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RESULTS OF TRANSIENT SIMULATIONS OF A DIGITAL MODEL OF THE ARIKAREE AQUIFER NEAR WHEATLAND, SOUTHEASTERN WYOMING

by Dwight T. Hoxie

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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)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

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ABSTRACT

Revised ground-water pumpage data have been imposed on a ground-water flow model previously developed for the Arikaree aquifer in a 400 square-mile area in central Platte County, Wyo. Maximum permitted annual ground-water withdrawals of 750 acre-feet for industrial use were combined with three irrigation pumping scenarios to predict the long-term effects on ground-water levels and streamflows. Total annual ground-water withdrawals of 8,806 acre-feet, 8,033 acre-feet, and 5,045 acre-feet were predicted to produce average water-level declines of 5 feet or more over areas of 99, 96, and 68 square miles, respectively, at the end of a 40-year simulation period. The first two pumping scenarios were predicted to produce average drawdowns of more than 50 feet over areas of 1.5 and 0.8 square miles, respectively, while the third scenario resulted in average drawdowns of less than 50 feet throughout the study area. In addition, these three pumping scenarios were predicted to cause streamflow reductions of 2.6, 2.0, and 1.4 cubic feet per second, respectively, in the Laramie River and 4.9, 4.7, and 3.7 cubic feet per second, respectively, in the North Laramie River at the end of the 40-year simulation period.

INTRODUCTION

The Missouri Basin Power Project involves the construction and operation of the 1,500 megawatt, coal-fired Laramie River electric generating station at a site 5 miles northeast of Wheatland in central Platte County, Wyo. (fig. 1). Most of the water requirements for the operation of this facility are to be met from surface-water storage in Grayrocks Reservoir on the Laramie River about 10 miles downstream from the Laramie River station. During anticipated periods of insufficient surface-water supply, additional water is to be obtained from wells. The Wyoming State Engineer, in an order dated August 26, 1977, granted permits for the construction of an industrial well field at a site 6 miles north of Wheatland. Wells tapping the unconfined Arikaree aquifer (informally called the "Red" aquifer) as well as a deeper confined zone (informally called the "Green" aquifer) were authorized. Ground-water withdrawals for industrial use were restricted to 750 acre-feet annually from the Arikaree aquifer and to 2,000 acre-feet annually from the "Green" aquifer. The industrial well field is to be located in an area in which 34 existing wells tap the Arikaree aquifer to provide water for irrigating a permitted maximum of 5754 acres of land (fig. 2).

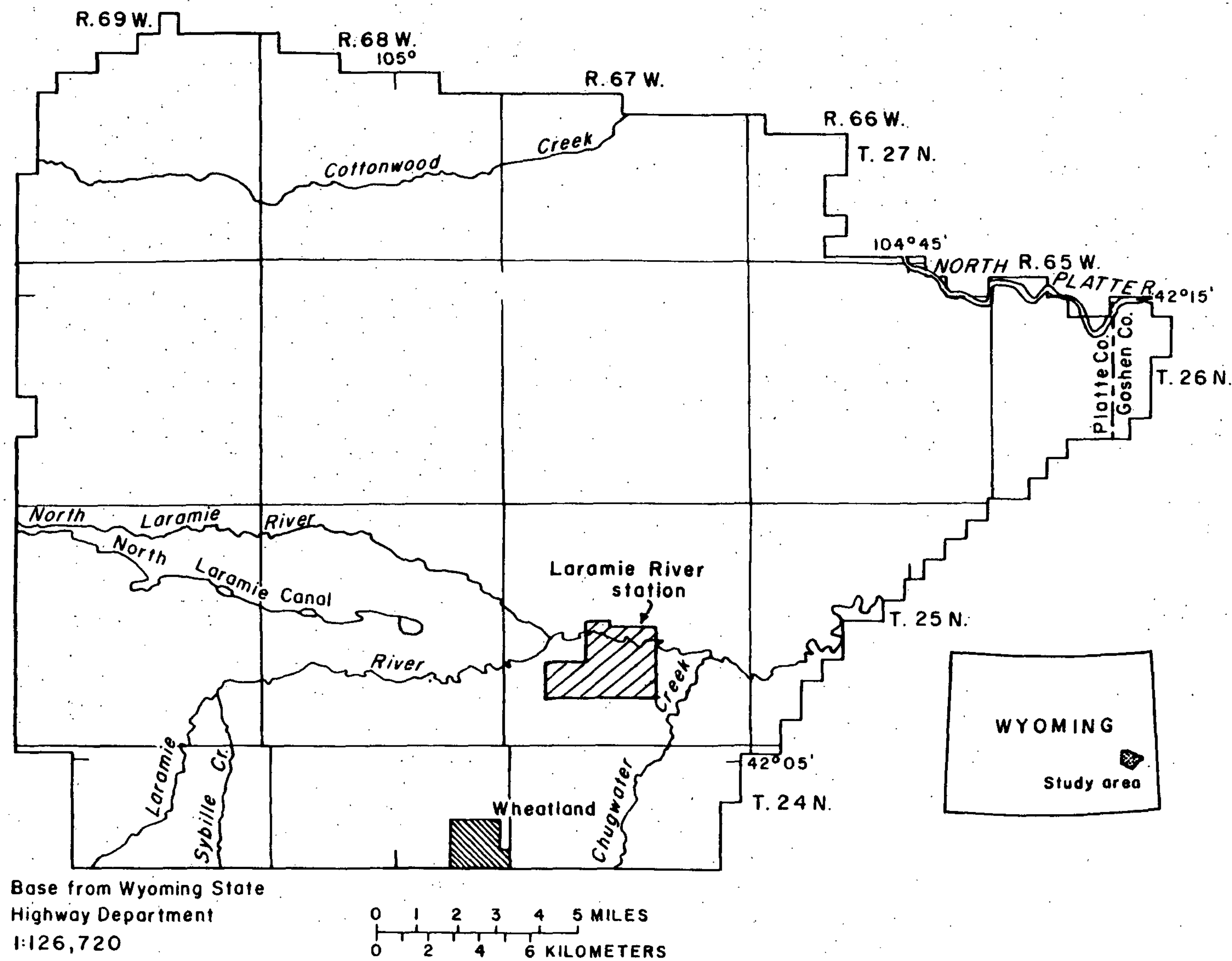


Figure 1.--Area described in this report.

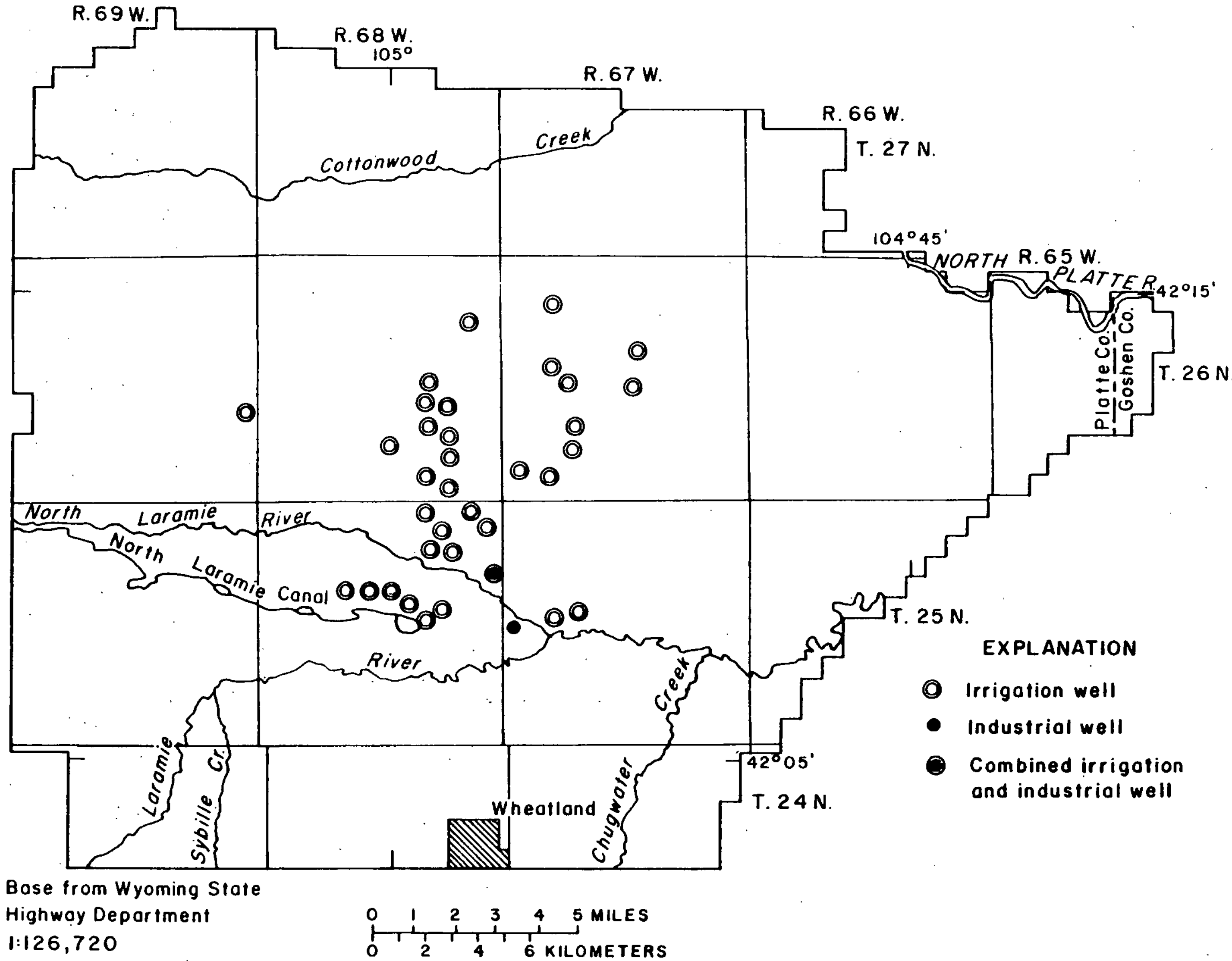


Figure 2.--Location of the irrigation and industrial wells imposed on the ground-water flow model.

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 is described by Hoxie (1977) and was based on hydrogeologic field data collected by Lines (1976) and Weeks (1964). The model was used to assess the effects that industrial and irrigation pumpage could have on ground-water levels and streamflows within the study area. The results of these simulations are presented in Hoxie (1977). The Rural Electrification Administration of the U.S. Department of Agriculture has requested that the U.S. Geological Survey use the model to generate a new set of predictions based on revised projections of industrial and irrigation pumpage in the area. These model simulations are to be used in preparing a supplemental environmental impact statement for the Missouri Basin Power Project. This report summarizes the results of these simulations and is supplemental to the report of Hoxie (1977).

HYDROGEOLOGIC SUMMARY

The study area (fig. 1) is underlain by a nonhomogeneous assemblage of predominantly 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). Siltstone in the Brule Formation of the White River Group generally defines the base of the aquifer, which 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 Lines (1976) and Hoxie (1977).

Exploratory drilling in the study area by the firm of J. T. Banner and Associates has indicated that a confined aquifer zone lies below the Arikaree aquifer at several localities within the study area (L. K. Wester, civil engineer, oral commun., 1979). This aquifer has been informally named the "Green" aquifer, and the Missouri Basin Power Project has been granted rights to withdraw up to 2,000 acre-feet of water annually from it. Preliminary testing indicates that this aquifer is probably incapable of sustaining such yields (L. K. Wester, civil engineer, oral commun., 1979). Because its nature, regional extent, and hydraulic properties are largely unknown, the "Green" aquifer was not included in the model developed by Hoxie (1977) and is not considered further in this report.

STEADY-STATE FLOW MODEL

The field data collected in 1973 by Lines (1976) and in 1959 by Weeks (1964) included the measurement of water levels in wells tapping the Arikaree aquifer; the determination of gains in streamflow in the Laramie River, the North Laramie River, Sybille Creek, Chugwater Creek, and Cottonwood Creek along their reaches within the study area (fig. 1); an estimate of the recharge rate from precipitation; and an estimate of the rates of underflow across the areal boundaries. These data were collected prior to significant ground-water withdrawal, and it is assumed (Hoxie, 1977) that these rates of flow together with the configuration of the water table as determined from the water-level measurements represent a long-term, approximately steady-state flow system within the Arikaree aquifer. The resulting water budget for the flow system is summarized in table 1.

A steady-state ground-water flow model for the aquifer system was developed on the basis of this water budget (Hoxie, 1977). The flow model employs finite-difference numerical techniques to solve the partial differential equation of ground-water flow in a two-dimensional flow approximation (Trescott and others, 1976). In this approximation the hydraulic head distribution is assumed to be coincident with the water-table configuration, and the hydraulic properties of the aquifer are taken as vertical averages over the saturated thickness. The steady-state model was used to generate the vertically averaged hydraulic-conductivity distribution for the aquifer. The resulting calibrated steady-state flow model constitutes the initial conditions for the subsequent transient simulations.

The spatial boundaries imposed on the flow model are coincident with those of the study area shown in figure 1. The western boundary is defined by the surficial contact between the Tertiary sedimentary rocks of the Arikaree aquifer and the presumably impermeable Precambrian igneous and metamorphic rocks exposed in the Laramie Mountains. The northern boundary is coincident with a ground-water divide situated north of Cottonwood Creek. The northeastern and eastern boundaries are determined by an escarpment along the North Platte River. The southeastern boundary is defined by the Wheatland fault system, along which the permeable rocks of the Arikaree Formation are in fault contact with the largely impermeable rocks of the underlying White River Group. Following a procedure developed by Hoxie (1977), these spatial boundaries were treated as flow boundaries in the model, no-flow boundaries being a special case of the flow boundaries. The rate and direction of flow across each of the boundaries was determined from the transmissivity and the hydraulic gradient near the boundary.

Table 1.--Assumed steady-state water budget for the Arikaree aquifer within the study area

Discharge rates

	Discharge rate (ft^3/s)
1. Discharge to streams:	
Laramie River	15.0
North Laramie River	6.0
Sybille Creek	6.0
Chugwater Creek	14.0
Cottonwood Creek	5.0
North Platte River	3.0
2. Underflow	3.1
3. Evapotranspiration	0.0
Total	52.1

Recharge rates

	Recharge rate (ft^3/s)
1. Precipitation	31.7
2. Underflow	17.5
3. Leakage from the North Laramie Canal	2.9
Total	52.1

TRANSIENT SIMULATIONS

The ground-water flow model was used in a transient mode in the present study to predict the response of the aquifer system to three water-utilization scenarios. In each of these scenarios, two industrial wells (fig. 2) were assumed to withdraw 750 acre-feet of water annually from the Arikaree aquifer in accordance with the order issued by the Wyoming State Engineer on August 26, 1977. The irrigation wells (fig. 2) were assumed to withdraw ground water at the annual rate of 1.4 acre-feet per acre for consumptive use on the total acreages listed in table 2. These acreages were provided by the Wyoming State Engineer (Richard Stockdale, ground-water geologist, written commun., 1978) and represent those lands in the study area having valid ground-water rights as of June 8, 1978. Case I(A) of table 2 represents the maximum irrigation usage in that it is assumed that all of the lands having ground-water rights receive their irrigation requirements from ground water. Case II(A) represents the mean irrigation usage in that it is assumed that those lands that also have existing surface-water rights derive only half of their irrigation requirements from ground water. Case III(A) represents the minimum irrigation usage because it is assumed that only those lands having ground-water rights senior to those of the industrial wells receive their irrigation requirements from ground water. The letter "A" is appended to each of the designated cases in order to distinguish these pumping scenarios from analogously defined pumping scenarios in Hoxie (1977).

The transient simulations were made by imposing the total combined industrial and irrigation pumpage rate for each of the three pumping scenarios instantaneously on the calibrated steady-state flow model and continuing the pumping at the prescribed annual rates for the entire simulation period. A 40-year simulation period was used for the case I(A) and case III(A) pumping scenarios. In order to indicate the time dependency of the transient effects, simulation periods of 10, 20, and 40 years were used for the case II(A) pumping scenario. In these transient simulations the specific yield was set at 0.12 in accordance with the determinations for the Arikaree aquifer by Weeks (1964) and Lines (1976). The transient effects on streamflow were calculated using the streamflow accounting procedure developed by Hoxie (1977).

Table 2.--Definition of the three irrigation pumping senarios

Case	Amount of land irrigated by ground water (acres)
I(A)	5,754.4
II(A)	5,202.3
III(A)	3,068.1

Predicted drawdown distributions at the end of a 40-year simulation period are shown in figures 3, 4, and 5 for the case I(A), case II(A), and case III(A) pumping scenarios, respectively. The drawdown distributions predicted for the case II(A) scenario at the end of 10-and 20-year simulation periods are shown in figures 6 and 7, respectively. At the end of the 40-year simulation period, the case I(A), case II(A), and case III(A), pumping scenarios cause predicted drawdowns of 5 ft or more over areas of 99 mi^2, 96 mi^2, and 68 mi^2. These areas represent approximately the areas over which significant drawdowns may be expected to occur as a result of these pumping scenarios. The case I(A) and case II(A) pumping scenarios were predicted to produce average drawdowns of more than 50 ft over areas of 1.5 and 0.8 mi^2, respectively. The case III(A) pumping scenario resulted in average drawdowns of less than 50 ft throughout the study area. The drawdowns in the immediate vicinity of the pumping wells generally will be appreciably greater than these areally averaged drawdowns.

Predicted depletions of streamflow in the Laramie and North Laramie Rivers for the various pumping scenarios and simulation periods are listed in table 3. These predicted streamflow depletions represent the capture of water that otherwise would have discharged from the Arikaree aquifer to the streams along their reaches within the study area. At the end of the 40-year simulation period, 62, 60, and 73 percent of the total pumpage is derived from captured ground-water discharge to the streams for the case I(A), case II(A), and case III(A) pumping scenarios, respectively. The rest of the pumpage is drawn from water held in storage within the aquifer.

Figures 4, 6, and 7 and table 3 display the time dependency of the drawdown distribution and of the rates of streamflow depletion for the case II(A) pumping scenario. When pumping is initiated, most of the water that is supplied to the wells will be derived from ground-water storage within the aquifer. As the cones of depression about the pumping wells spread and coalesce, an increasing amount of water that otherwise would have been discharged to the Laramie and North Laramie Rivers will be captured by the pumping wells. Eventually a steady-state regime will be established in which the total ground-water pumpage will be supplied by the capture of ground-water discharge into the streams as well as by the direct infiltration of surface-water flows from the streams. The time required for this steady-state flow system to be established will depend on the specific yield of the aquifer, the transmissivity distribution, the vertical hydraulic conductivity of the streambeds, and the rate of recharge to the aquifer. The ultimate effect will be the same, however, as long as there is sufficient surface-water flow in the streams and communication between the streams and the aquifer that the total pumpage can be supplied directly or indirectly from depletions in streamflow.

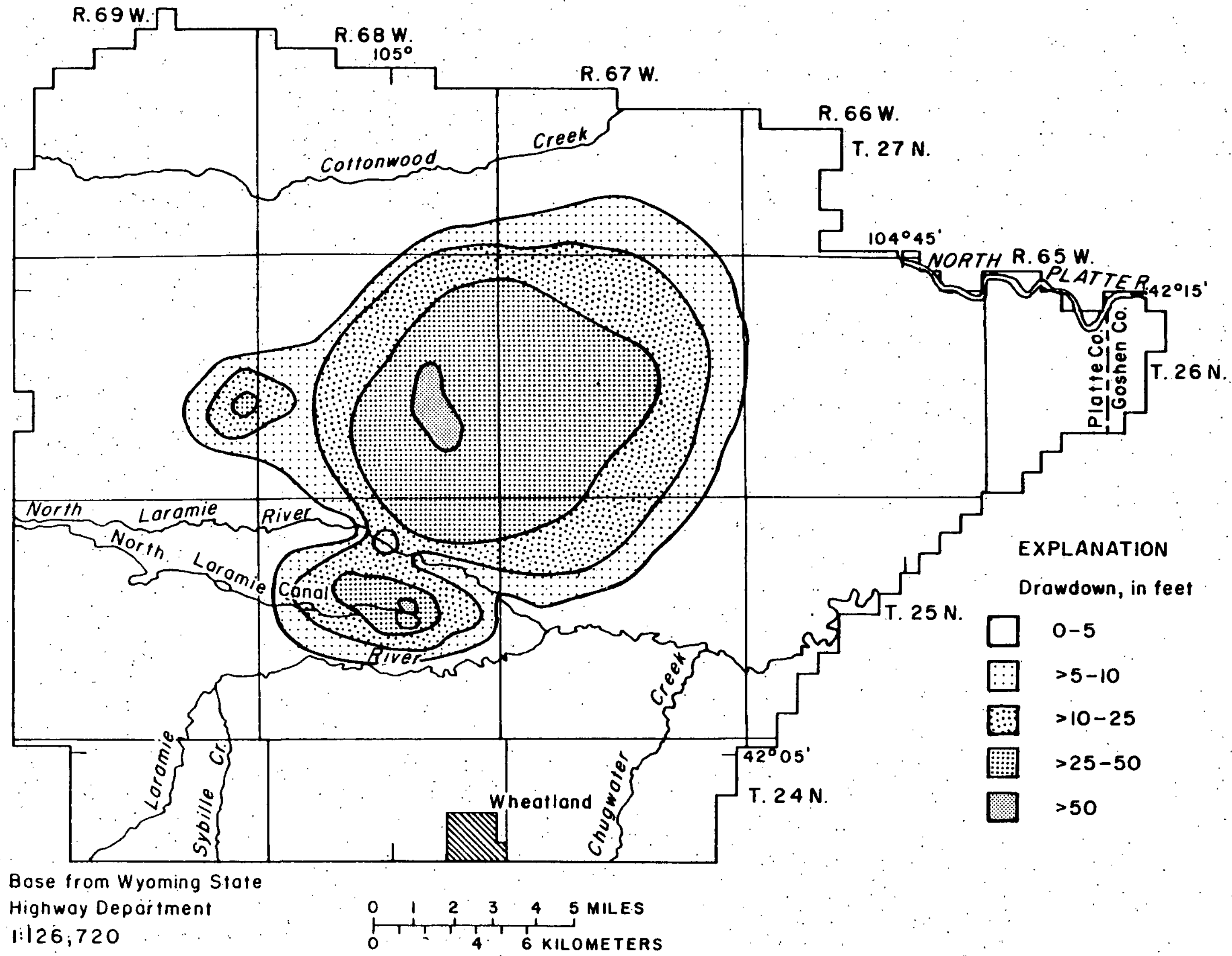


Figure 3.--Drawdown distribution for the case I (A) wells at the end of the 40-year simulation period.

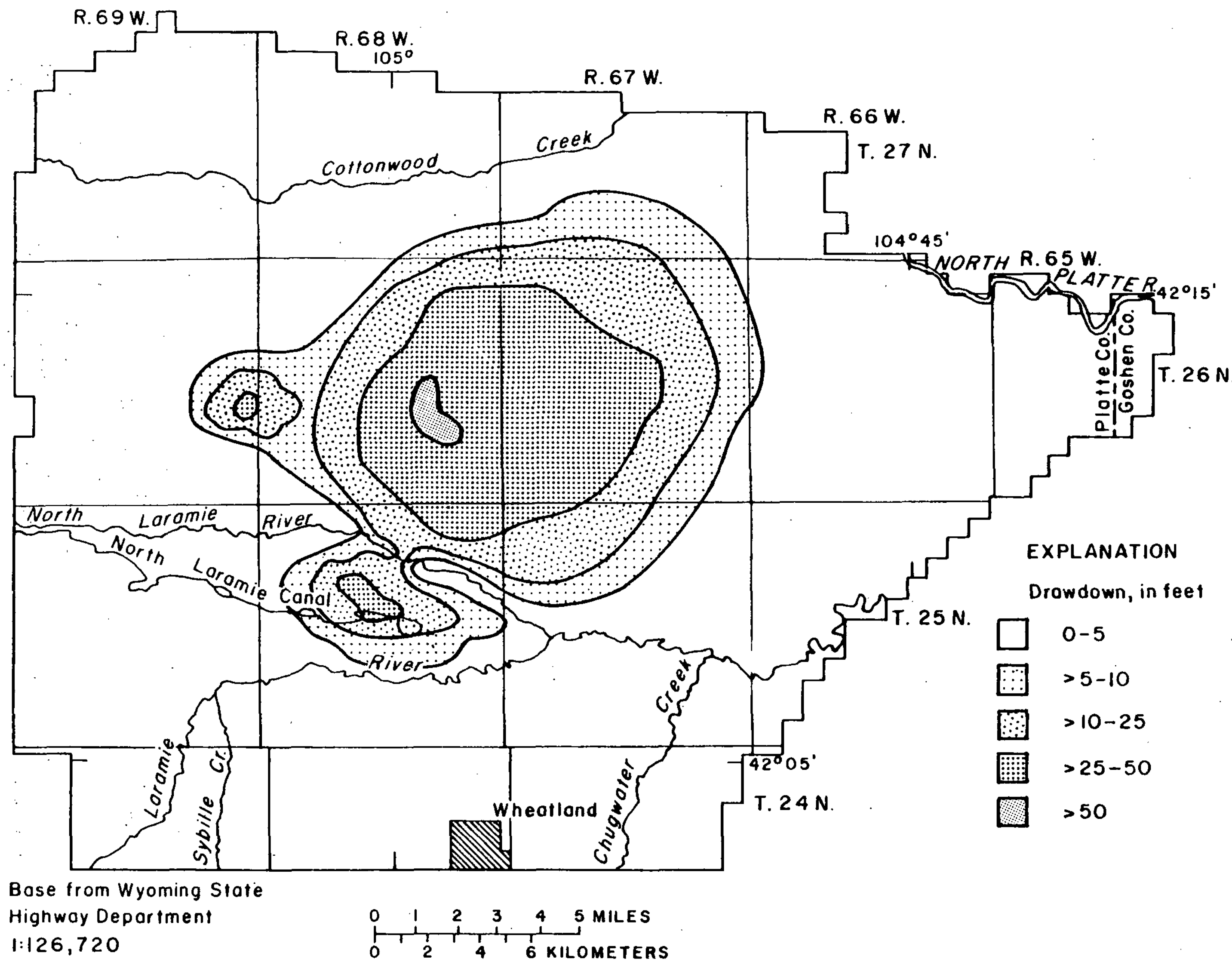


Figure 4.--Drawdown distribution for the case II (A) wells at the end of the 40-year simulation period.

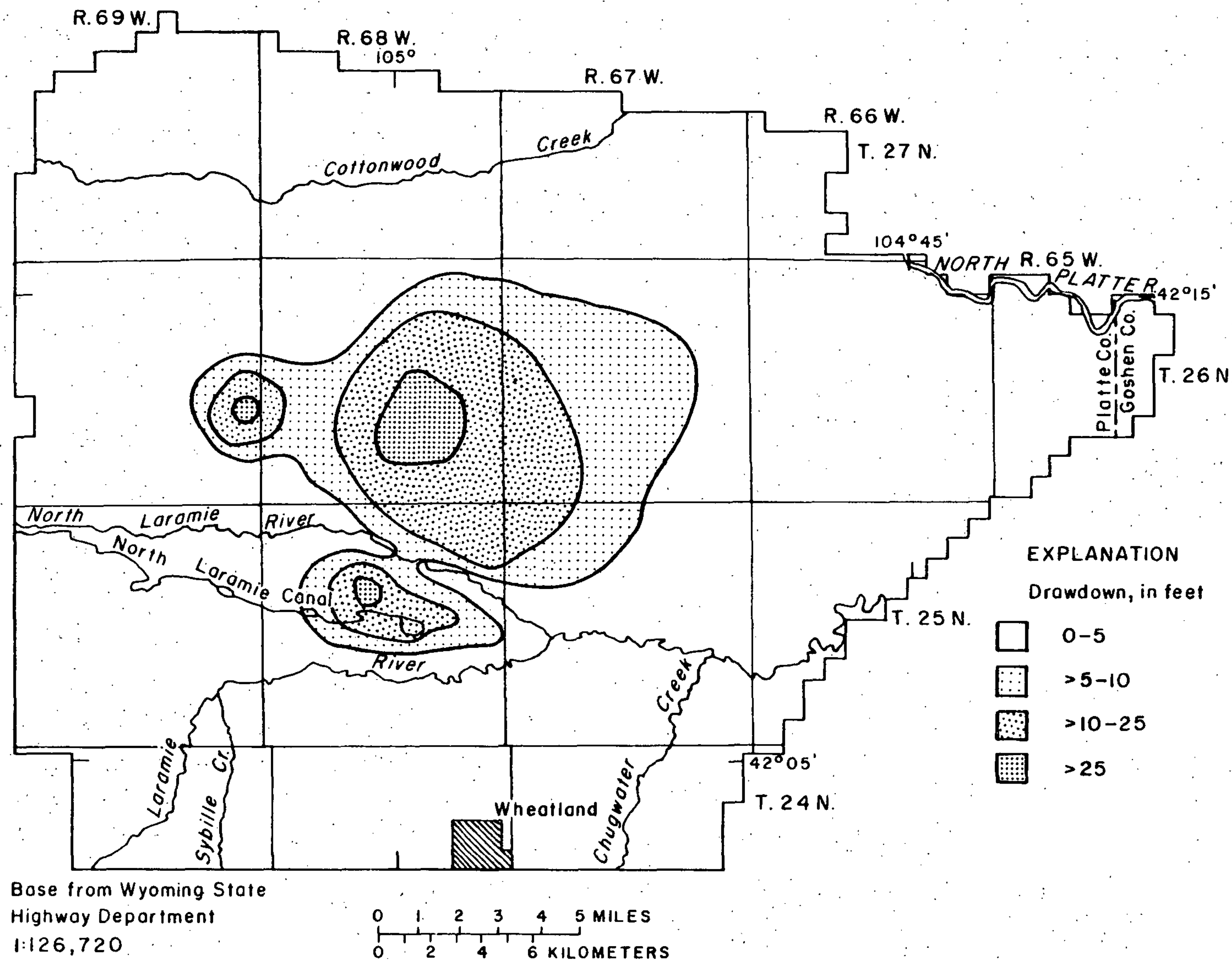
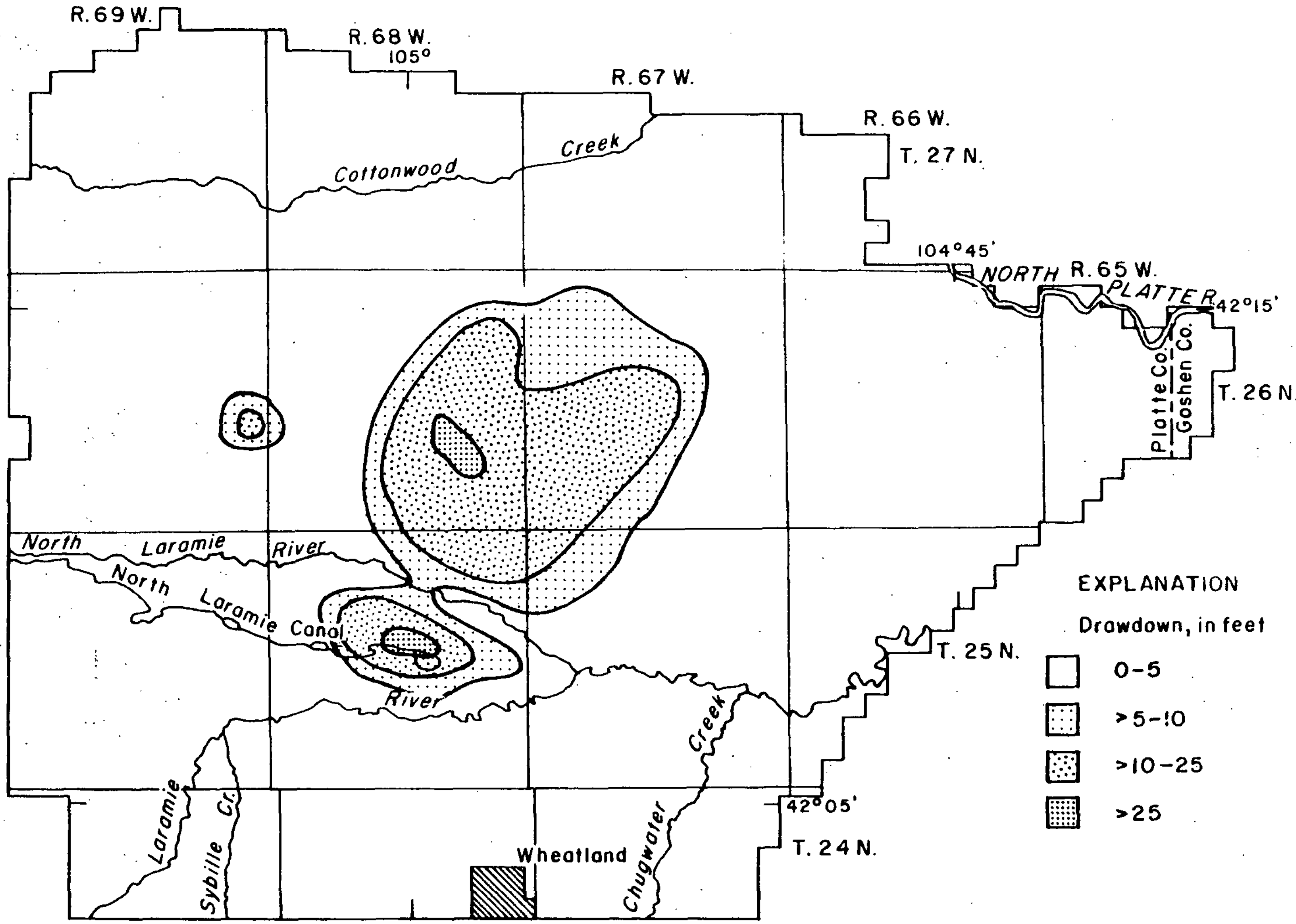


Figure 5.--Drawdown distribution for the case III (A) wells at the end of the 40-year simulation period.



Base from Wyoming State
Highway Department
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0 1 2 3 4 5 MILES
0 2 4 6 KILOMETERS

Figure 6.--Drawdown distribution for the case II (A) wells at the end of a 10-year simulation period.

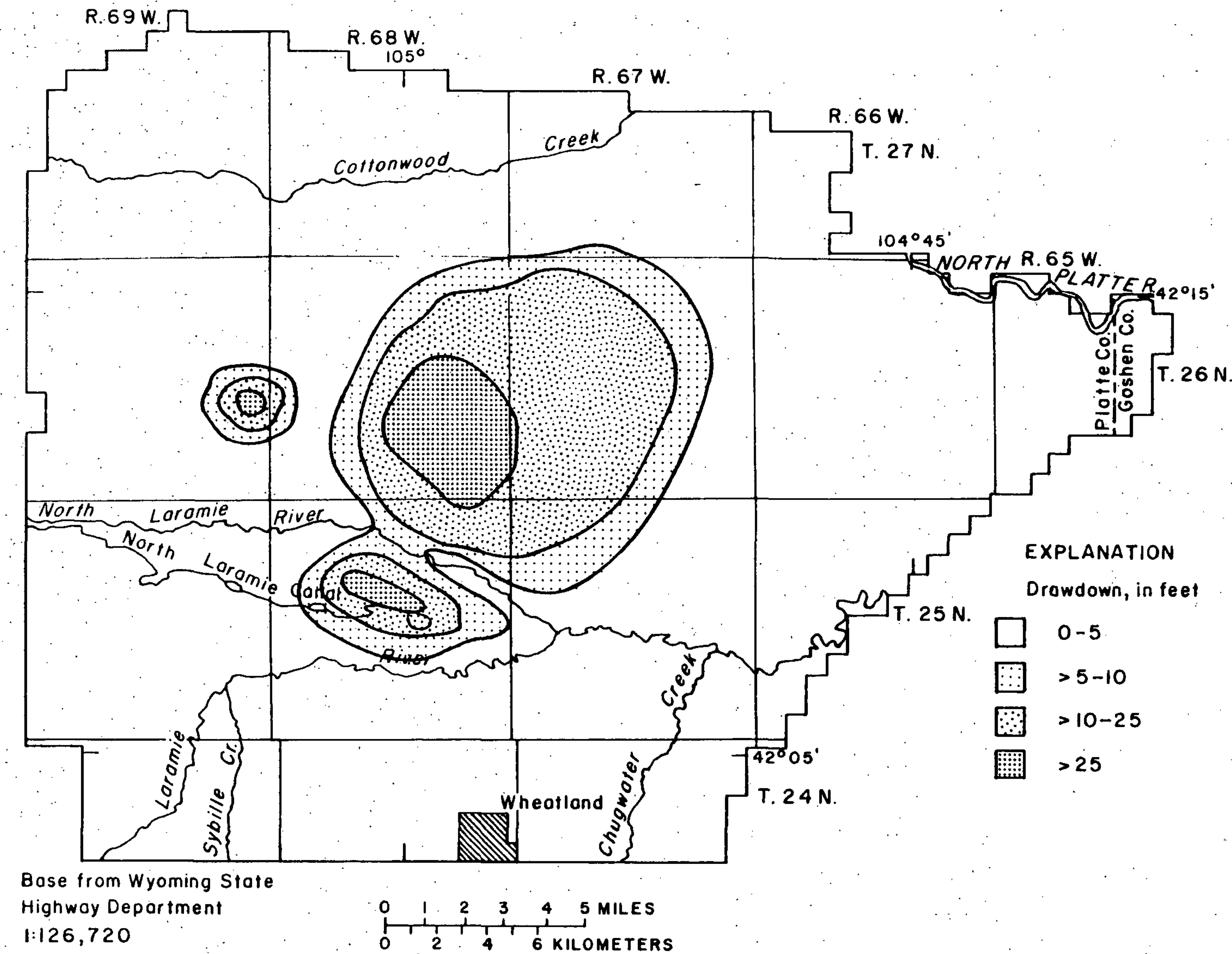

Figure 7.--Drawdown distribution for the case II (A) wells at the end of a 20-year simulation period.

Table 3.--Predicted streamflow depletions from the Laramie and North Laramie Rivers

Stream	Simulation period (yr)	Streamflow depletion (ft^3/s)		
		Case I(A)	Case II(A)	Case III(A)
Laramie River	10		1.2	
	20		1.6	
	40	2.6	2.0	1.4
North Laramie River	10		3.2	
	20		4.0	
	40	4.9	4.7	3.7

Hoxie (1977) discussed the uncertainties associated with the development of the ground-water flow model for the Arikaree aquifer and the subsequent transient simulations. Probably the most critical uncertainties involve the assumptions in developing the steady-state flow model, the vertical hydraulic conductivity of the streambeds, and the value used for the specific yield. In addition there exists the possibility that the lowering of heads in the Arikaree aquifer by pumping may induce vertical leakage upwards from the "Green" aquifer in those areas where it underlies the Arikaree aquifer. Hydraulic data pertaining to the "Green" aquifer are insufficient at present to permit a quantitative assessment of this potential effect, however. The steady-state model for the Arikaree aquifer could be improved only if long-term monitoring of the flow system prior to development were available. The vertical hydraulic conductivity values for the streambeds could be improved by conducting aquifer tests near the streams. The value of 0.12 for the specific yield was determined empirically and probably represents an approximate mean value for the Arikaree aquifer. The overall model can be improved by monitoring the flow system as development proceeds and requiring that the model adequately reproduce the observed effects on ground-water levels and streamflows.

SUMMARY AND CONCLUSIONS

A digital ground-water flow model developed by Hoxie (1977) was used to predict the long-term effects on ground-water levels and streamflows that may be caused by combined irrigation and industrial pumping from the Arikaree aquifer in central Platte County, Wyo. Ground-water withdrawals of 750 acre-feet annually for industrial use by the Missouri Basin Power Project were combined with estimated maximum, mean, and minimum withdrawals for irrigation of 8,056, 7,283, and 4,295 acre-feet, respectively, to define three pumping scenarios that were imposed on the model. At the end of a 40-year simulation period, these maximum, mean, and minimum pumping scenarios caused predicted drawdowns of 5 ft or more over areas of 99, 96, and 68 mi^2, respectively. The maximum and mean pumping rates resulted in predicted average drawdowns of more than 50 ft over areas of 1.5 and 0.8 mi^2, respectively; whereas, the minimum pumping rate resulted in predicted average drawdowns of less than 50 ft throughout the study area. In addition these pumping rates resulted in predicted streamflow depletions of 2.6, 2.0, and 1.4 ft^3/s, respectively, in the Laramie River and of 4.9, 4.7, and 3.7 ft^3/s in the North Laramie River at the end of the 40-year simulation period.

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