Form 9-014

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PROJECTED EFFECTS OF INTERMITTENT CHANGES IN WITHDRAWAL OF WATER FROM THE ARIKAREE AQUIFER NEAR WHEATLAND, SOUTHEASTERN WYOMING

Open-File Report 80-15

Prepared in cooperation with
the Wyoming State Engineer

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by: Dwight T. Hoxie

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Cheyenne, Wyoming

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For those readers interested in using the metric system, the following table may be used to convert the inch-pound units of measurement used in this report to metric units:

Inch-pound	Multiply by	Metric
acre	4.047×10^{3}	square meter (m^2)
acre-foot	1.233×10^{3}	cubic meter (m^3)
cubic foot per second (ft^3/s)	2.832×10^{2}	cubic meter per second (m^3/s)
foot (ft)	3.048×10^{1}	meter (m)
gallon per minute (gal/min)	6.309×10^{5}	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer
square mile (mi^2)	2.589	square kilometer (km^2)

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ABSTRACT

Effects on streamflows and ground-water levels attributable to a proposed intermittent change in use and sites of withdrawal of 3,146 acre-feet of water from the Arikaree aquifer in central Platte County, Wyo., are assessed with a previously developed ground-water flow model. This water has been permitted for agricultural use by the State of Wyoming, and under the proposal would supplement, when needed, existing industrial surface- and ground-water supplies for the Laramie River Station of the Missouri Basin Power Project. Under a scenario wherein the supplemental industrial usage occurs in every tenth year commencing in 1980, the model predicts a cumulative streamflow-depletion rate in the Laramie and North Laramie Rivers of 7.7 cubic feet per second in the year 2020 compared to a rate of 6.9 cubic feet per second that is predicted if the intermittent industrial usage does not occur. Areas in which drawdowns relative to the simulated 1973 head configuration exceed 5, 10, 25, and 50 feet are predicted to be 107, 78, 38, and 2 square miles, respectively, in 2020 under the intermittent-usage scenario compared to corresponding areas of 104, 76, 36, and 2 square miles that are predicted if the intermittent industrial usage does not occur.

INTRODUCTION

The Missouri Basin Power Project involves the construction and operation of the Laramie River Station, a 1,500 megawatt, coal-fired electric generating facility located 5 miles northeast of Wheatland in central Platte County, Wyo. (fig. 1). The water requirements for this facility are to be met principally from surface-water storage in Grayrocks Reservoir on the Laramie River about 10 miles downstream from the Laramie River Station. Additional water is to be obtained from wells tapping an unconfined aquifer (informally designated the "Red" aquifer) and an underlying confined aquifer (informally designated the "Green" aquifer). The terms "Red" and "Green" were introduced by the firm of J. T. Banner and Associates to designate these unconfined and confined aquifers, respectively, without regard to stratigraphic position of the aquifer material. The unconfined "Red" aquifer is equivalent to the unconfined Arikaree aquifer as defined by Lines (1976) and Hoxie (1977) and as used in this report. In an order dated August 26, 1977, the Wyoming State Engineer permitted ground-water withdrawals for industrial use by the Missouri Basin Power Project of up to 750 acre-feet annually from the Arikaree aquifer and of up to 2,000 acre-feet annually from the "Green" aquifer. Two industrial wells have been completed in each the Arikaree and the "Green" aquifers at the sites shown in figure 2. The locations and mean pumping rates of these wells are listed in table 1. These wells are located in an area in which an additional 35 wells (fig. 2) have been permitted in the Arikaree aquifer to supply water for irrigating 5,754 acres of land.

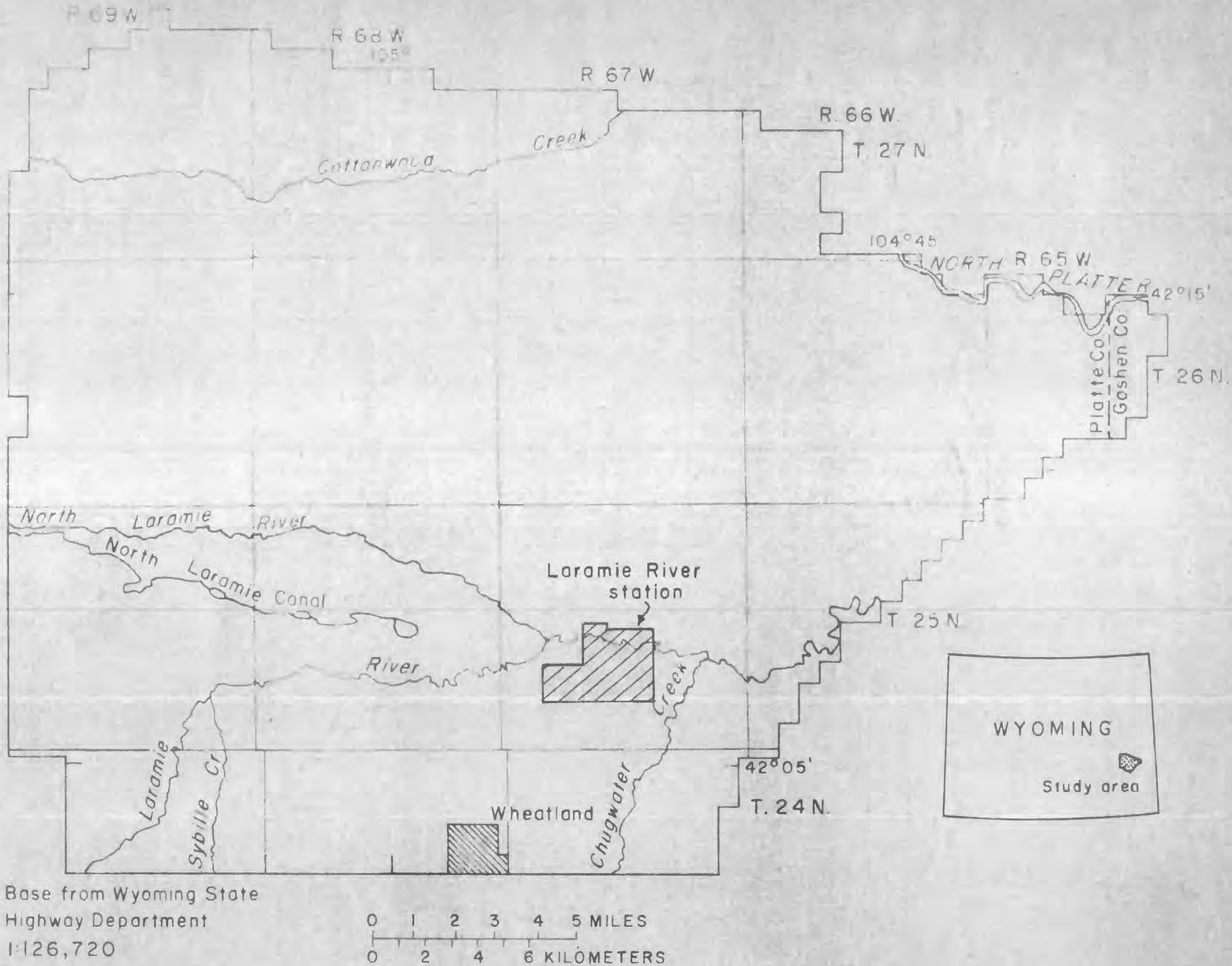

Figure 1.-- Area described in this report.

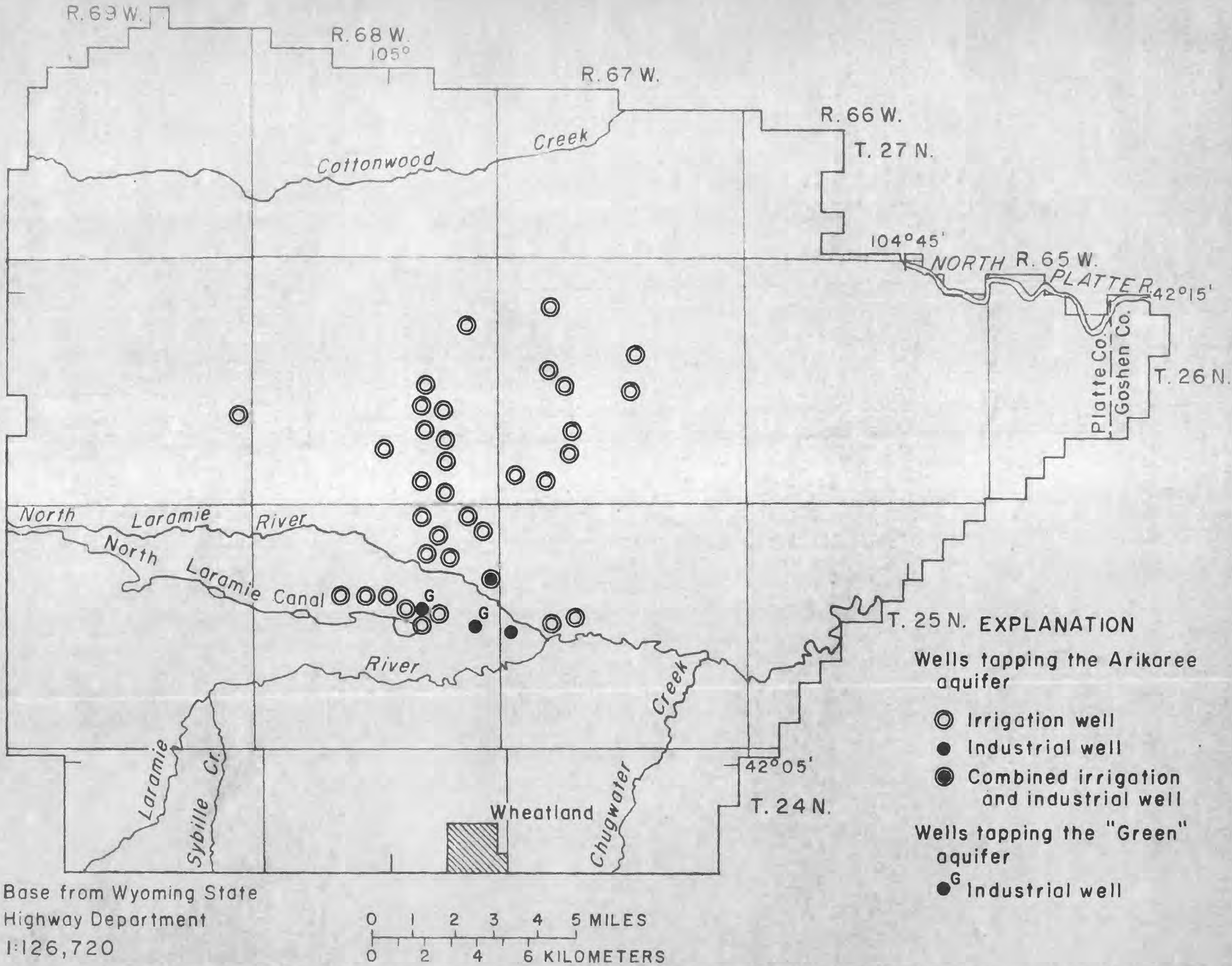

Figure 2.--Locations of existing irrigation wells and industrial wells that tap the Arikaree and "Green" aquifers.

Table 1.--Industrial wells tapping the Arikaree ("Red") and "Green" aquifers

Wyoming permit number	Location	Aquifer	Mean pumping rate (gal/min)
23653	SE¼, Sec.12, R.68W., T.25N	Arikaree	230
43369	NW¼, Sec.19, R.67W., T.25N	Arikaree	230
43368	SE¼, Sec.15, R.68W., T.25N	"Green"	150
17434	SW¼, Sec.13, R.68W., T.25N	"Green"	350

Operation studies of Grayrocks Reservoir indicate that the permitted industrial surface- and ground-water supplies may be inadequate to meet the demands of the Laramie River Station during periods of low flow in the Laramie River (Wester, 1979). Consequently the Wyoming State Engineer has been petitioned to permit the Missouri Basin Power Project intermittent industrial use of water from 14 irrigation wells (fig. 3) that tap the Arikaree aquifer. This supplemental usage by the Missouri Basin Power Project would apply over an entire irrigation season and would occur only when this additional suppy was deemed necessary for the operation of the Laramie River Station. During periods of industrial use this water would be withdrawn from the two existing industrial wells (table 1, fig. 2) in the Arikaree aquifer at a higher rate than is currently permitted and from two new wells to be completed in the Arikaree aquifer (fig. 3A). The locations and proposed pumping rates for these four industrial wells during periods when the Missouri Basin Power Project would exercise its optional industrial usage of the permitted agricultural water are listed in table 2. The maximum withdrawal of water from the Arikaree aquifer by these four wells during such periods would be 3,896 acre-feet annually. During these periods of industrial usage, the 14 irrigation wells shown as proposed for intermittent agricultural and industrial use in figure 3 would not be pumped.

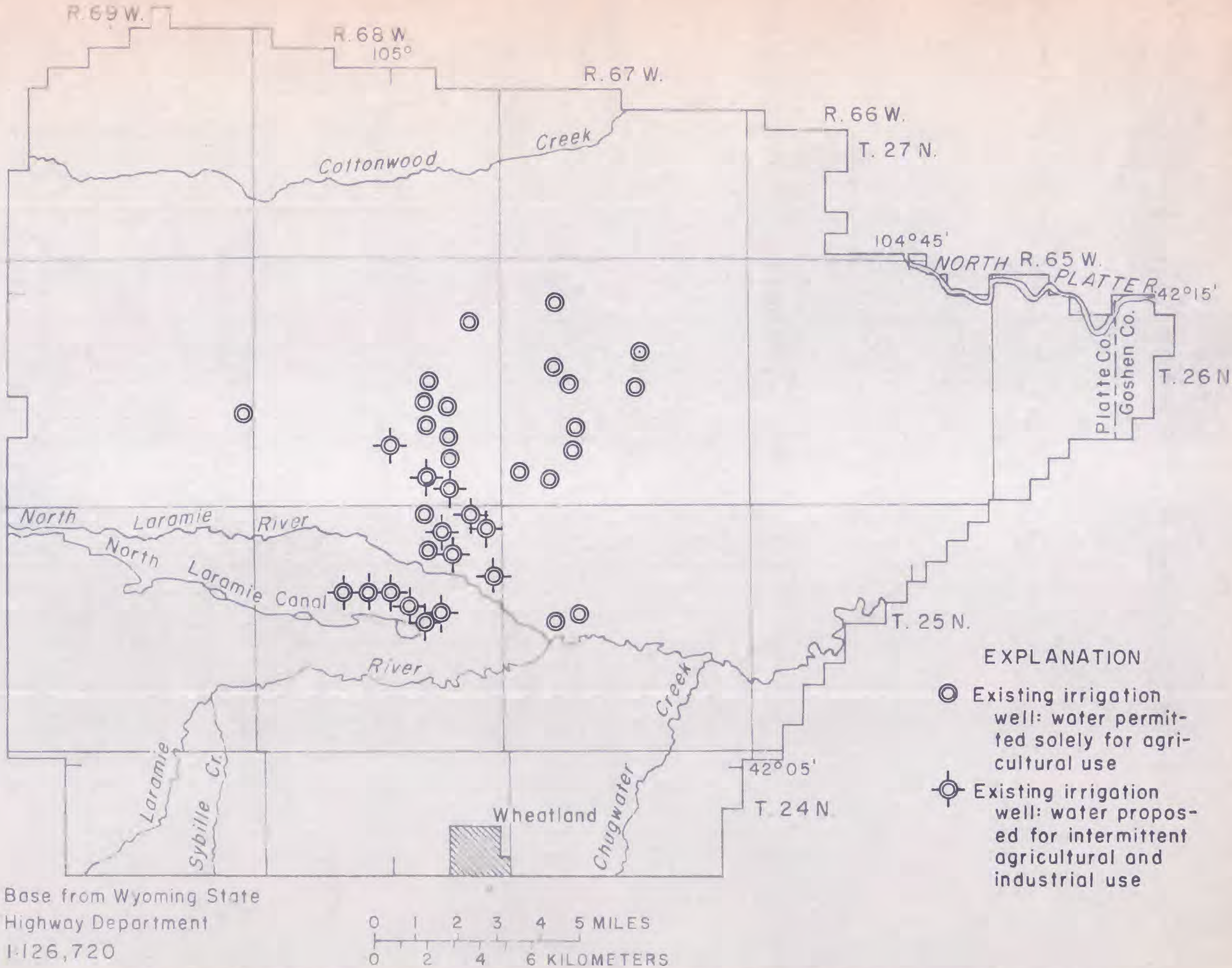

Figure 3.--Location of existing irrigation wells showing wells proposed for intermittent change in use.

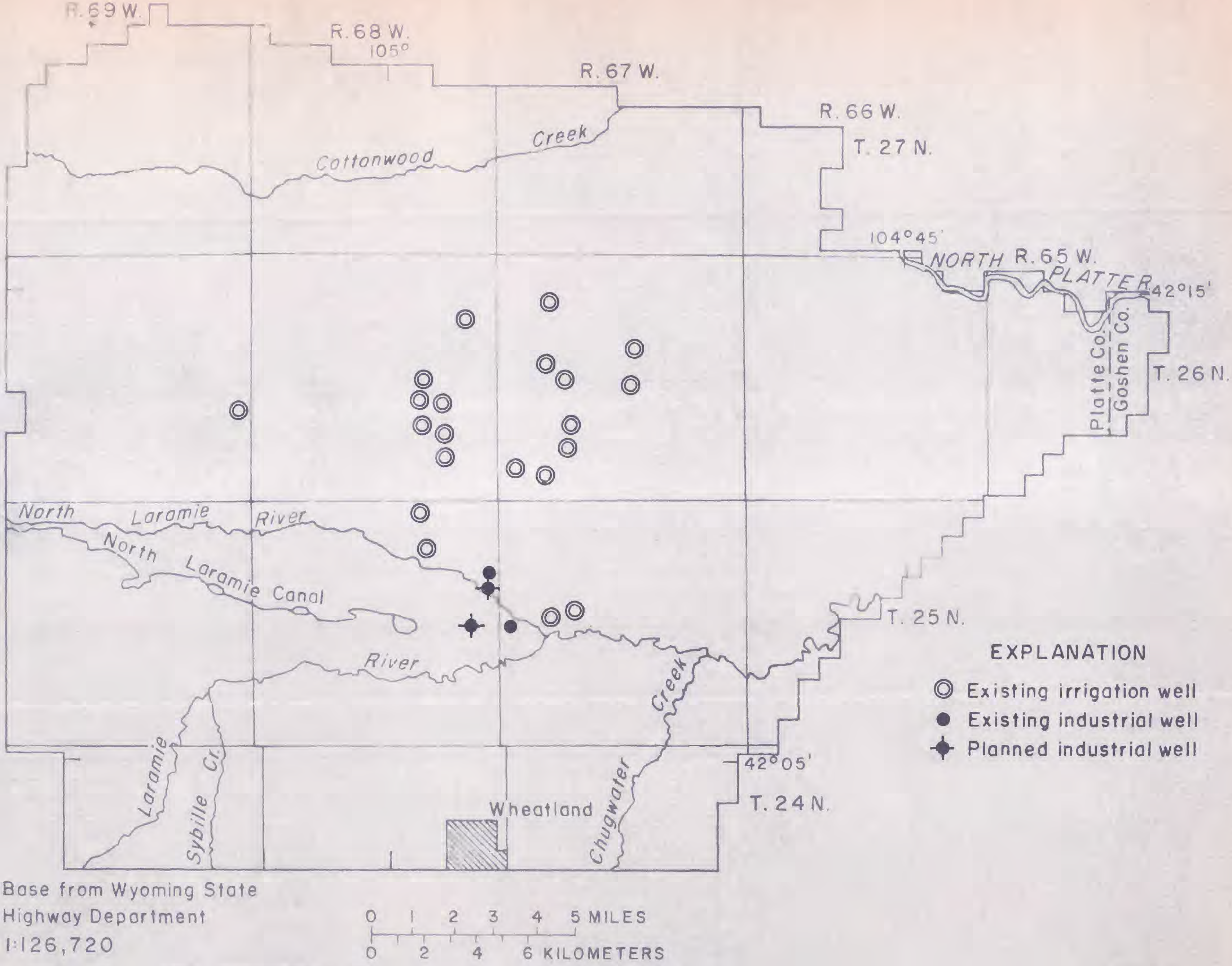

Figure 3A.--Location of wells to be pumped during periods of supplemental industrial usage.

Table 2.--Proposed intermittent withdrawals of water from industrial wells tapping the Arikaree aquifer

Existing wells

Wyoming permit number	Location	Proposed pumping rate [1] (gal/min)
23653	SE¼, sec.12, R.68W T.25N.	700
43369	NW¼, sec.19, R.67W T.25N.	1,100

Proposed New Wells

Location	Proposed pumping rate [1] (gal/min)
SW¼, sec.13, R.68W T.25N.	1,000
NE¼, sec.13, R.68W T.25N.	1,000

1/ Assumed for a pumping season of 232 days annually

The Wyoming State Engineer has requested that the U.S. Geological Survey apply the digital ground-water flow model that was developed as described by Hoxie (1977) to assess the effects on ground-water levels and streamflows attributable to the proposed intermittent change in use and points of withdrawal of water from the Arikaree aquifer. The present study was prepared in cooperation with the Wyoming State Engineer and is supplemental to the study described by Hoxie (1977).

HYDROGEOLOGIC SUMMARY

The study area (fig. 1) is underlain by a nonhomogeneous assemblage of predominatly clastic sedimentary rocks of middle to late Tertiary age. Portions of the Ogallala Formation of late Miocene age, the Arikaree Formation of early Miocene age, and the White River Group of Oligocene age constitute a virtually unconfined aquifer that is designated the Arikaree aquifer (Lines, 1976; Hoxie, 1977). The aquifer, whose base is defined generally by siltstone in the Brule Formation of the White River Group, ranges from 0 to almost 1,000 feet in saturated thickness over the study area. The hydraulic properties of the aquifer are poorly known; the available data have been summarized by Weeks (1964), Lines (1976), and Hoxie (1977).

Exploratory drilling by the firm of J. T. Banner and Associates indicates that a confined aquifer zone, informally designated the "Green" aquifer, underlies the Arikaree aquifer in the vicinity of the industrial wells listed in table 1. The Missouri Basin Power Project is permitted to withdraw up to 2,000 acre-feet of water annually from the "Green" aquifer and is presently withdrawing about 800 acre-feet from it annually (table 1). The "Green" aquifer is not included in the present study because its nature, hydrologic properties, and regional extent are poorly known; because the quantity of water being withdrawn from it is small compared to that being withdrawn from the Arikaree aquifer; and because there is no evidence that it is in hydraulic connection with the Arikaree aquifer. At the site of industrial well permit number 17434 (table 1), the "Green" aquifer is separated from the Arikaree aquifer by a confining bed consisting of about 70 feet of predominantly clayey material (Wester, 1979). Pumping of this well at the rate of 500 gal/min for 30 days resulted in a water-level decline in the well from 173 ft above land surface to 830 ft below land surface. This pumping produced no observed effects in a piezometer located 30 ft from the pumping well and open to the Arikaree aquifer at point about 270 feet above the "Green" aquifer (Wester, 1979).

TRANSIENT SIMULATIONS

The U.S. Geological Survey, in cooperation with the Wyoming State Engineer, developed a digital ground-water flow model for the Arikaree aquifer within the 400-square-mile study area shown in figure 1. The model mathematically simulates the flow of ground water through the aquifer system by employing finite-difference numerical techniques to solve the equation of ground-water flow in a two-dimensional, horizontal-flow approximation (Trescott and others, 1976). The model is described by Hoxie (1977) and is based on hydrogeologic field data collected by G. C. Lines in 1973 and 1974 (Lines, 1976) and E. P. Weeks in 1959 and 1960 (Weeks, 1964). The model has been used under various pumping scenarios to predict the effects of ground-water pumpage for agriculture and industry on ground-water levels and streamflows within the study area. The results of these simulations are described in reports by Hoxie (1977 and 1979).

To initiate the present study the model developed by Hoxie (1977) was brought forward in time from its initial state (1973) to the end of the 1979 irrigation season. During this six-year period projected mean annual consumptive withdrawals of water were imposed on the model from the irrigation wells shown in figure 2. By consumptive withdrawal is here meant the total quantity of water pumped reduced by any return flow to the aquifer. Where lands were irrigated solely by ground water, it was estimated, following Lines (1976), that the average annual consumptive withdrawal for irrigation was 1.4 acre-feet of water per acre of irrigated land. Where lands also had valid surface-water rights, the average annual consumptive withdrawal of ground water for irrigation was estimated to be 0.7 acre-feet per acre of irrigated land. The total acreage estimated to be irrigated by ground water from the Arikaree aquifer during each of the years 1974 through 1979 is listed in table 3. No industrial withdrawals of water from the Arikaree aquifer by the Missouri Basin Power Project where included in this simulation.

The resulting drawdown distribution that is predicted to occur at the end of the 1979 irrigation season is shown in figure 4. The drawdowns were computed relative to the head distribution that was calculated as described by Hoxie (1977) for the year 1973 under an assumption of steady-state flow within the aquifer. This calculated head distribution is virtually coincident with the water-table configuration mapped in September, 1973 (Lines, 1976). In addition a cumulative streamflow depletion of 2.8 ft^3/s is predicted to occur in the Laramie and North Laramie Rivers at the end of the 1979 irrigation season. This depletion results from the capture by the irrigation wells of ground water that was estimated to discharge to these streams under assumed steady-state flow in the aquifer in 1973. Because the North Laramie River is tributary to the Laramie River and because there are no major diversions from either stream within the reaches that are predicted to be affected by the subject pumping, the cumulative streamflow depletions summed over both streams are considered in this report. These cumulative rates are regarded as best representing the overall effect of pumping on these streams.

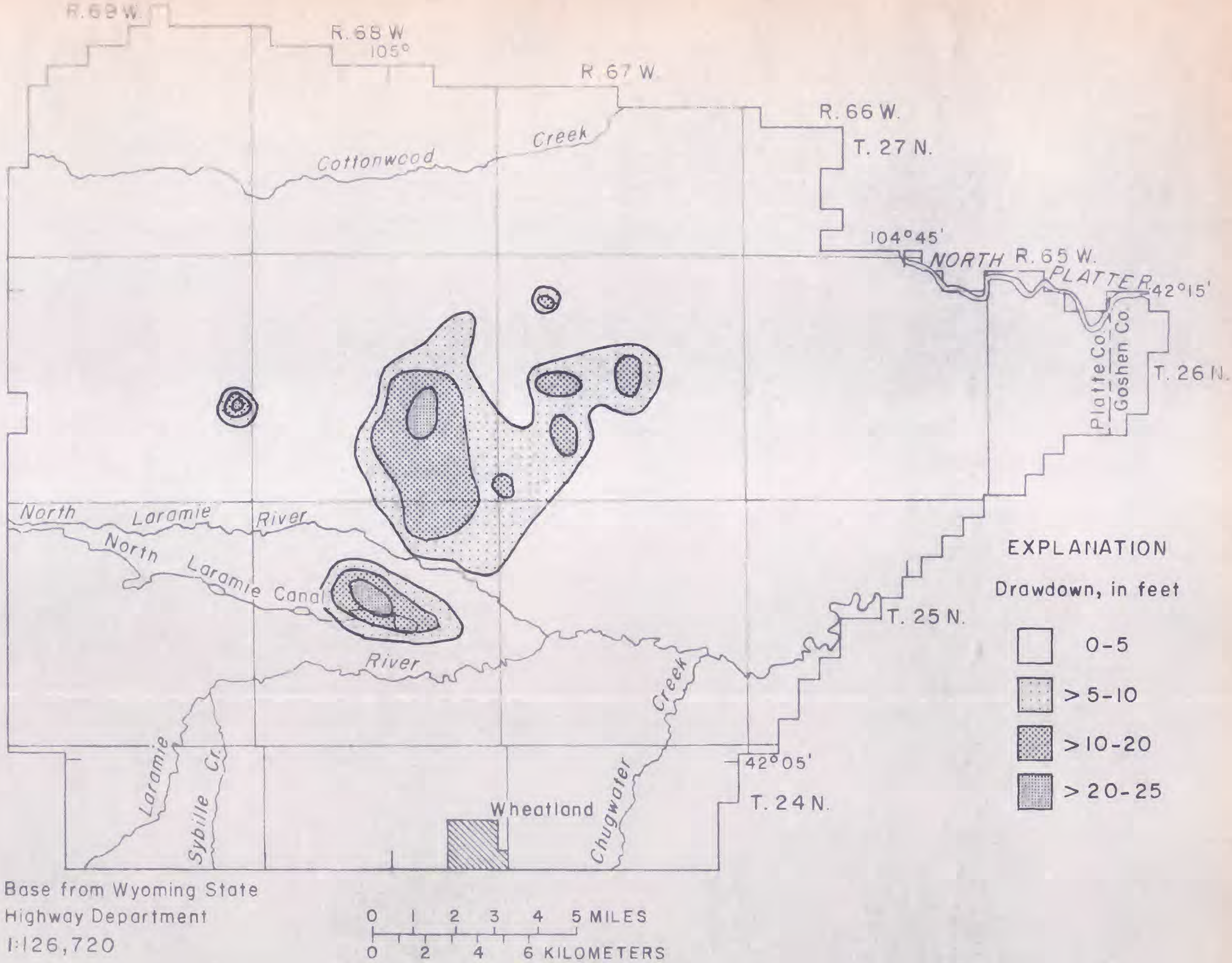

Figure 4.--Simulated drawdowns between 1973 and 1979.

Table 3.--Estimated acreage and mean annual consumptive withdrawals for lands irrigated by ground water from the Arikaree aquifer during the period 1974-1979

Year	Area (Acres)	Consumptive withdrawal (acre-feet)
1974	2,461	3,445
1975	2,655	3,717
1976	3,484	4,877
1977-1979	5,202	7,283

Two scenarios, here designated the subject and null-case scenarios, were imposed on the model in order to assess the effects that may be caused by intermittent change in use and points of withdrawal of water from the Arikaree aquifer. The subject scenario simulates a hypothetical intermittent change defined as follows (Stockdale, 1979): Commencing in 1980 and repeating in each tenth year thereafter through 2020, no water was withdrawn from the 14 irrigation wells shown as proposed intermittent irrigation wells in figure 3, and a total of 3,896 acre-feet of water for use by the Missouri Basin Power Project was assumed to be withdrawn from the four industrial wells shown in figure 3A. The rates of withdrawal from the individual industrial wells were as listed in table 2. The remaining 21 irrigation wells shown in figure 3A were assumed to consumptively withdraw water at their respective mean annual rates as previously defined. During each intervening 9-year period (1981-1989, 1991-1999, 2001-2009, and 2011-2019), all of the 35 irrigation wells shown in figures 2 and 3 were assumed to consumptively withdraw water for irrigation at their respective mean annual rates. The industrial withdrawals by the Missouri Basin Power Project were set equal to the currently permitted rate of 750 acre-feet annually from the two existing Arikaree industrial wells shown in figure 2.

The null-case scenario continued the estimated 1979 agricultural pumpage (table 3) through 2020 and included the permitted industrial pumpage. Specifically, the 35 irrigation wells shown in figures 2 and 3 were assumed to consumptively withdraw a total of 7,283 acre-feet of water annually at their respective mean annual pumping rates. The two existing Arikaree industrial wells (figures 2, table 1) were assumed to withdraw water at the cumulative rate of 750 acre-feet annually.

The drawdown distributions that are predicted to occur under the subject and null-case scenarios at the end of the 1980, 1990, 2000, 2010, and 2020 pumping seasons are shown in figures 5 through 14 at the end of this report. Each transient simulation yields a computer-printed numerical array listing the drawdown predicted to occur at the center (node) of each cell in the finite-difference grid. These drawdowns are calculated with respect to the head distribution computed under assumed steady-state flow conditions for the year 1973. Figures 5 through 14 were hand-contoured from the numerical drawdown data. In order to facilitate a comparison between the two scenarios, the results of the subject scenario are shown in figures 5, 7, 9, 11, and 13, and the corresponding results for the null-case scenario are shown on facing pages in figures 6, 8, 10, 12, and 14. Cumulative streamflow depletions that are predicted to occur in the Laramie and North Laramie Rivers under these scenarios are listed in table 4. The Laramie and North Laramie Rivers are the only streams in the study area (fig. 1) whose streamflows are predicted to be affected by the subject pumpage.

Table 4.--Predicted cumulative streamflow depletion rates in the Laramie and North Laramie Rivers

Year	Streamflow depletion rate (ft^3/s) Subject scenario	Null-case scenario
1980	4.6	3.4
1990	6.3	5.4
2000	6.9	6.2
2010	7.3	6.6
2020	7.7	6.9

Because there is no appreciable difference between the total quantity of water withdrawn from the Arikaree aquifer under the subject and the null-case scenarios (a difference occurs only during each of the years 1980, 1990, 2000, 2010, and 2020 and is then only 10 acre-feet annually), the predicted differences between these scenarios arise solely from the change in the points of withdrawal. The major difference between the results of the scenarios occurs in the predicted streamflow depletion rates in the Laramie and North Laramie Rivers. The cumulative streamflow depletion rates in these streams (table 4) are predicted to increase by 35, 17, 11, 11, and 12 percent over the null-case scenario in the years 1980, 1990, 2000, 2010, and 2020, respectively. During the intervening periods, 1981-1989, 1991-1999, 2001-2009, and 2011-2019, no difference in streamflow depletion rates is predicted between the subject and null-case scenarios. The greater streamflow depletion that is predicted to occur under the subject scenario arises because of the proximity of the existing and proposed new industrial wells to the Laramie and North Laramie Rivers (fig. 3).

By the year 2020 approximately 60 and 70 percent of the water pumped from the Arikaree aquifer under the null-case and subject scenarios, respectively, are predicted to be captured ground-water discharge to the Laramie and North Laramie Rivers. The remainder of the pumpage is predicted to be withdrawn from water held in storage within the aquifer. As pumping continues, the proportion of the pumpage derived from streamflow, both from captured ground-water discharge to the streams and from direct infiltration of surface flow into the aquifer, will increase. Ultimately all of the pumpage will be derived from streamflow at which time the net streamflow depletion will equal the net pumpage. When this occurs a system of virtual steady-state flow will become established within the aquifer. In this circumstance the maximum cumulative streamflow depletion from the Laramie and North Laramie Rivers would be about 11 ft^3/sec under either the subject or null-case scenarios.

Figure 5 through 14 indicate that the greatest difference in the areal distribution of drawdown between the subject and null-case scenarios would occur in the vicinity of concentrated pumpage by the industrial wells (fig. 3). By the year 2020 areas in which drawdowns exceed 5, 10, 25, and 50 ft are predicted to be 107, 78, 38, and 2 mi^2, respectively, under the subject scenario compared to corresponding areas of 104, 76, 36, and 2 mi^2 predicted under the null-case scenario. These net areas were calculated by summing over the areas of the finite-difference cells within which the drawdowns were predicted to exceed 5, 10, 25, and 50 ft.

The results predicted under the subject and null-case scenarios are indicative of differences to be expected if the proposed intermittent change in use and points of withdrawal does or does not occur. Care must be taken, however, not to attach more significance to the predicted streamflow depletion rates and drawdowns than is warranted by the precision achievable with the model. The overall precision with which the model simulates the response of the aquifer system to applied stress, such as pumpage, has yet to be assessed. In predicting the future behavior of the system, the model mathematically extrapolates from an assumed known state to projected future states. The present model is based on ground-water-level and stream-discharge measurements made in 1973 and 1974 (Lines, 1976) and in 1959 and 1960 (Weeks, 1964) under the assumption that these data pertain to a then-extant system of steady-state flow within the aquifer. To the extent that this assumption is true, the steady-state model described by Hoxie (1977) constitutes an appropriate initial state on which to impose the transient simulations. To insure that these simulations adequately replicate the actual behavior of the aquifer system, it is required that observed and predicted response of the system to a known stress, such as pumpage, be compared. This requires that pumpage, ground-water levels, and streamflows be monitored over a period of time during which the effects caused by pumping exceed those induced by natural fluctuations in the rates of recharge to and discharge from the aquifer system. It follows, for example, that if the present model adequately simulates the flow system within the Arikaree aquifer, the drawdown distribution shown in figure 4 and the streamflow depletions predicted for the end of the 1979 irrigation season should represent the present (1979) verifiable situation within the aquifer system.

Another restriction on the precision of the model is its ability to accurately resolve transient effects at prescribed distances from the cause of these effects. The major difference between the subject and null-case scenarios involves the change in points of withdrawal of ground water and not the quantity of water withdrawn. In order that the model resolve differences in effects produced solely by the relocation of pumping wells, it is required that the displacements of the wells as well as the distance from the wells to the sites at which effects are to be evaluated be large compared to the mean spacing between nodes in the finite-difference grid. In the present study this spacing is 2640 ft and is the minimum distance over which effects can be resolved by the model.

As an example of the problem introduced by the spatial resolution of the model, a third scenario was imposed on the model in which the proposed intermittent new industrial wells (table 2, fig. 3) were relocated to SW¼ sec.1 and NE¼ sec.2, T.25 N., and R.68 W. The results of this scenario were virtually identical to those of the original subject scenario. The model is, thus, unable to resolve regional effects attributable to changes in the locations of these industrial wells over distances on the order of 2 miles.

The problem of spatial resolution can become most severe where pumping wells near streams are seen by the model as being immediately adjacent to the streams. The model may then predict a greater short-term impact of these wells on streamflow than may be realized in nature. In the present situation, the pumpage by all of the wells within the study area, whether irrigation or industrial, must ultimately obtain their water at the expense of either ground-water discharge to or surface-water flow in the streams. Consequently the predicted long-term net streamflow depletion rates in the Laramie and North Laramie Rivers are better indicators of the overall impact of pumpage on these streams than are the predicted rates for the individual streams or along particular reaches of these streams.

The greatest source of uncertainty in predicting rates of streamflow depletion probably arises from the unknown values of streambed hydraulic conductivity for the streams within the study area (fig. 1). The values used in the present study are based on an empirical determination of streambed hydraulic conductivity along a reach of the Arkansas River in Colorado by Moore and Jenkins (1966). These assumed values are consistent with measured gains and losses of water to and from the streams in the study area under assumed steady-state flow conditions as discussed by Hoxie (1977). Hoxie (1977) showed, however, that a tenfold change in the values of the streambed hydraulic conductivities yield acceptable steady-state model results. Consequently, the values of streambed hydraulic conductivity used in the model must be regarded as uncertain by at least a factor of 10. If the values employed underestimate the true values, then the imposed pumpage in the transient simulations would tend to produce larger streamflow depletions than those predicted in table 4. On the other hand, if the values are overestimated, the impact on the streams would be decreased but there would be greater drawdowns as a result of the larger quantity of water required from aquifer storage to supply the pumping wells. It must be emphasized that until the model is refined and verified by comparing predicted and observed effects under transient conditions, its predictions must be assumed to be uncertain by yet-undetermined limits of error.

SUMMARY AND CONCLUSIONS

A digital ground-water flow model developed by Hoxie (1977) was used to predict the effects on ground-water levels and streamflows that may be caused by a proposed intermittent change in use and points of withdrawal of 3,146 acre-feet of water from the Arikaree aquifer in central Platte County, Wyo. The water is presently permitted by the State of Wyoming for agricultural use and would supplement permitted surface-water and ground-water supplies for the Missoure Basin Power Project during periods of low flow in the Laramie River. If the intermittent usage were to commence in 1980 and repeat in each tenth year thereafter through 2020, the model results predict that the cumulative streamflow-depletion rate in the Laramie and North Laramie Rivers will be 7.7 ft^3/sec in 2020 compared to 6.9 ft^3/sec that is predicted if the intermittent usage does not occur. In addition areas in which drawdowns, referred to the 1973 head configuration, exceed 5, 10, 25, and 50 ft are predicted to be 107, 78, 38, and 2 mi^2, respectively, in 2020 compared to areas of 104, 76, 36, and 2 mi^2 that are predicted if the intermittent usage does not occur.

The quantitative signifigance of these results depends on the precision with which the model simulates the actual response of the aquifer to imposed stresses, such as pumping. Because field data are lacking by which to assess this precision, these results must be regarded as subject to yet-undetermined limits of error.

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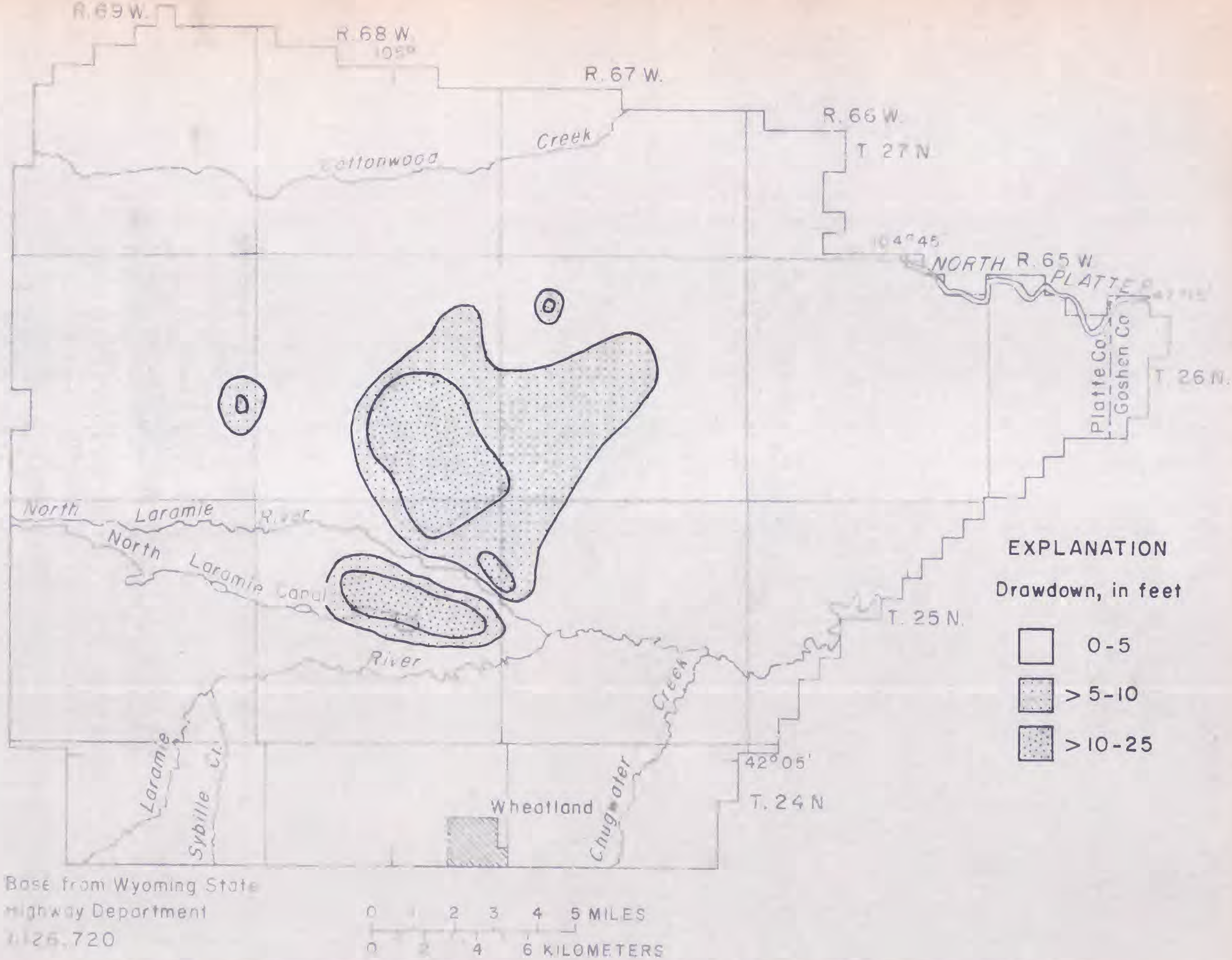

Figure 5.--Simulated drawdowns between 1973 and 1980 under the subject scenario.

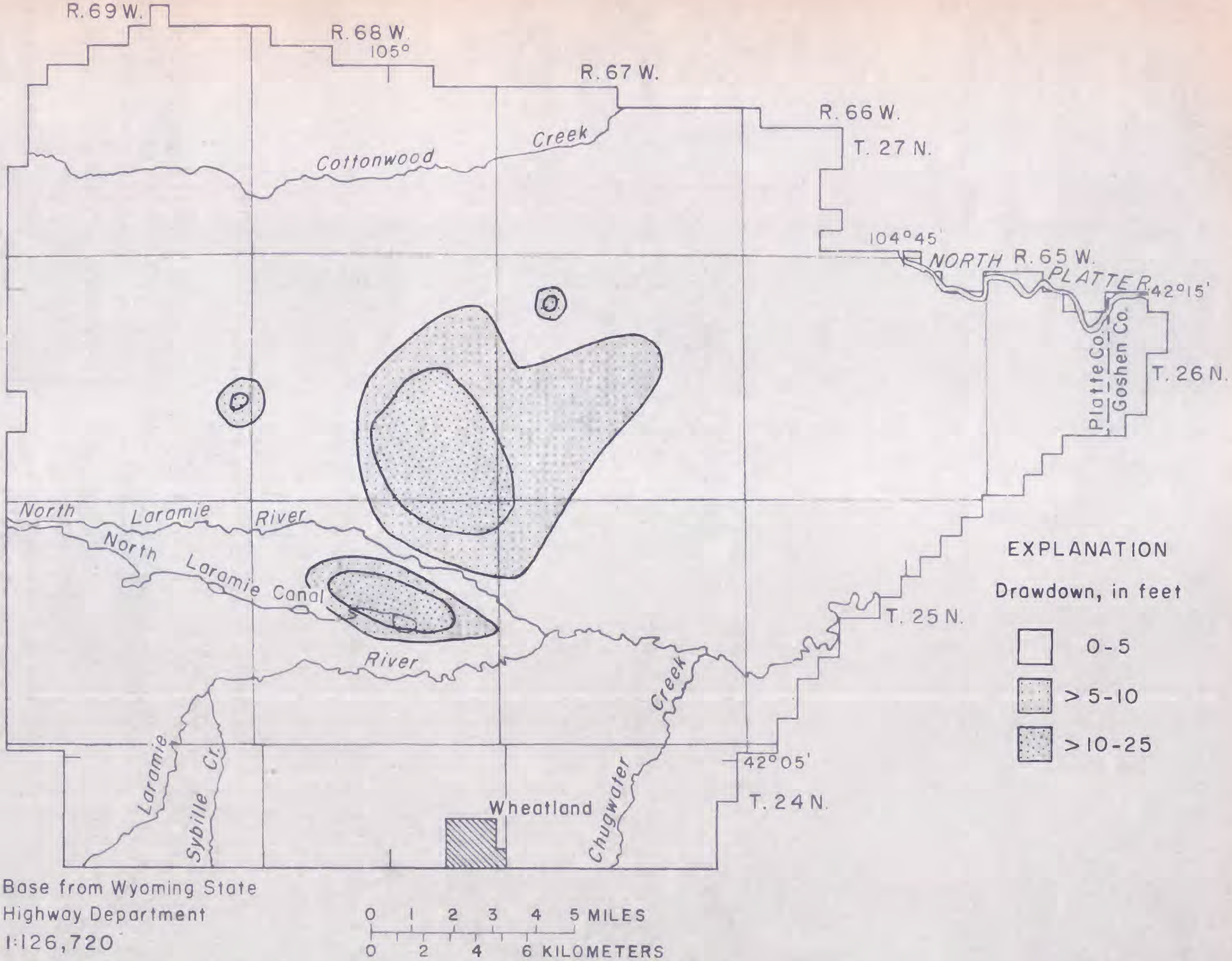

Figure 6.--Simulated drawdowns between 1973 and 1980 under the null-case scenario.

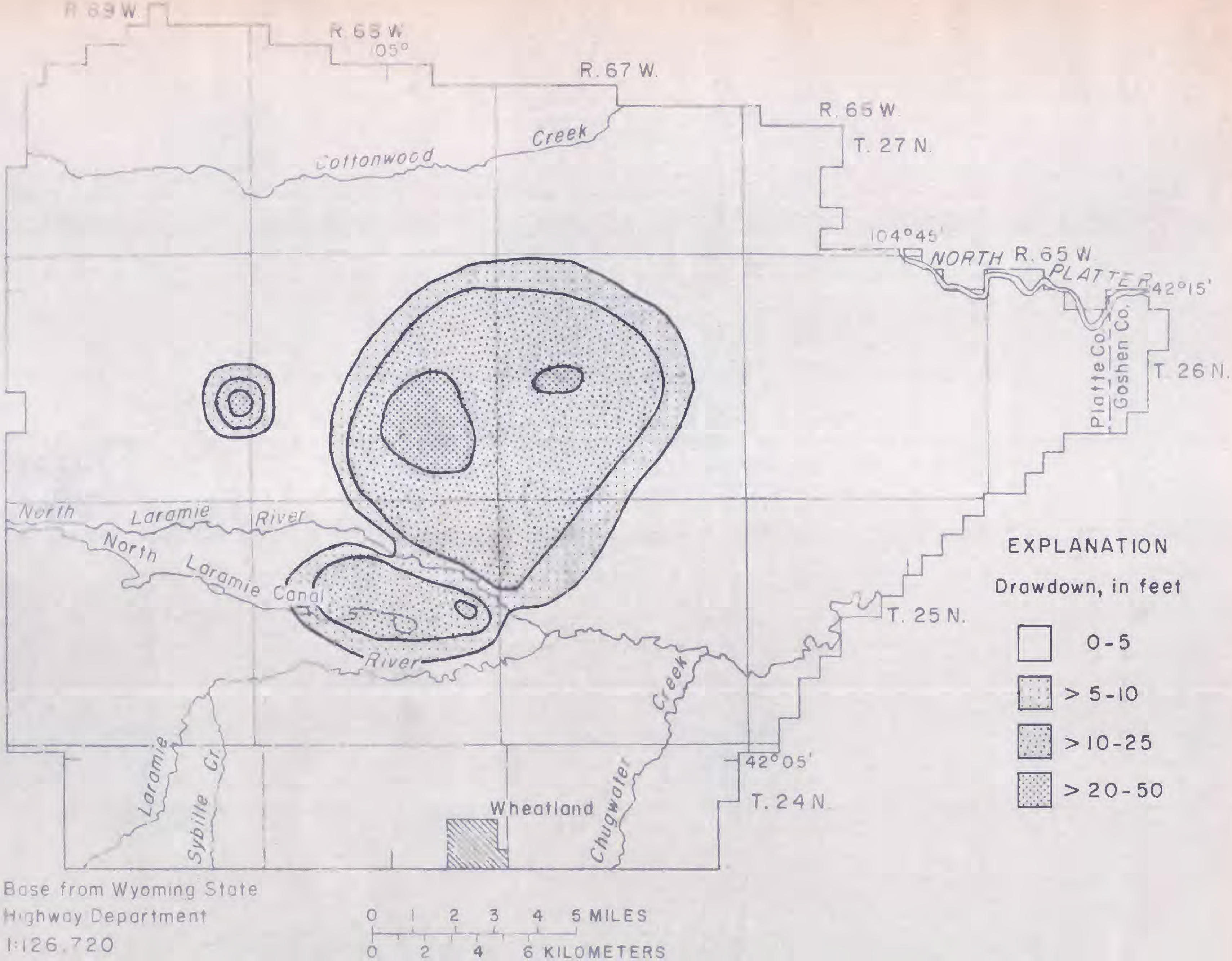

Figure 7.--Simulated drawdowns between 1973 and 1990 under the subject scenario.

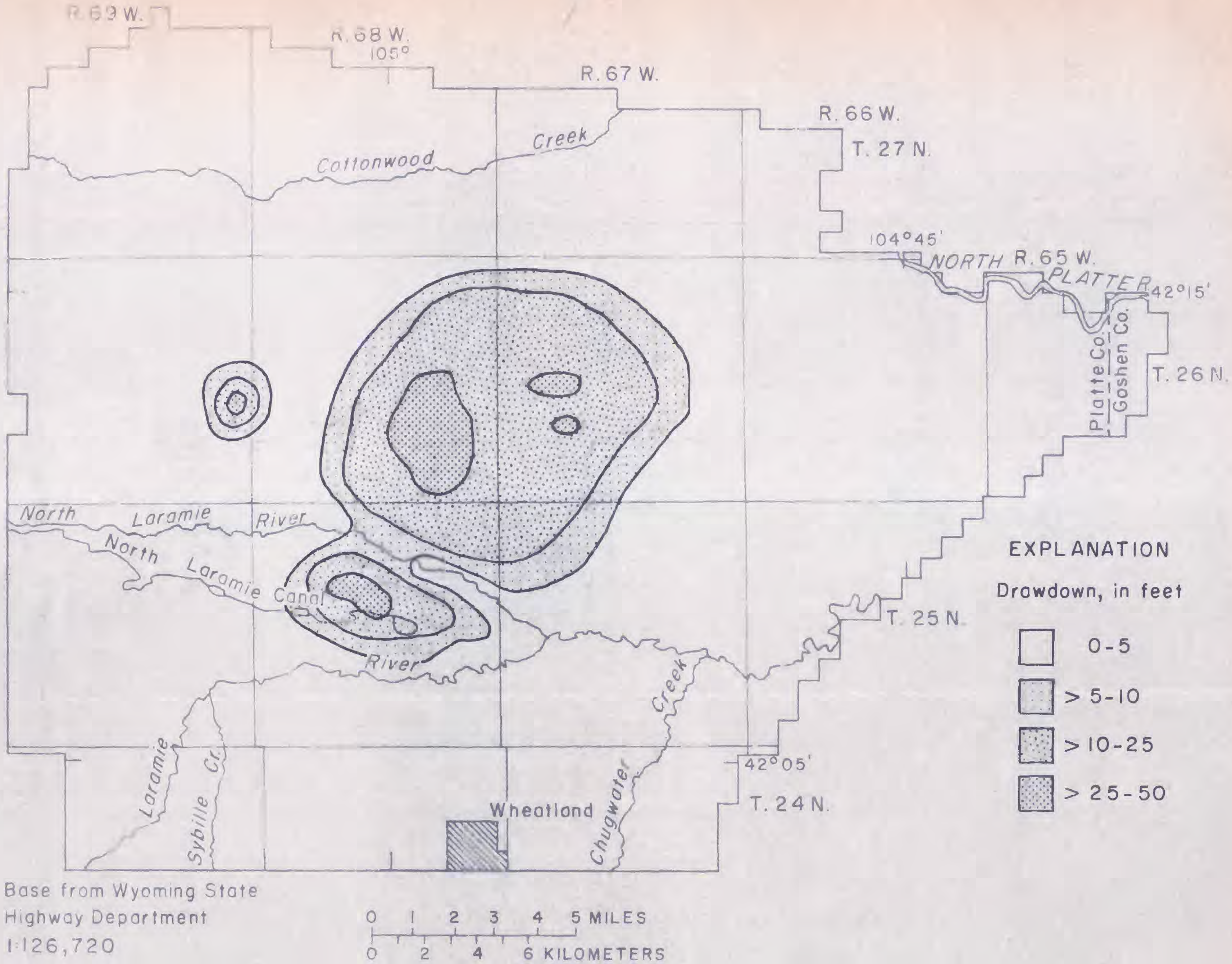

Figure 8.--Simulated drawdowns between 1973 and 1990 under the null-case scenario.

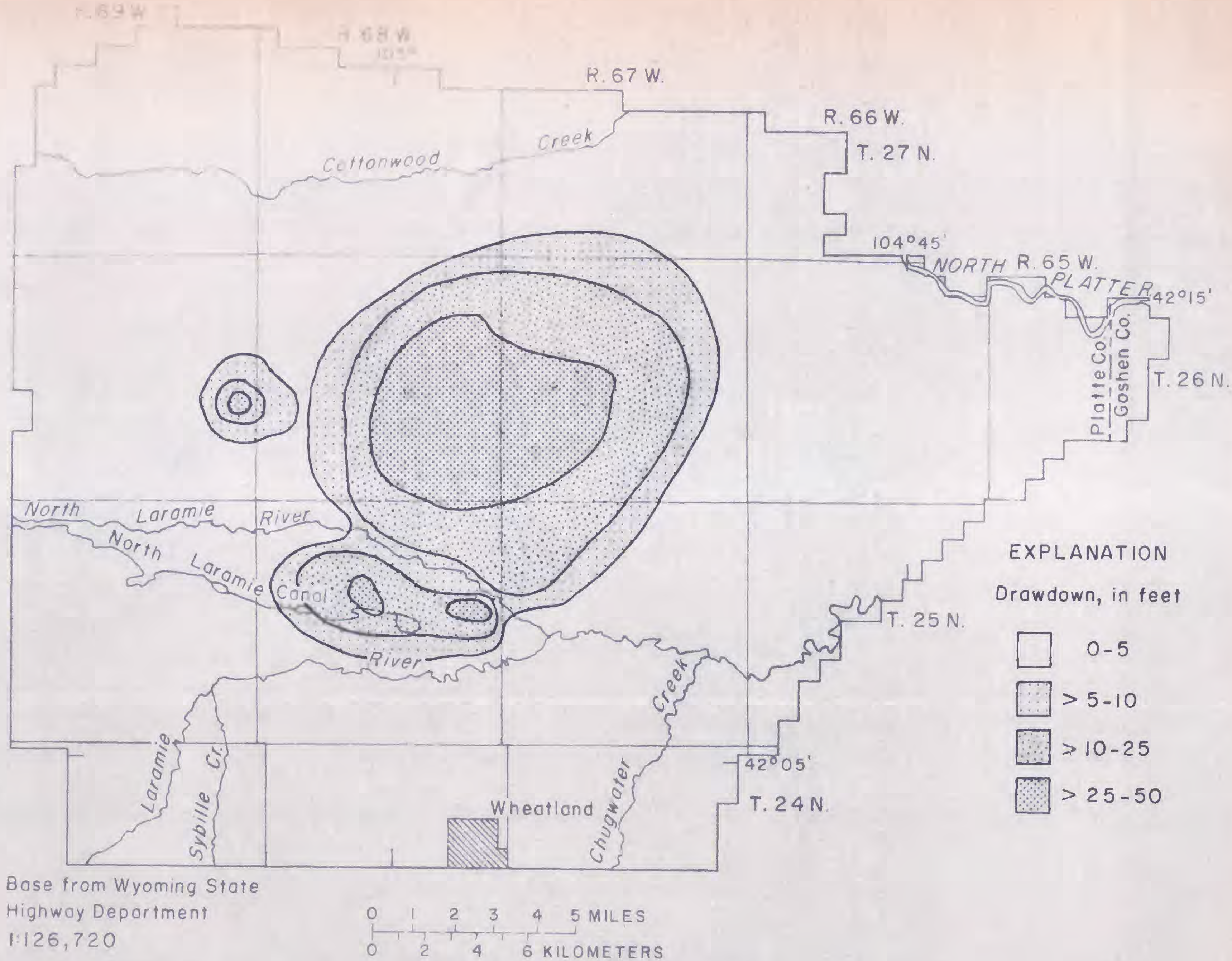

Figure 9.--Simulated drawdowns between 1973 and 2000 under the subject scenario.

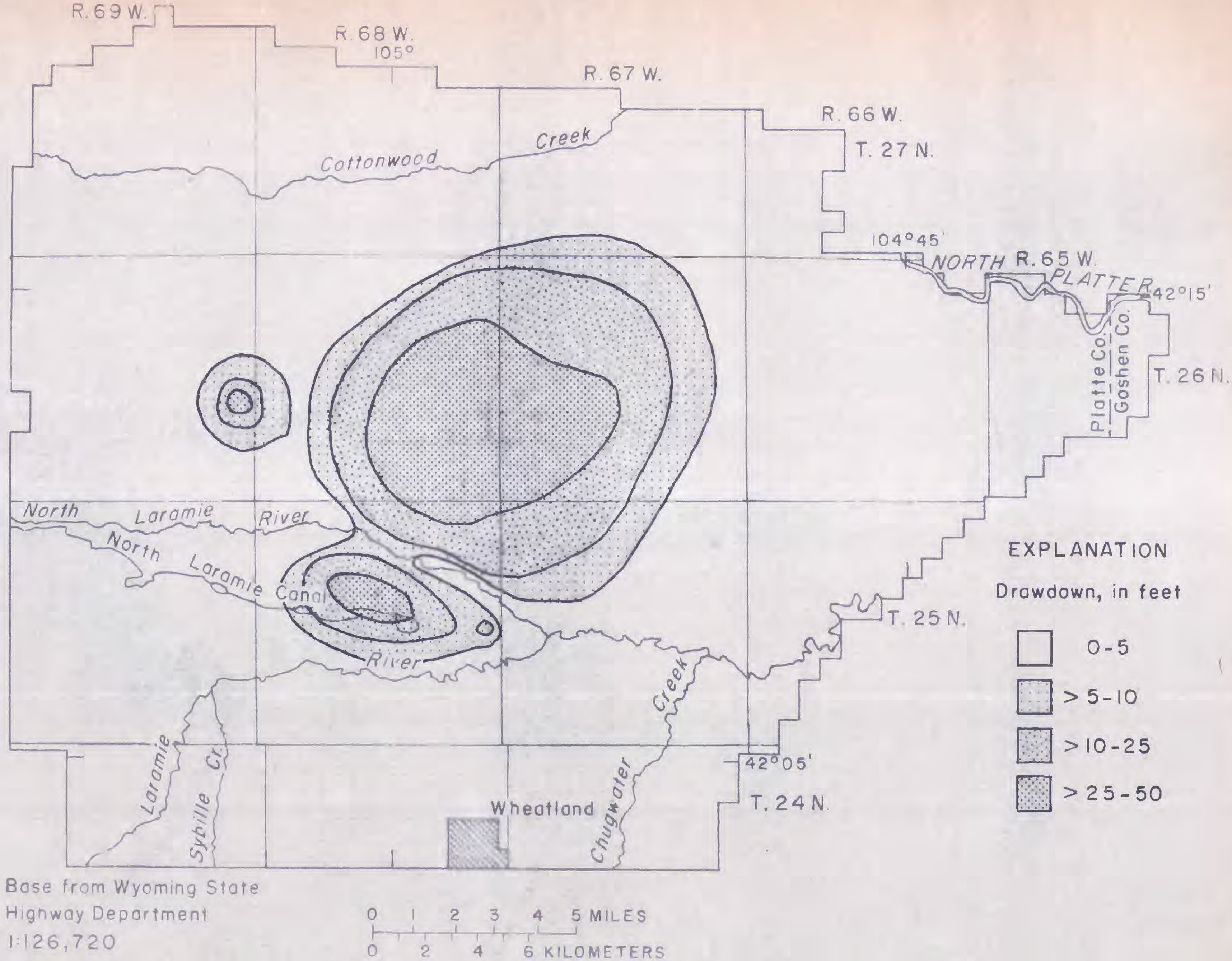

Figure 10.--Simulated drawdowns between 1973 and 2000 under the null-case scenario.

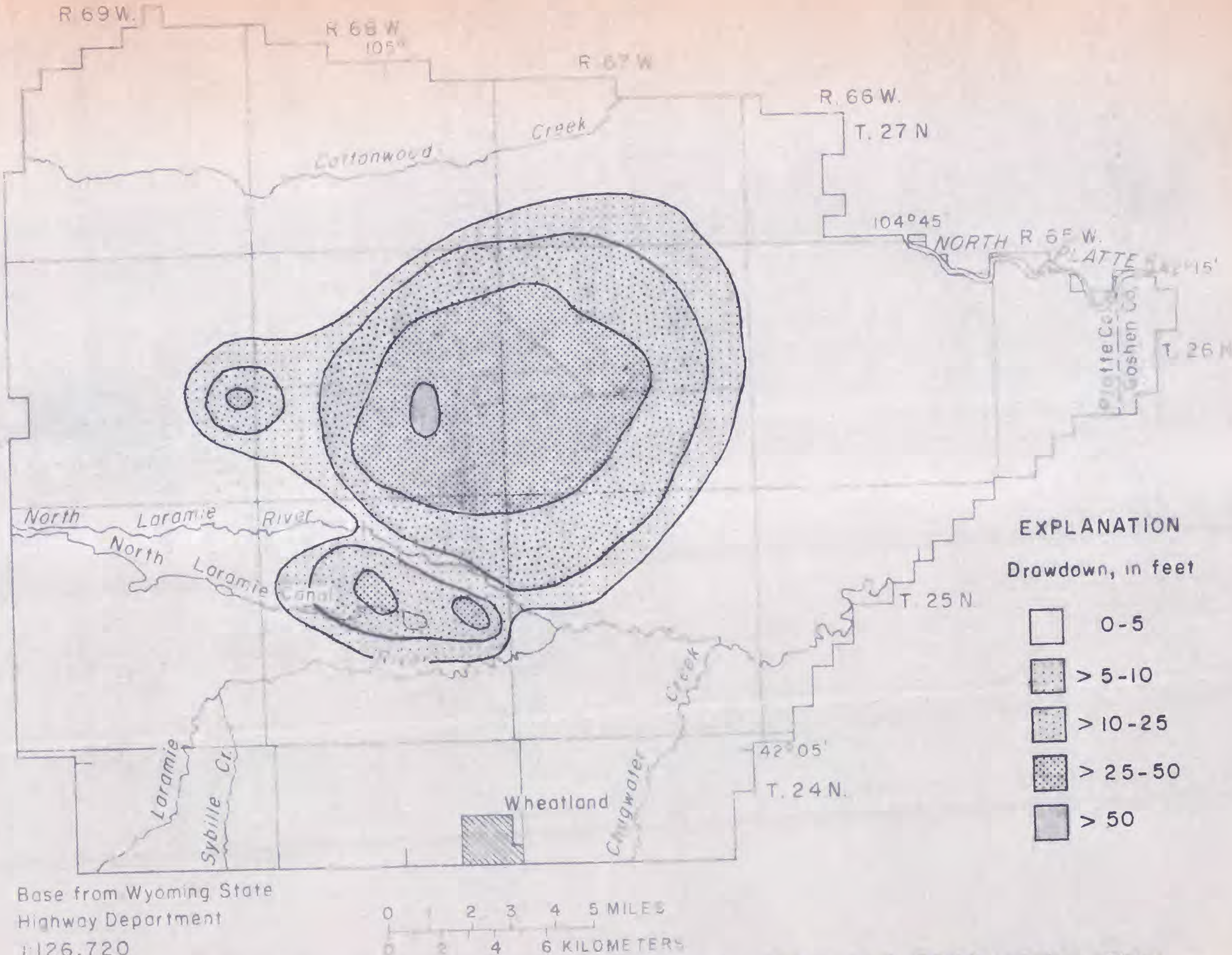

Figure 11.--Simulated drawdowns between 1973 and 2010 under the subject scenario.

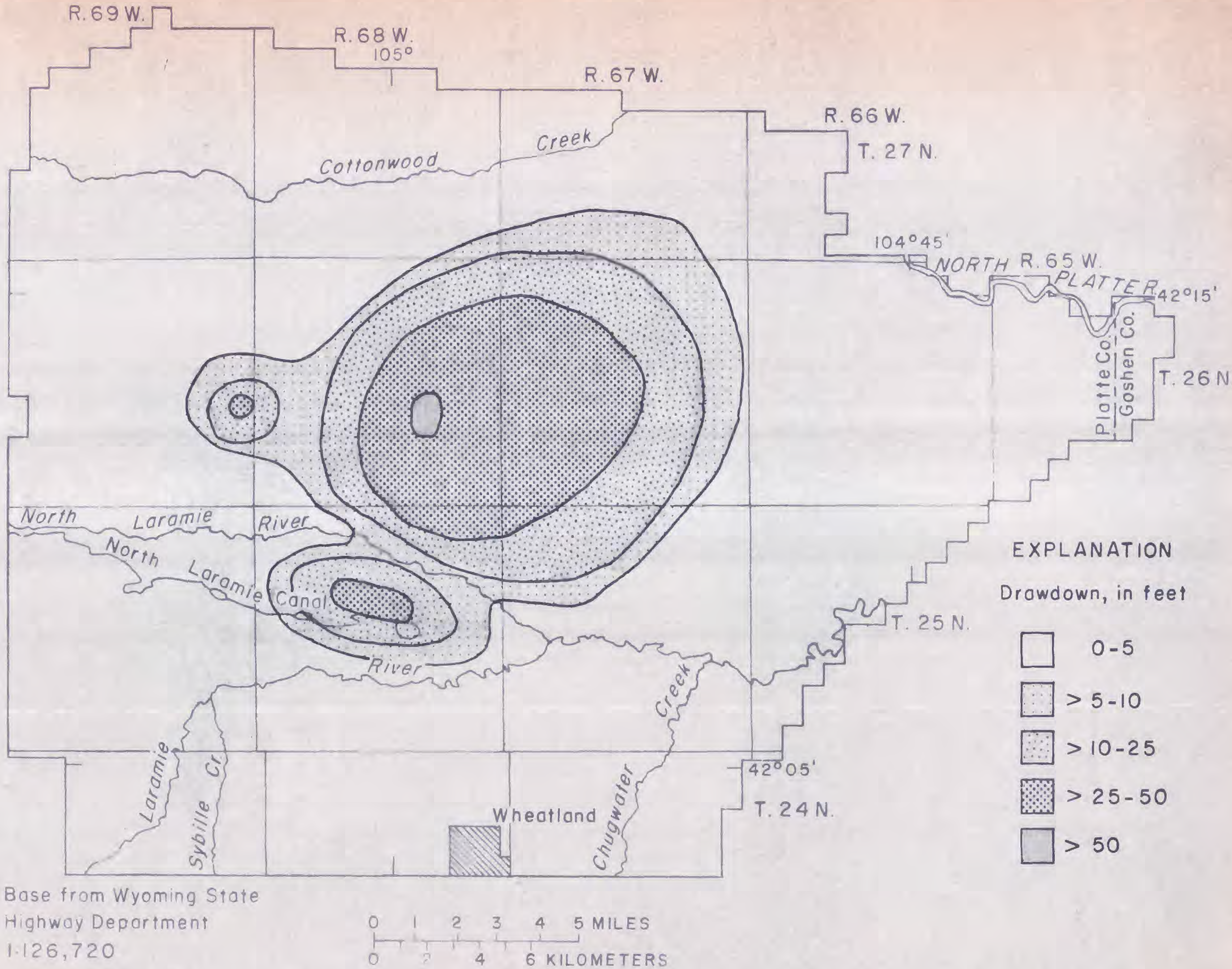

Figure 12.--Simulated drawdowns between 1973 and 2010 under the null-case scenario.

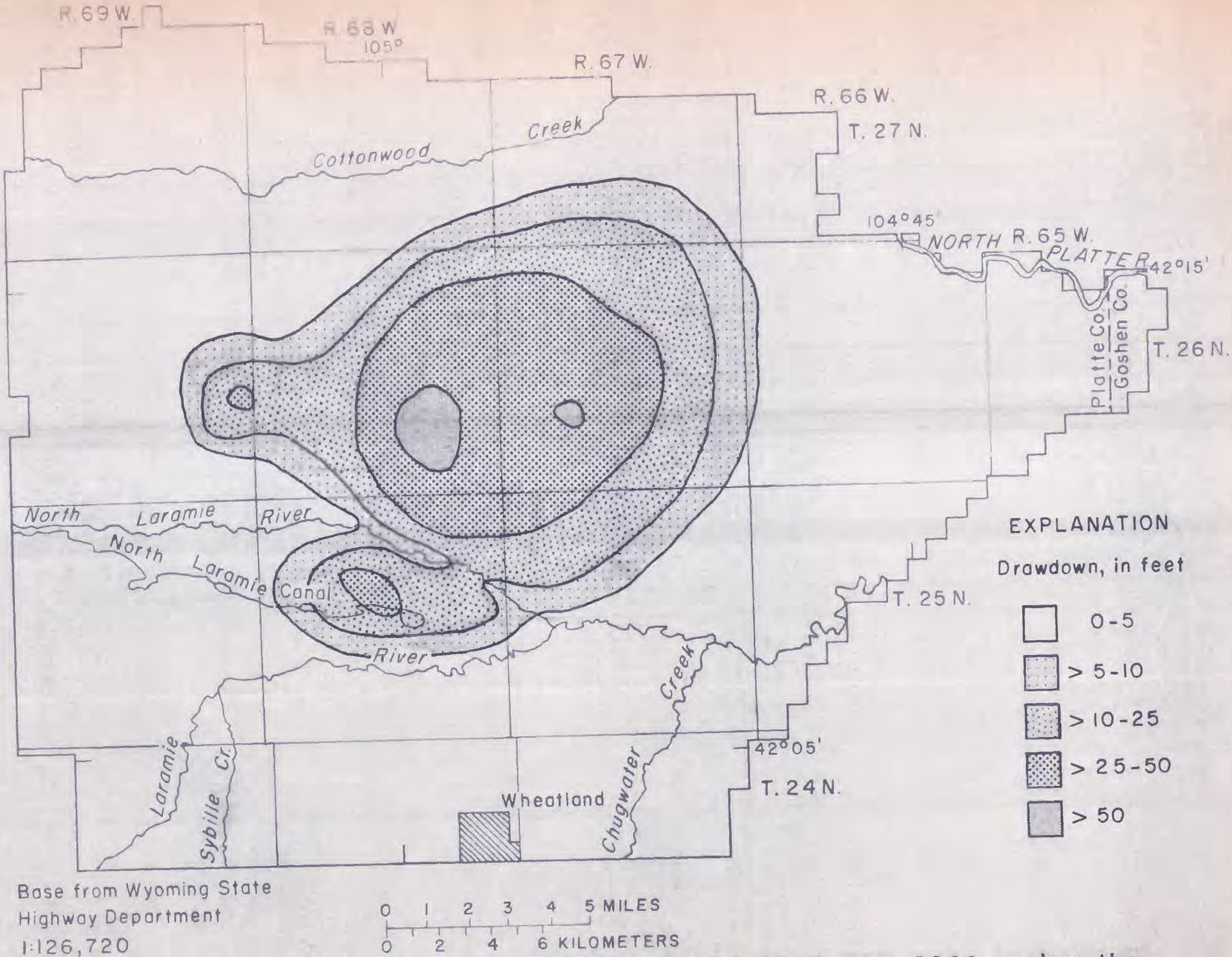

Figure 13.--Simulated drawdowns between 1973 and 2020 under the subject scenario.

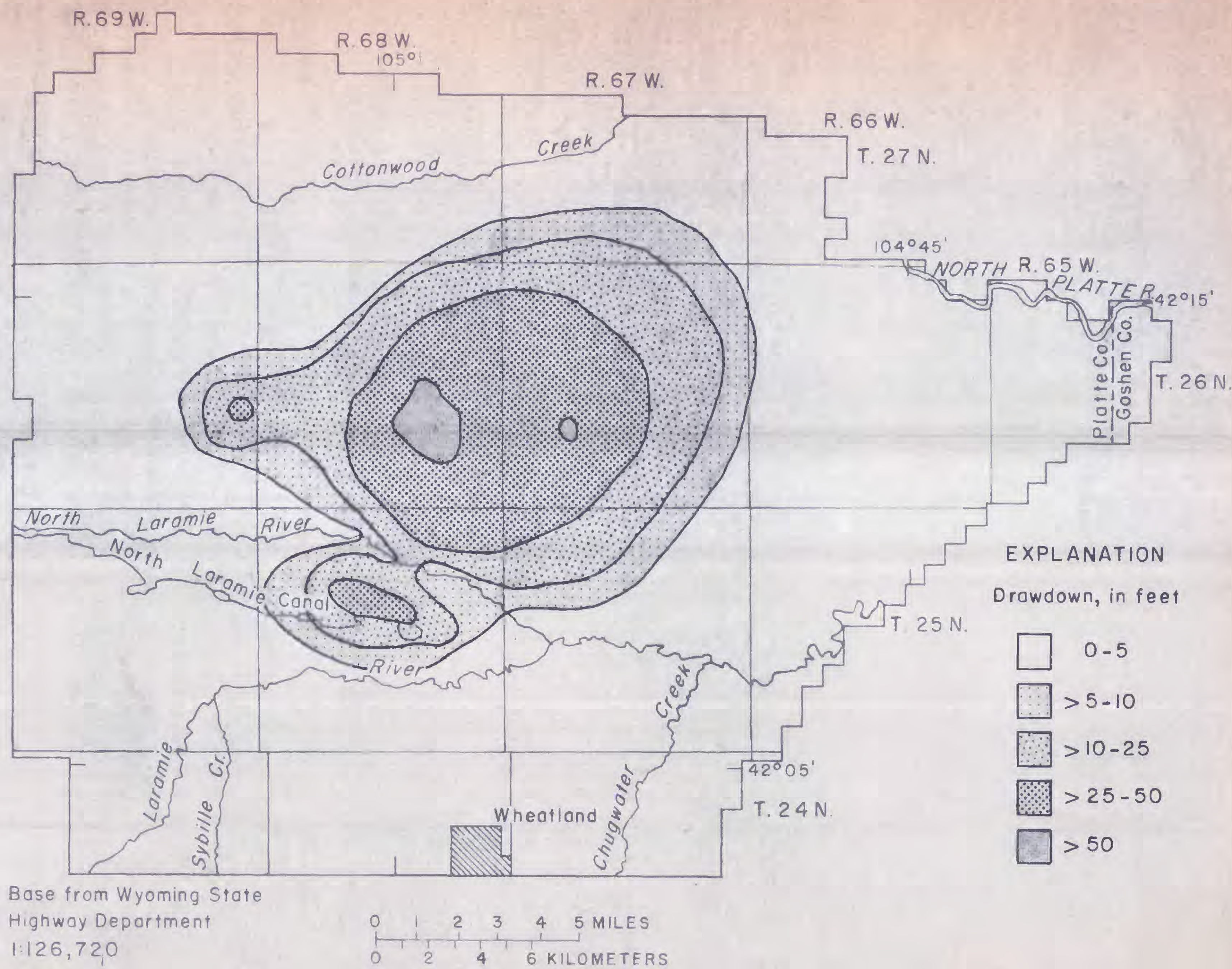

Figure 14.--Simulated drawdowns between 1973 and 2020 under the null-case scenario.