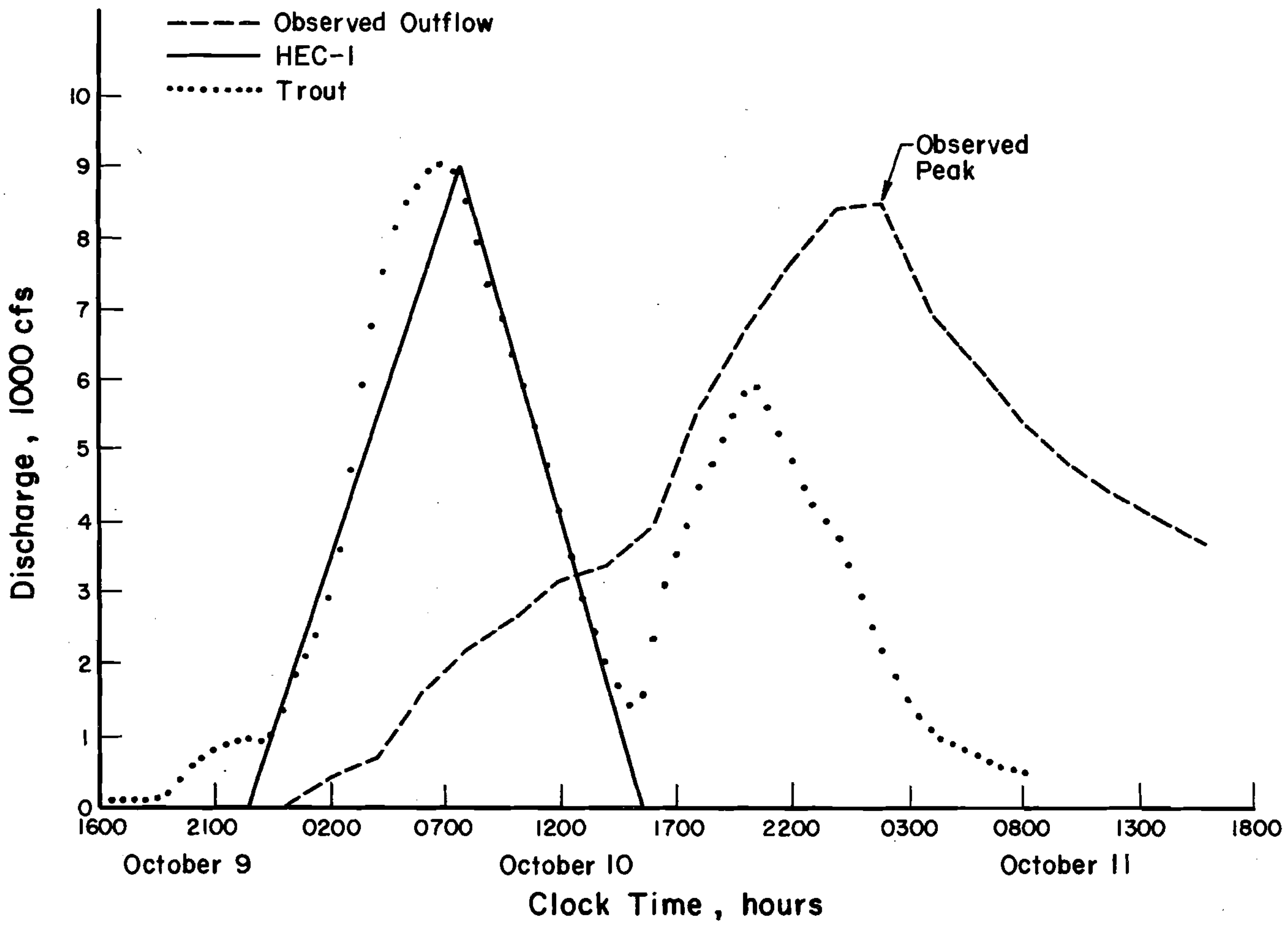


Figure 3.3 Outflow Hydrographs for October 11, 1954

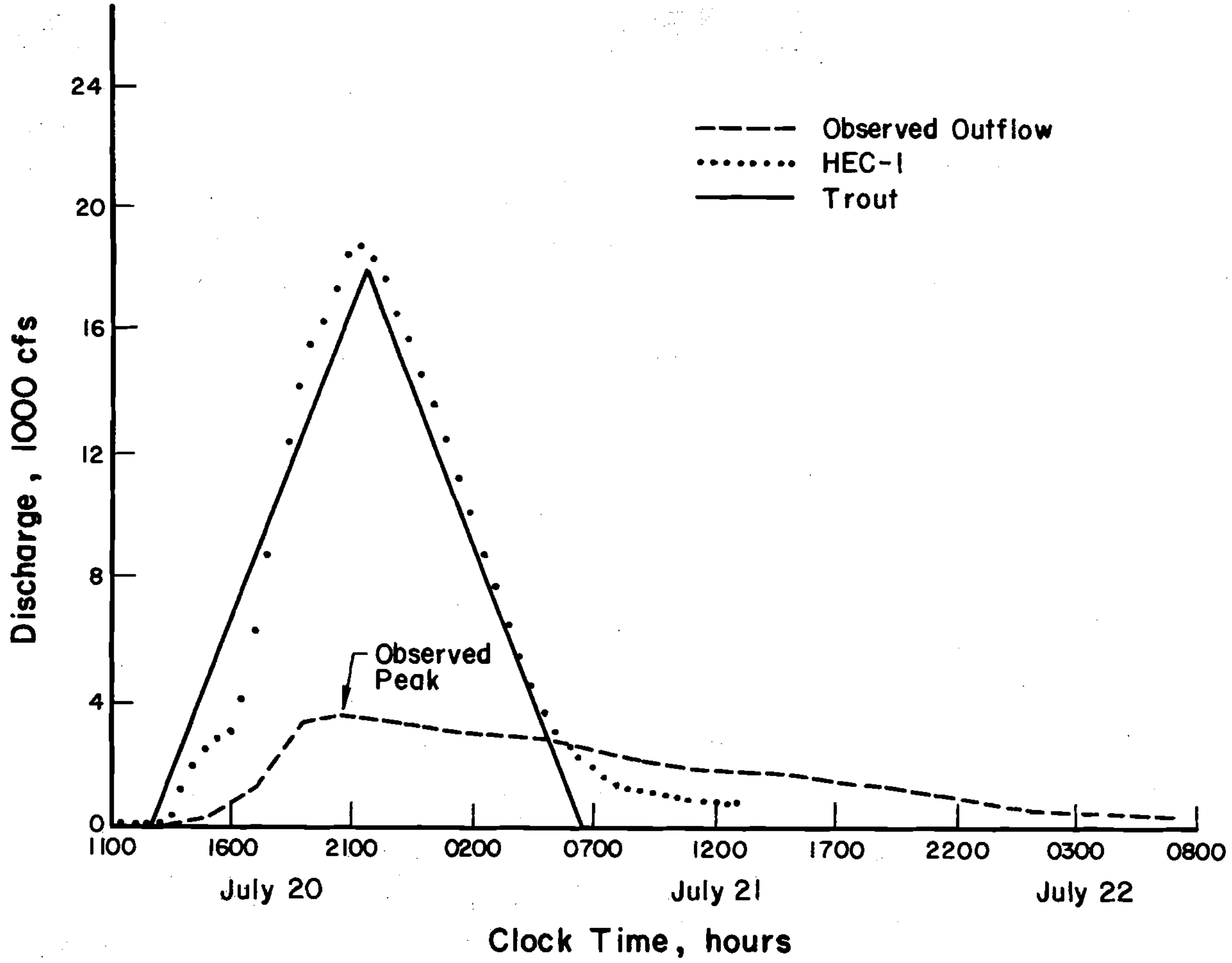


Figure 3.4 Outflow Hydrographs for July 21, 1976

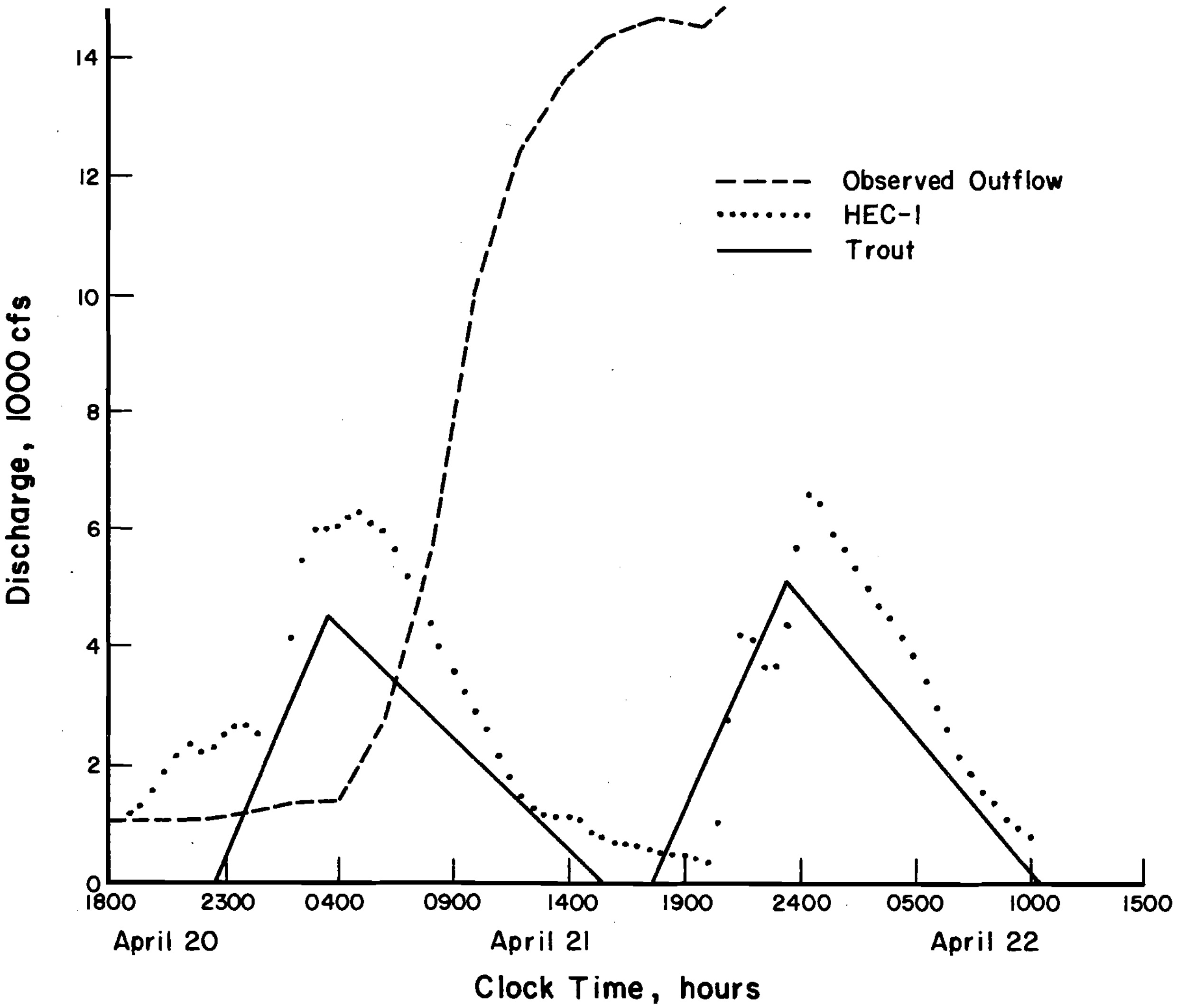


Figure 3.5 Outflow Hydrographs for April 22, 1973

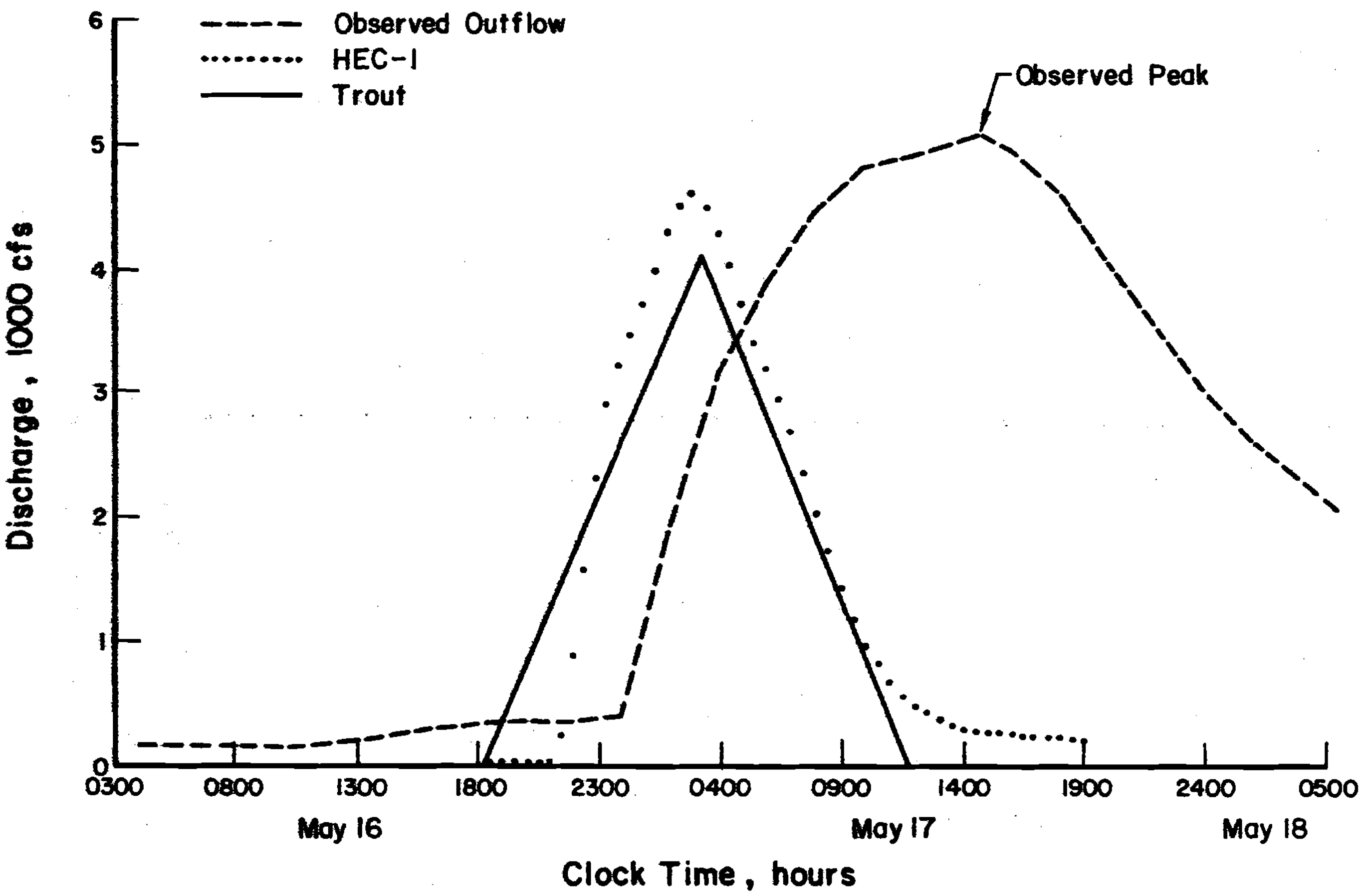


Figure 3.6 Outflow Hydrographs for May 17, 1974

subbasin, the use of TROUT gives a reasonable representation of the outflow hydrograph at the downstream end of Hickory Creek. Because the purpose of the comparison is to determine whether TROUT is sufficiently sensitive to be used in an optimization model, and because damages are a function of peak flow alone, it is not necessary to investigate the differences in the times of peak flows as closely as the peak flows themselves. The times of peak flows are of interest only in how they affect the peak flows in other subbasins when two hydrographs are combined.

The substantial differences in peak flows and times to peak between the recorded hydrographs for the 1973 and 1976 storms and the hydrographs predicted by both TROUT and HEC-1 suggest that the locally generated hydrographs used as input to TROUT and the Muskingum routing of HEC-1 are incorrect. One possible reason for the difference between predicted and actual flows for these two storms is that the precipitation data came from a single station not in the river basin. Furthermore, it was not the same station for each storm. The fact that precipitation data came from single stations and were applied uniformly over the watershed could produce significant errors in runnoff hydrograph computation, particularly if the storm was of the connective or thunderstorm type. When the overall shape and total volume of the observed outflow hydrographs are compared to those predicted by either of the two routing models, none of the storms matches very well. This observation would tend to reinforce the conclusion that rainfall input variation may be the cause.

Due to the apparent variation in rainfall across the watershed and the lack of detailed data, it was concluded that it was impossible to compare either routing model to reality. The problem therefore becomes one of comparing TROUT to a widely accepted routing model, the Muskingum method as programmed in HEC-1. The HEC-1 program was chosen as a reference of comparison because its validity is relatively well established.

3.4 Comparison with Muskingum Method

3.4.1 Comparison

Table 3.2 shows the differences between the hydrographs predicted by TROUT and HEC-1 at the downstream end of Hickory Creek. The flow values predicted by TROUT and HEC-1 are not very different from each other at the downstream end of Hickory. The variation between the HEC-1 and TROUT predictions is far less than the variation between either the HEC-1 or TROUT predictions and the recorded hydrographs. This result is not surprising because the input hydrographs to TROUT are merely the input hydrographs for HEC-1 converted to triangles. The peak flow, time of peak flow, and total volume of flow are maintained.

3.4.2 Discussion

For all storms the peak flow at the outlet of Hickory Creek from TROUT was consistently less than that from HEC-1. However, the greatest difference is no more than 30 percent. Except for the doubly peaked storms, the differences are less than 13 percent. As mentioned previously, this closeness in values is to be expected as both models are essentially the same locally generated hydrographs. However, investigation of subbasins (see Figures 3.7-3.11) of the watershed indicates that TROUT peak flow values are not consistently below those produced by HEC-1.

Figures 3.7 through 3.11 show the comparison between HEC-1 and TROUT on upstream reaches of Hickory Creek and along its tributaries for the five storms run with 67 subbasins. This lack of consistency between the TROUT and HEC-1 values indicates that the results observed at the outlet to the basin are more a function of the characteristics of the particular watershed than of the characteristics of the two models. Consequently, it is not reasonable to expect similar results for other watersheds.

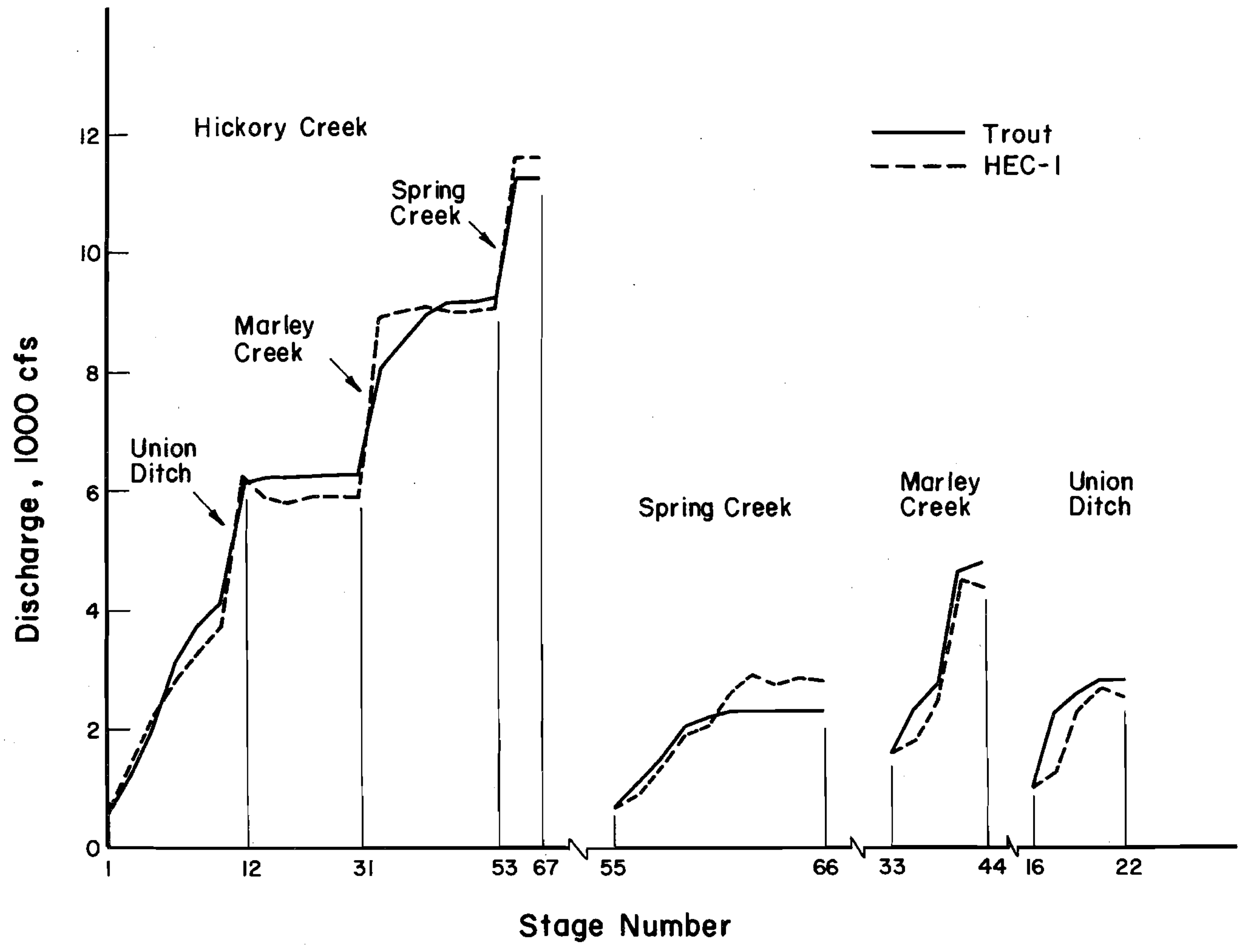


Figure 3.7 Peak Flows along Main Channels Storm of April 5, 1947

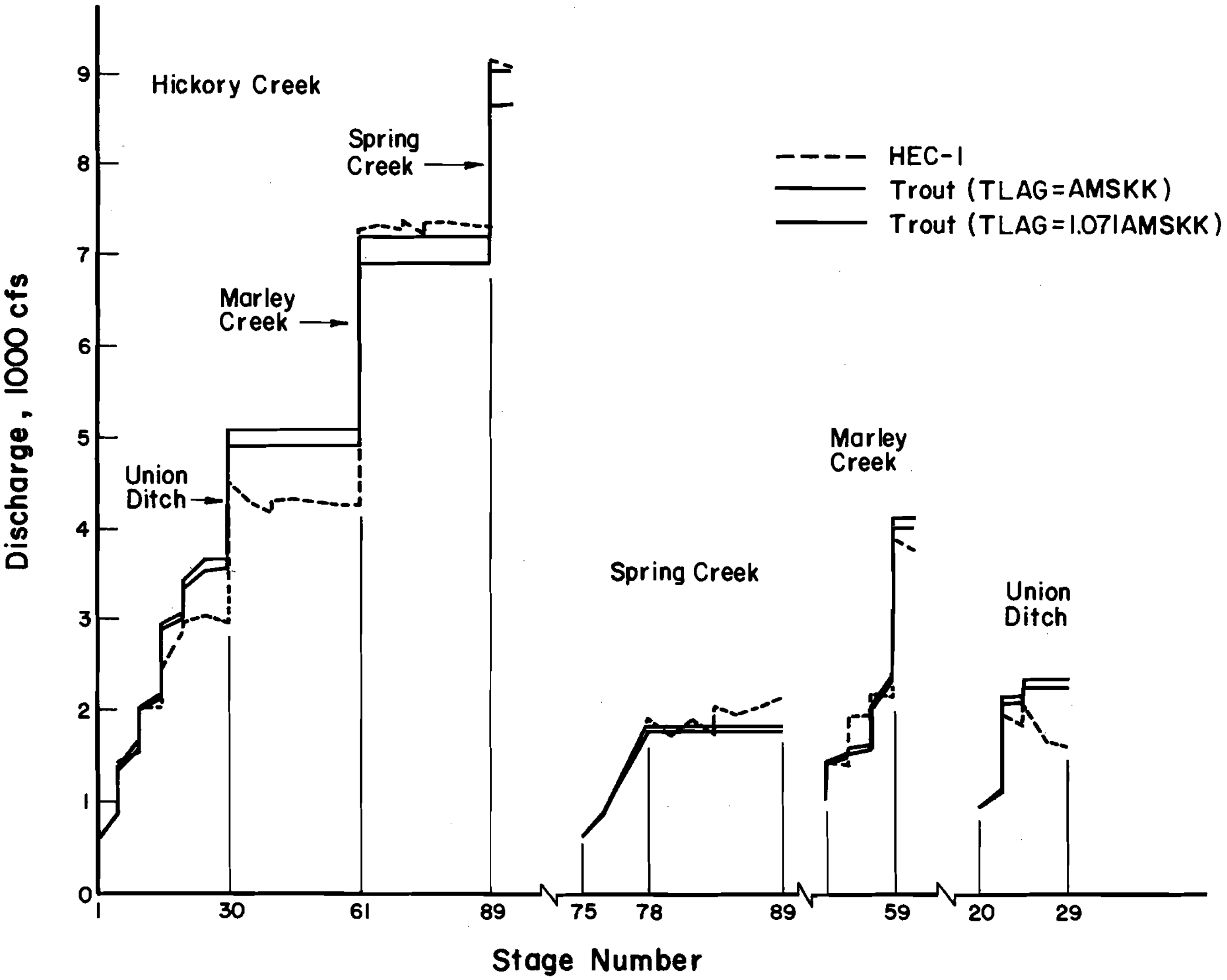


Figure 3.8 Peak Flows along Main Channels Storm of October 11, 1954

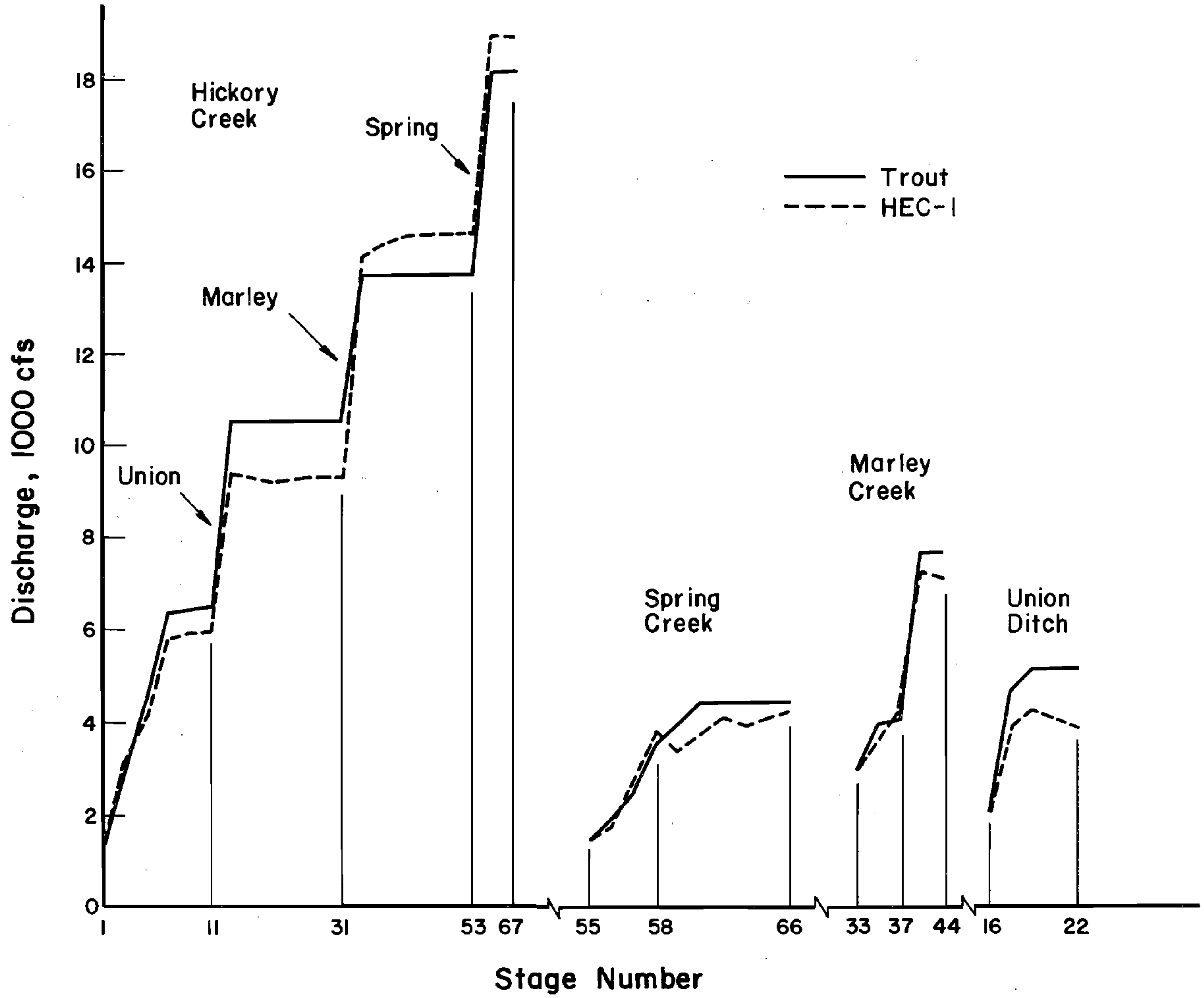


Figure 3.9 Peak Flows along Main Channels Storm of July 21, 1976

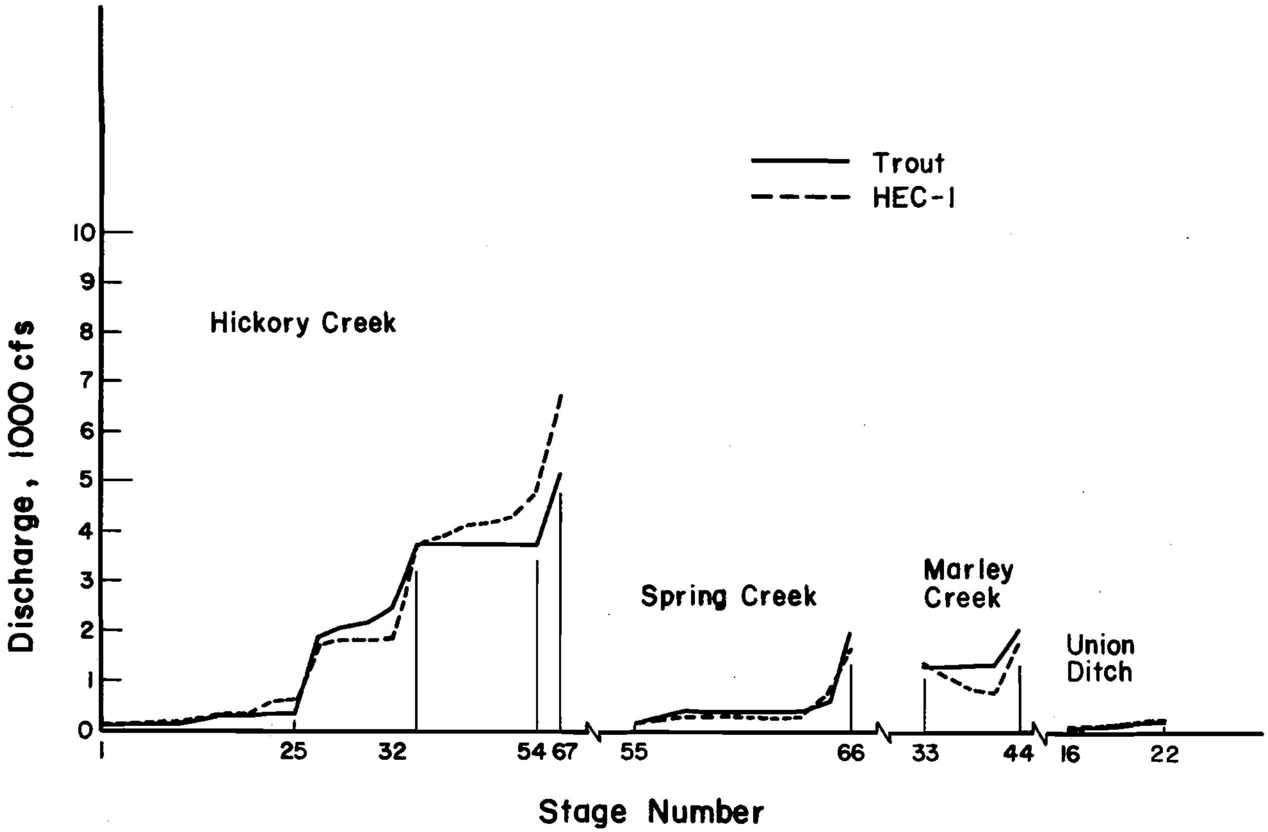


Figure 3.10 Peak Flows along Main Channels Storm of April 22, 1973

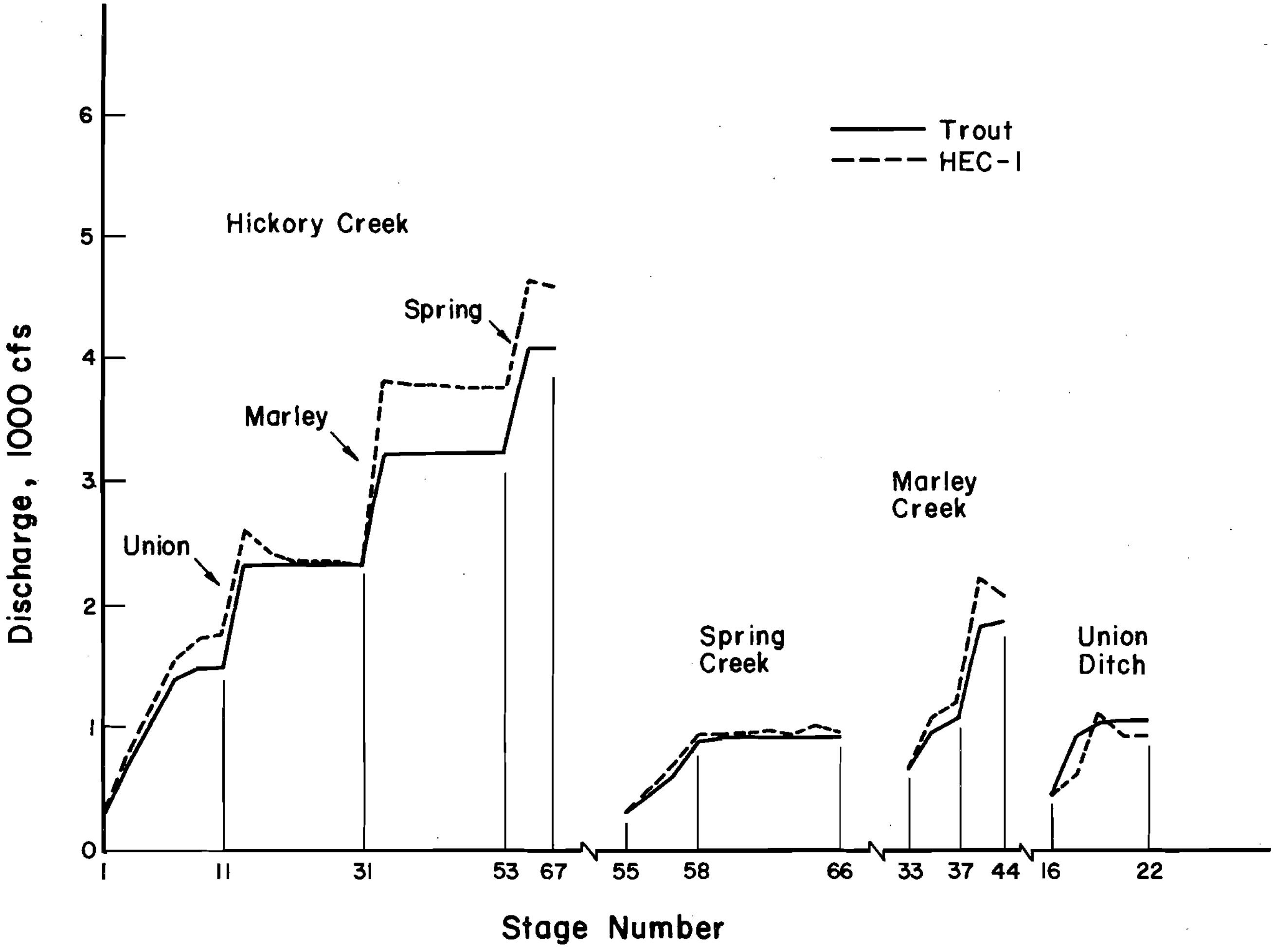


Figure 3.11 Peak Flows along Main Channels Storm of May 17, 1974

Further investigation of Figures 3.7 through 3.11 indicates that TROUT values are neither consistently higher nor lower than the HEC-1 values, either for a single storm or at single point in the watershed. However, the major relative differences in flow values occur where the major tributaries meet the main channel of Hickory Creek. The hydrographs before and after these junctions were investigated. However, once again no real pattern was found either in peak flow or time of peak differences. The differences appear to be caused by effects of the timing of the peak flows and the flattening of the falling limbs of the HEC-1 hydrographs. Although it was found that a coefficient on lag time in TROUT would reduce the mean squared error compared to HEC-1, the reduction was insufficient to justify the added complexity and could not be achieved with the same coefficient for all storms.

In summary, although the TROUT model yields final outflows quite close to those from HEC-1, when all reaches are considered the two procedures yield sufficiently different results to require more detailed comparison of TROUT to HEC-1. It is desirable to estimate whether the potential error introduced by using TROUT affects the policy implications obtained from the land use allocation model (see Chaper 1).

3.5 Sensitivity Analysis of Land Use Allocation Model

If the range of potential error introduced by the simplified routing model does not alter the solutions or the conclusions drawn from the land use allocation mode, then the simplified routing procedure is adequate for its intended task. The usual approach for testing whether solutions are sensitive to data error is to introduce uncertainty about the data values. A probability distribution can be used to represent the likelihood that a particular item of data will take on a particular value (Zieman et al., 1971;

Mercer and Morgan, 1976). The problem can then be solved repeatedly, drawing random numbers to determine which data value from the distribution to use in each run. This process results in a distribution of solutions that can then be analyzed to determine the uncertainty associated with the solution as a result of uncertainty in the data. In simple applications, such as cost benefit analysis, the result is a distribution of a single variable, such as net benefits, that measures the value of a solution. The sensitivity analysis here concerns the uncertainty resulting from simplification of the routing procedure used in the model. The identification of a suitable error distribution is therefore more difficult than in the case of uncertainty in data. One cannot establish, for example subjectively, a range of error about a given data value. Rather, a method must be prescribed for computing the error distribution about any value that the variable might take on during the operation of the model. This approach raises difficulties in expressing error, which are discussed below.

For the land use allocation model, the presentation of results is also more difficult. One could compare the aggregate land value from the model with aggregate land values resulting from other policies (Hopkins et al., 1978) to determine the uncertainty of choice among policies. However, this choice among policies is less sensitive to uncertainty in the model than is the land use pattern resulting from the allocation model, as evidenced by other error analyses. (See Hopkins, 1978). Therefore, the present tests focus on the sensitivity of solutions, in the sense of land use patterns, to error in the routing procedure. In contrast to error distributions for simple measures, such as net benefits, there are no generally satisfactory ways to express differences among discrete spatial patterns. (See Hopkins, 1973, 1975; Chang et al., 1979). Therefore, the description of uncertainty in land use patterns is based on several kinds of comparisons as discussed below.

3.5.1 Description of Error Distributions

The first task is to describe the probability distribution of expected error. For the present, the concern is solely with inaccuracy in the routing model. Therefore, a probability distribution for the outflow in cubic feet per second at the base of each reach of the stream must be established. The available data, aside from direct subjective judgment, are the differences in outflows from the HEC-1 model versus the TROUT model for the five storms run with 67 subbasins as described in section 4. Assuming that the HEC-1 routing is an appropriate standard of reference, then the deviation of the TROUT results from this reference is an estimate of the error introduced by the simplified routing model.

There are at least three ways of describing this error. It could be expressed as a percent of the HEC-1 value, as an absolute difference measured in cubic feet per second, or as some function of flow measured in cubic feet per second. The first approach considered was to express the error of TROUT with respect to HEC-1 as a percent. The percent errors were then classified in discrete positive and negative intervals, and a frequency distribution was established by counting the number of times that the errors observed for each reach from the five storms fell into each class. All reaches of the stream were considered together so that one error distribution was derived that would apply to all reaches. During the run of the dynamic programming algorithm that solves the land use allocation problem (see Hopkins et al., 1978), the outflows at each reach were modified by adding or subtracting the percent error indicated by a randomly drawn class interval in the frequency distribution. This procedure is equivalent to Monte Carlo simulation, but in this case with respect to uncertainty in model structure rather than to probabilistic external events.

This procedure was infeasible because the percent errors cumulated to yield unreasonably high flows. If the random draw happened to indicate several additions to the initial outflow estimate, this increase could become successively larger as the percent errors were applied to successively larger outflow estimates. A constraint was added to cut off unreasonable flows and thereby make running of the model feasible, but this operational difficulty was indicative of conceptual difficulties.

The use of percent as an error description implies that the error remains proportional as the estimated outflow varies. For example, if the flow changed from say 2000 cubic feet per second (cfs) to 6000 cfs, then the error for a given probability would change from say 400 cfs to 1200 cfs. Inspection of the data indicated that the large percent errors were associated with small absolute flow values, a hint that error was not proportional. Therefore, the description of error in percent terms would be inappropriate. To test this hypothesis, a linear regression was run of percent error versus flow. The coefficient of determination, R^2, was .05, and the coefficient was negative, indicating that percent error was a poor descriptor and that the proportional error probably decreased with increases in outflow.

The alternative of using absolute error was then considered. A regression of absolute error versus flow had an R^2 of .24 and a positive coefficient of .04 that was significant at the .01 level. This relationship implied that a change of 1000 cfs in flow led to a change in the error of 40 cfs. For the range of flows considered in the model, 0 cfs to 40,000 cfs, the range of variation in the expected error would be 1,600 cfs. The largest absolute error from HEC-1 flow predictions, ranging up to 19,000 cfs or half the range considered in the model, was approximately 1400 cfs. One could, therefore, assert that errors greater than 2800 were highly unlikely. With percent errors ranging as high as 70 percent, the percent descriptions of error could clearly lead to spuriously high estimates of error. The inappropriateness of percent error was again confirmed.

Although it would be desirable to incorporate the relationship between flow and absolute error obtained statistically, there is no easy way to do so. It would be necessary to establish some reference frequency distribution that would then be adjusted by the functional relationshop between error and flow. However, derivation of an error distribution for a particular reference flow would be difficult from the very limited available data. Also, the expression of the absolute error relationship must approach zero as a limit, which requires a complicated function beyond that from the simple linear regression. Such elaborate derivation of an error distribution from so little·data is not justifiable from conducting a simple sensitivity analysis.

Recalling that the differences observed between HEC-1 and TROUT appeared to be dependent on the characteristics of the particular watershed, the frequency distribution of absolute errors for each reach across the five storms was used. This approach avoided the difficulties with percent error, but related the absolute error roughly to flow, because flow is correlated with reaches. The use of reach specific distributions also takes direct cognizance of the idiosyncrasies of the observed errors. For example, if TROUT consistently underestimated at a particular reach but overestimated at another, this difference in error would be incorporated.

A disadvantage of this approach is that the implied frequency distributions were very irregular as shown in Table 3.3. That is, there might be a probability of .4 of an error of 300 cfs but a zero probability of errors less than that. In the present case, there is no deductive basis for the traditional notion that error is approximately normal around an estimated mean data value, and the data do not support such an hypothesis. This lack of smoothness in the error distributions does not affect the simulation other than potentially to yield solutions that are different from each other in a discontinuous way.

Simulation runs were made using the reach specific frequency distributions of absolute errors. Although the regression indicated that absolute error would increase slightly with flow, the error distribution was constant for the reach even if the model considered flows in that reach that were greater than any of the flows at that reach from the comparative runs of the routing models. Although this approach could be argued to underestimate error, the cumulation of error as the model progresses downstream more than compensates for this. The observed differences between HEC-1 and TROUT are the cumulated error to that reach. In the simulation, the error is applied at each reach. Therefore, the probabilistic compensation for error in one reach is included again in the probabilistic compensation at all succeeding reaches.

Using absolute errors, it is possible for an estimated flow to become negative, such as when the provision of detention storage renders estimated flow at a particular reach much less than currently observed. Such negative flows were changed to a flow of one cfs. Flow quantities of one or two hundred cfs are relatively insignificant in the model so the fact that this may be an underestimate of minimum flows is not important. It is much less of a problem to underestimate low flows by a couple of

Table 3.3. Frequency of Differences Between Peak Flows From HEC-1 and TROUT

Number of Storms with Peak Differences in Flow Ranges Shown

(Flows in cfs)

Stage No.	-1450	-1350	-1250	-1150	-1050	-950	-850	-750	-650	-550	-450	-350	-250	-150	-50	50	150	250	350	450	550	650	750	850	950	1050	1150	1250	1350	1450
2													1	1	3															
4												1	1	1	2															
5														2	1	1					1									
7														2	2			1												
8														1	2	1				1										
10															3		2													
11													1		1		1				2									
12													1		1		1	1		1										
14												1			1				1	2										
15												1			1			1		1	1									
16												1			1			1	1			1								
18														2	1	1	1													
19															2	1		1			1									
21															3			1	1											
22														1	1		2					1								
23															2			2						1						
25														1	1			2					1							
26															1	1					2							1		
28															1	2					1				1					
29															1	1		1				1					1			
30													1		2						1						1			
31														1	1			1					1					1		
33														1	1			1					1				1			
34															2					1				1					1	
36															2				1				1					1		
37															2				1				1						1	
39														1	2	1	1													
40															2				1				1				1			
41															2				1				1				1			
42															2				1				1				1			
43															1	1			1				1					1		
46															5															
47															1	2					1		1							
49												1			2			1		1										
50												1			2			1	1											
52													3		1			1												
53														1	1	1	2													
56															5															
57														1	1		1			1		1								
58															2			1							1				1	
59											1				1	1	1		1											
60													1		1				1	1		1								
61						1			1		1				2															
62								1	1	1				1	1															
63									1		1	1		1	1															
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66			1						1					2	1															
67			1							1					3															
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70		1								1				1	1		1													
72		1								1				1	1		1													
73	1									1				2			1													
74			1							1				2			1													
76															3		2													
77													1	1	1	1	1													
78												1		2	1	1														
79															2	1	1					1								
80												1		1	2							1								
81													1		2	1					1									
83										1			1	1	1				1											
84										1				2	1					1										
85										1			1	1	1					1										
87											1		1	1	1			1												
88										1		1		1	1		1													
89							1		1		1		1	1																
90								1		1	1			2																

hundred cfs than to overestimate high flows by ten or fifteen thousand cfs as occurs when percent errors are used. In the runs reported in the next section, flows were set to one in only a few cases.

3.5.2 Results of Sensitivity Runs

Ten runs of the allocation model were made using the error analysis approach described above. The absolute error intervals are shown in Table 3.3 with the probability distributions of error for each reach. The allocation model was also run without the error analysis to provide a reference with which to compare the error analysis runs. The error analysis and reference runs are compared in Tables 3.4 and 3.5

There is little variation across the eleven runs in the total economic rent for the watershed. The total variation between the largest and the smallest values is 1.6% of the value for the reference runs. In absolute terms, there is one run with a value $10 million higher than the reference run; all other runs are within $5 million of the reference run. When the allocation model was used to compare policies, the optimal solution from dynamic programming was preferred to the next best policy by $80 million. (See Chapter 1). The choice of policies based on total economic rent would, therefore, not be affected by the estimated error in the routing model. This result indicates that the TROUT routing procedure is adequate to the task of distinguishing among policies for the case investigated here.

The range of differences in final outflow from the error analysis runs requires more subtle analysis. Table 3.5 gives a reach-by-reach analysis of the sensitivity runs. Each column refers to a run. Each triplet of rows gives the subbasin use, the floodplain use, and the outflow from the subbasin indicated. Subbasins are indexed in Figure 3.1. Four of the ten error

Table 3.5 (continued)

Stage #	Reference Run	Error Analysis Runs									
		1	2	3	4	5	6	7	8	9	10
17. Subbasin	8	8	8	8	8	8	8	8	8	8	8
Floodplain	3	3	3	3	3	3	3	3	3	3	3
Flow	329	329	329	329	329	329	329	329	329	329	329
18. Subbasin	8	8	8	8	8	8	8	8	8	8	8
Floodplain	3	3	3	3	3	3	3	3	3	3	3
Flow	623	423	723	523	723	423	623	723	623	623	723
19. Subbasin	8	8	3	8	8	3	8	3	8	8	8
Floodplain	3	3	3	3	3	3	3	3	3	3	3
Flow	710	510	961	310	810	826	610	961	610	610	710
20. Subbasin	8	8	8	8	8	8	8	8	8	8	8
Floodplain	3	3	3	3	3	3	3	3	3	3	3
Flow	543	543	543	543	543	543	543	543	543	543	543
21. Subbasin	8	8	8	8	8	8	8	8	8	8	8
Floodplain	3	3	3	3	3	3	3	3	3	3	3
Flow	745	445	745	445	745	745	745	745	345	745	745
23. Subbasin	4	4	4	4	4	4	4	8	4	4	4
Floodplain	3	3	3	3	3	3	3	3	3	3	3
Flow	1904	702	1955	1222	1804	1985	405	1826	422	1904	1404
24. Subbasin	7	7	7	7	7	7	7	7	7	7	7
Floodplain	3	3	3	3	3	3	3	3	3	3	3
Flow	309	309	309	309	309	309	309	309	309	309	309
26. Subbasin	4	4	4	4	4	4	4	4	4	4	4
Floodplain	9	3	9	9	9	9	9	3	3	3	9
Flow	3574	1780	3784	3465	3470	3821	3157	2996	1777	2950	3320
27. Subbasin	8	8	8	8	8	8	8	8	8	8	8
Floodplain	3	3	3	3	3	3	3	3	3	3	3
Flow	239	239	239	239	239	239	239	239	239	239	239
29. Subbasin	4	8	4	4	4	4	4	4	4	4	4
Floodplain	9	3	9	9	9	9	9	9	3	3	9
Flow	4745	1605	3655	4236	3341	3892	3027	4166	1762	2321	4091
31. Subbasin	3	3	3	3	3	3	3	3	3	3	3
Floodplain	9	3	9	9	9	9	9	9	9	9	9
Flow	12942	9285	10588	16484	11366	14484	11458	11339	15097	14192	11379
32. Subbasin	4	4	4	4	4	4	4	4	4	4	4
Floodplain	9	9	9	9	9	9	9	9	9	9	9
Flow	1085	1085	1085	1085	1085	1085	1085	1085	1085	1085	1085

Table 3.5 (continued)

Stage #	Reference Run	Error Analysis Runs									
		1	2	3	4	5	6	7	8	9	10
34. Subbasin	3	3	3	3	3	3	3	3	3	3	3
Floodplain	9	9	9	9	9	9	9	9	9	9	9
Flow	12942	9385	10288	15984	10866	12784	10158	10539	14697	11992	11379
35. Subbasin	3	3	3	3	3	3	3	3	3	3	3
Floodplain	9	9	9	9	9	9	9	9	9	9	9
Flow	3171	3171	3171	3171	3171	3171	3171	3171	3171	3171	3171
37. Subbasin	3	3	3	3	3	3	3	3	3	3	3
Floodplain	9	9	9	9	9	9	9	9	9	9	9
Flow	12942	8585	10288	14584	9666	11584	8853	8439	13097	9792	10979
38. Subbasin	3	3	3	3	7	3	7	7	3	7	3
Floodplain	9	9	9	9	3	9	3	3	9	3	9
Flow	1629	1629	1629	1629	252	1629	252	252	1629	252	1629
39. Subbasin	3	3	3	3	3	3	3	3	3	3	3
Floodplain	9	9	9	9	9	9	9	9	9	9	9
Flow	2317	2117	2117	2317	1870	2417	1870	1770	2117	1770	2417
41. Subbasin	3	3	3	3	3	3	3	2	3	3	3
Floodplain	9	9	9	9	9	9	9	9	9	9	9
Flow	12942	7385	9488	13784	9962	10384	7954	7599	12697	10247	9779
42. Subbasin	2	2	2	2	2	2	2	2	2	2	2
Floodplain	9	9	9	9	9	9	9	9	9	9	9
Flow	12942	7385	9488	13784	9962	9184	7954	7599	12697	9847	9779
43. Subbasin	2	2	2	2	2	2	2	2	2	2	2
Floodplain	9	9	9	9	9	9	9	9	9	9	9
Flow	12942	6585	8188	13784	9862	7884	7154	7199	12697	9747	8979
44. Subbasin	7	7	7	7	7	7	7	7	7	7	7
Floodplain	3	3	3	3	3	3	3	3	3	3	3
Flow	417	417	417	417	417	417	417	417	417	417	417
45. Subbasin	3	3	7	3	3	3	7	3	7	3	3
Floodplain	3	3	3	3	3	3	3	3	3	3	3
Flow	1542	1542	190	1542	1542	1542	190	1542	190	1542	1542
47. Subbasin	7	7	7	7	3	7	7	7	7	3	7
Floodplain	9	3	3	3	9	9	3	3	3	9	9
Flow	2281	1481	329	1681	3352	2181	329	1481	829	3252	2181
48. Subbasin	7	7	7	3	7	7	7	7	7	7	7
Floodplain	3	3	3	9	3	3	3	3	3	3	3
Flow	319	319	319	2193	319	319	319	319	319	319	319

Table 3.5 (continued)

Stage #	Reference Run	Error Analysis Runs 1	2	3	4	5	6	7	8	9	10
81. Subbasin	6	6	6	2	6	2	6	2	2	2	2
Floodplain	9	9	9	9	2	9	2	9	9	9	9
Flow	2513	2413	2513	5530	1713	5667	1913	5567	7246	5962	6062
82. Subbasin	2	6	2	2	6	2	6	2	2	2	2
Floodplain	9	9	9	9	9	9	9	9	9	9	9
Flow	1492	220	1492	1492	220	1492	220	1492	1492	1492	1492
84. Subbasin	2	2	2	2	6	2	2	2	2	2	2
Floodplain	9	9	9	9	9	9	9	9	9	9	9
Flow	2725	2333	2225	6230	1812	5894	2333	6094	7346	6089	6689
85. Subbasin	3	7	7	3	7	3	7	3	3	3	3
Floodplain	3	3	3	9	3	9	3	9	9	9	9
Flow	2725	2621	2913	6730	2500	5894	2021	6294	6846	6589	6689
86. Subbasin	3	7	3	3	3	3	7	3	3	3	3
Floodplain	1	1	1	1	1	1	1	1	1	1	1
Flow	843	158	843	843	843	843	158	843	843	843	843
88. Subbasin	*	*	*	*	*	*	8	*	*	*	*
Floodplain	3	3	3	9	3	9	3	9	9	9	9
Flow	2882	2792	2813	7330	2913	6493	1892	6494	7846	7387	6489
90. Subbasin	3	3	3	3	3	3	3	3	3	3	3
Floodplain	3	3	3	9	9	3	3	3	9	9	3
Flow	19839	16985	17441	25807	25720	17578	14006	17888	26849	23986	20526

*Subbasin is 100% flooded.

analysis runs yield outflows at the base of the watershed that are 2,000 to 3,000 less than that for the reference run. Reach-by-reach analysis of the results indicates that this difference occurs, at least in part, because the flow along the mainstem between the entries of Union Ditch and Marley Creek (see map in Figure 1.2) is successively reduced in the error analysis. TROUT overestimated flows in this set of reaches compared to the Muskingum method, so the correction is appropriate. Examine, for example, runs 4 and 6 in Table 3.5. At the entry of Union Ditch (stage 31), the flow in run 6 (11,458) is similar to that in run 4 (11,366). Just before the entry of Marley Creek (stage 43) the flow for run 6 has become 2,000 cfs less than for run 4 despite the fact that the land uses assigned in each case are the same. The difference is, therefore, due solely to the random draw yielding a succession of reductions in the flow value for run 6. As mentioned above, this difference probably overestimates the error because the difference between the flows from TROUT and from the Muskingum method remains about the same between the two tributaries. The error analysis, however, allows the possibility of cumulating this error because it is possible to adjust for the error at each reach in the model and there are 5 reaches along the mainstem between these two tributaries.

This difference in flows is further exacerbated with the entry of Marley Creek. Because in these four runs the flows before the junction with Marley Creek are lower, it apparently becomes worthwhile to keep them even lower in order to allow urban development in the floodplain below Joliet (stage 90). Therefore, additional detention is provided in stages 57 and 58 on a Marley Creek tributary to cut down the flow and therefore the combined hydrograph after Marley Creek. This is an example of the complexity of relationships involved in the land use allocation model.

The relative size of final outflow is fairly well determined before the inflow of Marley Creek. This is not surprising because most peak flows from subbasins and from tributaries below the entry of Union Ditch occur earlier in time than the peak on the mainstream and therefore do not change significantly the relative peak flows. The absolute sizes of the peak flows continue to increase, however, from the addition of flows from the tails of the hydrographs downstream.

Four other runs have outflows 4,000 to 6,000 cfs higher than for the reference run. These flows are also largely determined at the entry of Union Ditch. Allocations in these cases cannot take advantage of reduced flows at Marley Creek sufficiently to permit urban uses below Joliet. Therefore, detention is not assigned in both stages 57 and 58, which further increases these flows. In addition these four runs tend to increase more in stages 70, 73, and 74 due to cumulated error adjustments than do the other runs.

Run 6 has a very low outflow of 14,000 cfs. This apparently results, first, from the same phenomena described for the other low outflows and, second, from two other conditions. Through stages 70 to 74, the flows on this run actually decrease slightly, while those for all other runs increase. The increase is the much more likely result given the error probabilities. Further, this very low flow just before the entry of Spring Creek is apparently sufficient to justify additional detention on Spring Creek in order to permit higher density urban in Joliet (stage 88). This is the only run in which stage 88 is not completely flooded by the 100 year storm. This reduction in flow further decreases the combined final outflow yielding the significantly low flow of 14,000 cfs.

The tenth run yields approximately the same flow as the reference run, although not from an identical land use pattern.

These results emphasize that the observed range of outflows is not due solely to error in the routing procedure, although it results from such error indirectly. If the error in routing is sufficient that a different allocation of land uses is optimal, perhaps through complex relationships, then the difference in final outflow will be due in part to the different land use allocation from which it results. That is, the error will be amplified by the resulting land use pattern. Because of the cumulative effect of the error analysis, the range of outflows is probably overstated. However, it is clear that simulations using more complex routing models should be undertaken before land use decisions for specific subbasins are implemented.

The usefulness of the allocation model is dependent on being able to determine choices for land uses in particular subbasins. Therefore, it is important to consider the sensitivity of land use decisions for individual subbasins to the estimated error in the routing model. The non-floodplain land uses are the same across all eleven runs in 57% of the subbasins and the floodplain uses are the same in 69% of the subbasins. In other words, 63% of all land use deicisions do not vary. This relative stability of land use decisions suggests that at least a majority of individual subbasin decisions can be determined by the model within the estimated error in the simplified routing model. Further, the error analysis approach used here is a successful means for identifying the subbasins that are unchanged, and for which decisions indicated by the model are therefore reliable.

Additional careful analysis of the error results permits even more land use decisions to be determined at the subbasin level. Most of the subbasins for which land use decisions are unstable across the runs are in the upper reaches of Hickory Creek before intersecting the first major tributary or in the tributaries. In at least some of these cases the tributaries can be separated into largely independent subproblems to further consider the subbasin level decisions. For example, there are variations in land use deicisions for ten of the twelve subbasins along Spring Creek. However, there are really just two cases. In one case detention is required in most reaches, therefore, permitting urban use at the base of the tributary in Joliet (stage 88). In the second case, very little detention is assigned, and nonurban use is required in the Joliet subbasin. In general these differences do not affect land use decisions elsewhere in the watershed. Therefore, the decisions for this tributary could be analyzed more carefully with a simulation model as an independent subproblem to confirm the best land use decisions, given the estimated error in the routing model.

Even the subbasins that fit none of the above cases are not highly variable with respect to the routing model error when the significance of variation in decisions is considered. In all subbasins the variation consists of detention or nondetention for the same land use, the same urban use or a nonurban use in the floodplain, or in a few cases, a shift of one density level in the land use. The only exception to these types of shifts is the appearance of land use 8 in Joliet (stage 88) with the extremely low flow that leaves the subbasin only partially flooded for the 100 year flood. The shifts from detention to nondetention or from urban to nonurban uses are significant differences, but the fact that the variation is consistently of a particular type renders simulation a reasonable means for conducting further analysis. Only the tradeoffs between detention or nondetention for a particular use, versus nonurban floodplain or a particular use, need be considered. The number of alternative land use patterns is therefore greatly reduced so that complex simulations can be used to analyze each alternative. Further, in many cases, the particular subbasins involved in the tradeoffs can be identified so that the cases to be investigated are even simpler.

It is also pertinent that the results of sensitivity analysis on land value data also yield similar patterns with most of the undecidable land uses occurring in tributaries and involving localized tradeoffs between detention and floodplain land uses. (See Chapter 2). This correspondence implies that simulations to deal with difficult subproblems can consider the potential error in several parts of the allocation model and data at the same time.

3.6 Conclusions

The primary question of this analysis is whether TROUT, the simplified routing model that is required to make the dynamic programming solution algorithm possible, is sufficiently accurate to yield reliable solutions to the land use allocation problem. When the comparison to observed flows is rejected as invalid because of inadequate precipitation data, any conclusion must be based on a comparison with a widely accepted routing procedure such as the Muskingum method. The two methods do not yield sufficiently similar results upon direct comparison to assert that the TROUT procedure replicates the Muskingum results. Therefore, the adequacy of the TROUT procedure must be evaluated by determining whether the estimated error is sufficient to render the allocation model results unreliable.

The error analysis described above indicates that the total economic rent of the watershed is insensitive to the estimated error in the routing model. This result implies that policy comparisons based on total economic rent for land are reliable for the watershed studied here. Further, 63% of the land use decisions at the individual subbasin level, considering both floodplain and non-floodplain decisions, are insensitive to the estimated error for the watershed under study. Such subbasins can be successfully identified by an error analysis of the kind used here. Many of the remaining subbasins can be analyzed effectively by simulation using a more accurate, but concomitantly more complex routing model. This approach is feasible because the subbasins with undecided land uses can usually be separated into subproblems and because the question is usually one of localized tradeoffs between detention and nonurban use in the floodplain. In summary then the TROUT routing model is adequate for use in a floodplain management model used for screening good land use patterns from the many possible land use patterns. The differences among these selected patterns are also sufficiently structured that they can be further analyzed effectively with simulation models.

APPENDIX A

HYDROLOGY COMPUTATIONS

Most of the hydrology computations were carried out using programs included in HEC-1: Flood Hydrograph Package developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers. Section A.1 describes the computation of the hydrographs for each use on each subbasin. Section A.2 describes the computations for the Muskingum routing method, which was used as a standard of comparison for the triangular routing method and to obtain more accurate hydrologic response data for land use patterns found by the dynamic programming model.

A.1 Calculation of Unit Hydrographs

The unit hydrographs were computed using the Clark method (Clark, 1945) as programmed in the HEC-1 package. The HEC-1 programs perform "lumped parameter modeling of the precipitation runoff process," which means that spatial and temporal average values of the input parameters are used. The synethetic dimensionless time-area curve provided in the HEC-1 package was used. As described in the HEC-1 User's Manual, this is

$$AI = T^{1.5}/0.707 \text{ for } 0<T<0.5 \tag{A1}$$

$$1 - AI = (1-T)^{1.5}/0.707 \text{ for } 0.5<T<1 \tag{A2}$$

where

AI = area as a ratio of total basin area

T = time as ratio of time from beginning of runoff to time of concentration

This dimensionless curve is first transformed into a dimensional curve using the basin area and time of concentration. It is then converted to a time-area runoff curve, I, with a total of one inch of precipitation excess. The unit hydrograph is this runoff curve routed through storage at the outlet of the subbasin using the Muskingum routing procedure with the Muskingum X coefficient set equal to zero and the storage coefficient, R, set at the appropriate rate for the subbasin. This is described in the HEC-1 User's Manual as

$$Q_2 = (CA \cdot I) + (CB \cdot Q_1) \quad \text{(A3)}$$

$$QUNGR = 0.5(Q_1 + Q_2) \quad \text{(A4)}$$

$$CA = TRHR/(R + 0.5 \cdot TRHR) \quad \text{(A5)}$$

$$CB = 1\text{-}CA \quad \text{(A6)}$$

where

Q_2 = instantaneous flow at end of period

Q_1 = instantaneous flow at start of period

I = incremental area during period (converted to cfs per inch of rainfall)

QUNGR = unit hydrograph ordinate

TRHR = tabulation interval in hours

R = basin storage coefficient in hours

The HEC-1 program terminates its computation of unit hydrograph ordinates when the hydrograph volume exceeds .995 inches or when 100 ordinates have been computed. An exponential recession of the flow from preceding runoff is used to describe base flow.

$$Q_2 = Q_1 / RTIOR^{0.1} \tag{A7}$$

where

RTIOR = ratio at recession flow to that 10 intervals later

Fitting of parameters for the hydrologic models was hampered because there was only one stream gauging station with a sufficiently long record , and this was at the base of Hickory Creek, in Joliet. A flood hydrograph was constructed from the flow records by plotting the peak flow and the time at which it occurred and the average daily flows from the preceding and succeeding days, each as of noon of the day they occurred. These points were then joined to form a flood hydrograph. The storm of April 28, 1959 was used to fit the parameters because the resulting hydrograph was relatively smooth and could therefore be readily manipulated. The HEC-1 program for fitting parameters was used to find the loss rate parameters that minimized the weighted squared deviations between the observed hydrograph and the hydrograph generated using the given rainfall data. This was done for the Hickory Creek basin as a whole because only one gauging station provided useful observed flows. The sensitivity of the peak flow to variations in these parameters enabled the most significant parameters to be isolated so that more emphasis could be placed on estimating them.

Some of the parameters determined for the whole basin are not applicable to the subbasins used for the dynamic program; time of concentration and storage coefficient were determined on a subbasin level. From the characteristics of the eight land uses and the parameter fitting just described, the loss rates and runoff parameters for each subbasin and land use were determined. These are shown in Table A1.

Table A.1

Summary of Coefficients Used for Each of the Eight Land Uses

RTIMP = Proportion at basin that is impervious

STRTL = Initial rainfall loss in inches

CNSTL = Uniform rainfall loss in inches/hour

Land Use	STRTL	CNSTL	RTIMP
1	0.22	0.5	0.34
2	0.21	0.5	0.40
3	0.20	0.5	0.45
4	0.20	0.5	0.46
5	0.1	0.5	0.95
6	0.35	0.05	-
7	0.4	0.5	-
8	0.5	0.5	-

For rural land uses, the time of concentration for each of the subbasins was determined by measuring the longest flow path to the downstream boundary of the subbasin and its average slope. These were taken from United States Geological Survey topographic maps. Time of concentration was then computed using the Kirpich formula.

$$t_i = \frac{L}{\sqrt{s}}^{\,0.77} \tag{A8}$$

where

L = length of channel in feet
s = channel slope
t_i = time of concentration in hours

For urban land uses a drainage system was assumed to have been installed. A grid with block width of 500 feet was superimposed on each subbasin and the longest flow path for that system determined. A typical flow velocity of 5 feet per second in gutters and sewers was applied to this flow length and the effective time of concentration computed as

$$t_c = \frac{L}{v} \tag{A9}$$

where

L = longest flow length in feet
v = flow velocity in feet/second
t_c = time of concentration in seconds

The storage coefficient in hours for the Clark unit hydrograph method could not be obtained directly. However, investigation of the sensitivity of the peak to variations in this parameter showed that the peak flow was not particularly sensitive to these changes. A value of .3, which is typical for areas of the size of the subbasins in this project, was assumed for all 42 subbasins. The ratio of the recession flow to that ten intervals later, a required input parameter, was taken from the hydrograph generated at the gauging station in Joliet.

The proportion of the subbasin that would be impervious for the various land uses was taken from tables in SCS National Engineering Handbook (Soil Conservation Service, 1969), Urban Storm Drainage Criteria Manual (Wright-McLaughlin Engineers, 1969), and The Costs of Sprawl (Real Estate Research Corporation, 1974). The initial rainfall loss and constant loss rate after this initial rainfall loss had been fulfilled were taken from the first two references.

These data were then used in the Clark method hydrograph generation program of the HEC-1 package to generate and plot hydrographs for each land use on each subbasin. The triangular hydrographs for use in the dynamic programming model were fitted to the plotted hydrographs by eye. The peak of the original hydrograph was taken as the peak of the triangle. The rising limb, which was very close to a straight line in most cases, was approximated by a straight line from the point of initial rise to the peak. The recession limb was approximated by a straight line such that the total area under the line was equal to the total area under the recession limb of the original hydrograph.

A.2 Calculations for Muskingum Routing Method

The Muskingum routing method (Chow, 1964; Rockwood, 1964) as programmed in the HEC-1 package was used to provide more accurate hydrologic response from the land use patterns found by the dynamic programming model than could be generated by the triangular routing method used within the dynamic program. In the Muskingum method, storage in the reach is a function of both inflow and outflow, where the relative importance of these flows is given by the coefficient X.

$$Q_2 = (CA\text{-}CB)\ I + (1\text{-}CA) \cdot Q_1 + CB \cdot I_2 \qquad \text{(A10)}$$

$$CA = 2 \cdot TRHR/(2 \cdot AMSKK \cdot (1\text{-}X) + TRHR) \qquad \text{(A11)}$$

$$CB = (THRH\text{-}2\ AMSKK \cdot X)\ /(2 \cdot AMSKK \cdot AMSKK \cdot (1\text{-}X) + TRHR) \qquad \text{(A12)}$$

where

X = Muskingum weighting coefficient
AMSKK = subreach travel time (Muskingum 'K coefficient')
I_1 = inflow at beginning of period
I_2 = inflow at end of period

As there were no flow records within the watershed except for the gauging station at Joliet, it was not possible to use the HEC-1 program package to obtain initial estimates of the required parameters. The Muskingum method was used because the parameters required could be more easily estimated. Cross sections were available for subbasins on the Spring Creek and Marley Creek watershed within the Hickory Creek watershed. Other channel cross sections had to be estimated though field work is currently in progress at the Illinois State Water Survey. A basic shape as shown in Figure A.1 was assumed with variations in D, d, and W as the cross sections were taken further upstream.

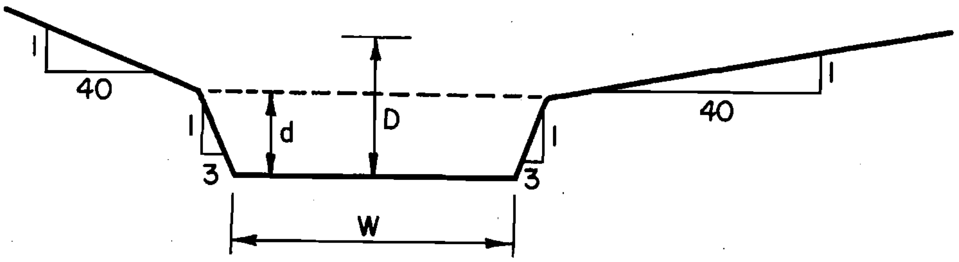

Figure A.1   Cross Section

Given the cross section for each reach and an average slope for each reach, computed from a topographic map, a flood flow for each reach was calculated. It was assumed that the peak flow at the gauge at Joliet could be used as a base and that the magnitude of flows at each upstream reach was directly proportional to the total area upstream of the reach; the flow at ease reach is the same portion of the flow at Joliet as the area of above the reach is of the total area above Joliet.

The time of travel for each reach was calculated under the assumptions of uniform flow in the cross section of that reach. Manning's formula was used to compute velocity in the cross section.

$$V = \frac{1.49}{n} \cdot R^{2/3} \cdot S^{1/2}$$

where

R = hydraulic radius = wetted perimeter/flow area

n = Manning's n

S = channel slope in feet/foot

V = velocity in feet/second

This velocity was assumed to be the average velocity in that reach, which yields the travel time in the reach as

$$AMSKK = \frac{L}{V} \tag{A14}$$

where

L = length of reach channel in feet

The assumption of uniform flow ignores backwater effects and nonsteady and nonuniform flow; these assumptions are consistent with the assumptions of the dynamic programming formulation.

The Muskingum X coefficient was set at a typical value of .3 for all reaches because it was not possible to estimate values from the available data.

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