UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

HYDROGEOLOGIC CONSIDERATIONS FOR AN INTERSTATE GROUND-WATER COMPACT ON THE MADISON AQUIFER, NORTHERN GREAT PLAINS

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By Leonard F. Konikow

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HYDROGEOLOGIC CONSIDERATIONS FOR AN INTERSTATE GROUND-WATER COMPACT ON THE MADISON AQUIFER, NORTHERN GREAT PLAINS[1]

Leonard F. Konikow

ABSTRACT

The development of an interstate ground-water compact for the Madison aquifer in the Northern Great Plains may provide a framework to allocate equitably this large ground-water resource while avoiding possible future interstate legal conflicts. However, some technical problems will have to be resolved first. A compact designed to regulate or to allocate the available ground water will have to be written in very precise, legally acceptable definitions. The required definitions may infer a degree of measurement accuracy that cannot be technically or economically provided. Therefore, a trade off may be required between preserving natural conditions and allowing beneficial use of the ground-water resource.

[1]Based on a talk given at the 22nd meeting of the Missouri River Basin Commission, November 3, 1977.

INTRODUCTION

Ground-water withdrawals from the Madison aquifer may increase significantly in the future as water demands for energy development become greater in the Northern Great Plains. The Madison forms an areally extensive and generally continuous aquifer that underlies parts of Wyoming, Montana, South Dakota, North Dakota, and Nebraska (fig. 1). This area lies entirely within the Missouri River basin. Because of its extent and continuity, the effects of developing ground water from the Madison in one state may ultimately extend into another state. One method of avoiding future interstate conflicts is to develop an interstate ground-water compact that will provide a legal framework for allocating the ground-water resource in a logical and equitable manner. However, some technical considerations and problems will have to be resolved prior to formulating such a precise legal agreement. Nevertheless, an item was placed on the agenda of the 22nd meeting of the Missouri River Basin Commission (held in Omaha, Nebraska, November 2-3, 1977) to consider the formation of a committee to investigate the development of an interstate ground-water compact on the Madison Limestone.

The concept of forming an interstate compact to allocate or regulate water resources is not new. But interstate water compacts traditionally have focused on surface water, although some compacts also consider ground-water flow through shallow alluvium adjacent to the river to be part of the overall water resource governed by the compact. There are no existing interstate compacts whose primary function is to allocate a ground-water resource.

If a compact is to allocate or regulate a resource, it is implicit that the resource can be measured with an acceptable degree of accuracy. While measurement can be accomplished relatively easily and economically at a few gaging stations for a surface-water system draining a specific watershed, measurement is more difficult and costly for a ground-water system in which the flow is diffuse. Presently, the rates and direction of ground-water flow in the Madison aquifer can not be reliably defined in many areas.

It is the purpose of this brief report to discuss some of the practical problems that should be considered before a logical and equitable ground-water compact is formulated. It is not my intention to speak either for or against the development of an interstate ground-water compact, nor will I discuss its advantages and disadvantages. Rather, I hope to demonstrate that a severe gap exists between the very precise definitions required and desired for a legal document and our ability to correspondingly measure and define the ground-water variables that are to be apportioned, regulated, or monitored according to the compact.

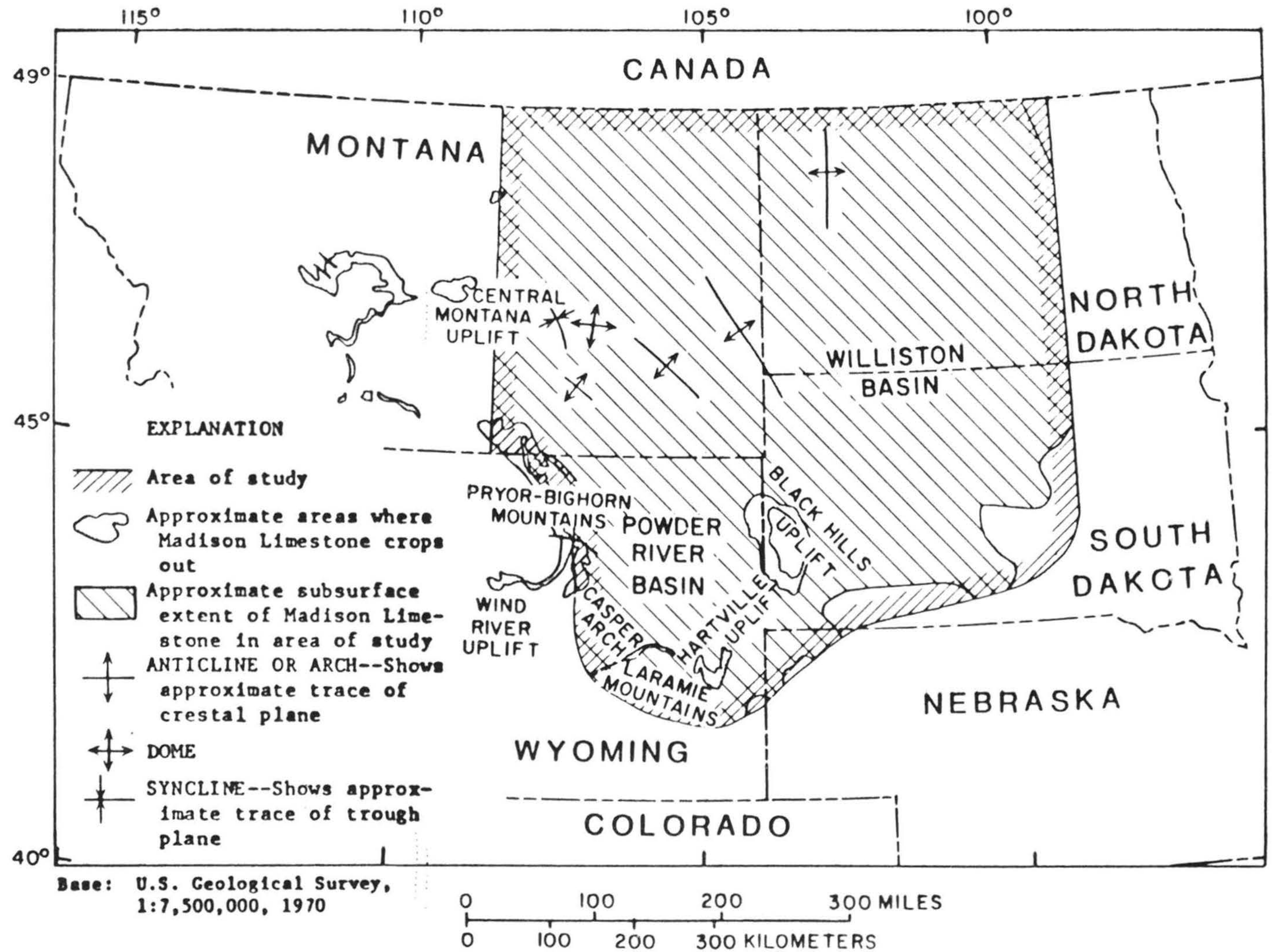

Figure 1.--Outcrops and subsurface extent of Madison Limestone and major tectonic features (from U.S. Geological Survey, 1975).

AQUIFER DEFINITION

The first basic difficulty comes from trying to define the aquifer itself. The Mississippian Madison Limestone (or Madison Group where subdivided) consists of one or more distinguishable rock units in the area of interest. These geologic units are recognized and defined primarily on the basis of lithology and on age of deposition of the rocks. Thus, we are capable of precisely defining these units in a geologic sense, and we can accurately map their depths and thicknesses. The same is true for geologic formations that overlie or underlie the Madison. However, geologic recognition leads to an important hydrologic question. Can the Madison be considered as a distinct entity or as a separate and isolated hydrologic unit? The answer is no, at least not in the same sense that a river basin can be defined by the drainage divides of its watershed. Rather, the Madison is really only one element of a three-dimensional ground-water flow system. In places the Madison may act effectively as an isolated aquifer; in other areas flow may cross its upper and lower boundaries. Sometimes the flow is into the Madison and sometimes the flow is out of the Madison. These facts lead to the conclusion that ground-water flow does not always respect the geologic boundaries of a rock formation. Therefore, a geologic definition of the Madison may not be satisfactory for a hydrologic definition required for a ground-water compact.

One approach may be to define for the purpose of a compact a "Madison aquifer" that is different from the geologically defined Madison Limestone (or Group). In many areas, the Madison is underlain by either the Bighorn Dolomite or the Red River Formation, though they are usually separated from the Madison by intervening formations. These units in places may be more permeable and more porous than the Madison. The degree of interconnection between these units and the Madison is governed by vertical permeability of the intervening rocks, which in turn may be controlled primarily by the degree of fracturing. In any event, vertical permeability is very difficult to measure. It may be found that the only consistent lower boundary for ground-water circulation is the relatively impermeable Precambrian crystalline rocks that underlie the entire area. Above the Madison are other geologic units, such as the Minnelusa Formation, that may be porous and permeable and interconnected to some degree with the Madison. Perhaps some of the low permeability shale units in the overlying Mesozoic rocks, such as the relatively thick Pierre Shale of Cretaceous age, will be found to represent a reasonable upper boundary to ground-water circulation in the Madison and adjacent formations.

In any event, a very basic problem is simply defining the aquifer or aquifers of interest. This problem has to be resolved and it may require a consideration and evaluation of all rocks between the Precambrian crystalline rocks and the Cretaceous Pierre Shale.

GROUND-WATER VARIABLES

A number of variables can be used as indicators of the status of ground water in the Madison aquifer. One or more of these variables might be considered for a basis of regulations to be stipulated in an interstate ground-water compact. Following is a more detailed discussion of these variables.

Rate or Volume of Flow

In a manner analogous to interstate river basin compacts, a ground-water compact might consider monitoring and apportioning the rate or annual volume of ground-water flow at specified points or cross sections, such as state lines. However, unlike rivers, ground-water flow cannot be measured directly. It has to be computed on the basis of observed hydraulic gradient and estimated aquifer transmissivity. Neither of these two factors is presently well determined for the Madison. Drilling a sufficient number of observation wells to accurately calculate ground-water flow along a specified cross section may cost millions of dollars. Furthermore, because the effects of ground-water developments take a considerable amount of time to spread through the aquifer, a large ground-water withdrawal in one area may not affect ground-water flow at a specified gaging section for many years. The lag time between development stresses and resulting regional responses is very much longer in a ground-water system than in a surface-water system. Therefore, a significant time lag should somehow be acknowledged in a ground-water compact.

Also, the probable rate of ground-water flow in the Madison only represents an annual spatial transfer of a very small fraction of the total volume of water in storage in the aquifer. The flow rate may bear little relation to the quantity of ground water in storage in the Madison or to its economic recoverability in any given area. Thus, the allocation of existing ground-water flow rates may not provide a logical basis for distributing or allocating the development of the ground-water resource.

Hydraulic Head

Another consideration is to formulate the compact to monitor or regulate hydraulic head or artesian pressure in the aquifer, or perhaps restrict the rate of decline or depletion of hydraulic head. Although this is somewhat analogous to regulating water-level changes in a surface reservoir, major differences exist that present obstacles to equitable regulation of ground water solely on the basis of hydraulic head.

First of all, there are serious measurement problems. At this time, existing data on the head distribution in the Madison are very sparse. My assessment of compiled data indicates that in most areas the head can only be estimated with an average accuracy of about ±200 feet (±60 meters). This degree of uncertainty could lead to significant errors in any subsequent calculations of the rates and directions of ground-water flow in the Madison in various parts of the area of interest. Much of the uncertainty exists because most existing data on hydraulic head were derived from drill-stem tests in petroleum exploration wells, and these tests are not specifically designed to measure accurately hydraulic heads in aquifers. Among other factors, shut-in pressures are commonly measured over a time interval that is too short to allow the pressure in the well to equilibrate with the static pressure in the formation.

The hydraulic head also varies with depth and with time at any given location. Unfortunately, very few of the available data represent tests of just the full thickness of the Madison. In many wells, only one or two small intervals of the Madison were tested; in other wells, production was from a hole that was simultaneously open to the Madison and underlying or overlying formations. Therefore, even if pressure measurements were made with 100 percent accuracy during these tests, the heads computed from these measurements may still differ from the true average head for the Madison interval. Also, in an observation well, the head may vary with time because of natural variations in recharge caused by seasonal or longer term climatic cycles. Presently the normal or natural range of fluctuation in wells is not known. If a compact were to require allocation based on observations of changes in hydraulic head, then the head changes caused by pumping stresses would have to be distinguishable from the natural fluctuations in head in order for consequent water management actions to be hydrologically logical. Furthermore, we once again face the problem of recognizing the time lag between the initiation of pumping and the observation of resultant aquifer responses at some distant designated monitoring points.

If the designers of an interstate ground-water compact were to consider regulating or monitoring the decline in hydraulic heads (or in artesian pressures), they should first know the present head distribution in the aquifer, as well as its natural range of fluctuations, so that they would have an accurate basis for evaluating future changes. But again, because of inadequacies in existing head data, the accurate determination of the head distribution may require expensive collection of new data from tests specifically designed to evaluate the Madison.

If primary consideration is given to preserving artesian pressures, then we should also recognize the costs in terms of future water use that will be precluded. The Madison aquifer represents a tremendous reservoir of water. Just in the area of greatest interest (U.S. Geological Survey, 1975), which includes the Powder River Basin in northeastern Wyoming and southeastern Montana and also includes western South Dakota, approximately 2 billion acre-feet of water is in storage in the aquifer. Only a small percentage of this volume is economically recoverable; but this very fact implies that ground-water development will not significantly deplete the volume of water in storage. What will be depleted, in general, is the hydraulic head. So the designers of a ground-water compact may be faced with the problem of setting priorities. A formula may have to be developed that allows a fair and reasonable trade off between tolerable declines in head (or pressure) and beneficial ground-water use. Then a compact should also consider the effects of existing abandoned, free-flowing, artesian wells that are continually depleting head and flow in the Madison.

I have already mentioned problems with flow or leakage between the Madison and underlying or overlying formations. Because of this likely hydraulic interconnection between adjacent formations, ground-water development from the Madison could affect the hydraulic head in these other units. Similarly, ground-water withdrawals from these other units could affect the head in the Madison. This leads to some additional questions. For example, will the compact govern withdrawals from other formations that may affect the head (or pressure) in the Madison? Will some critical observed head decline in the Madison preclude further pumping from the Madison even though the decline may have been caused mostly by withdrawals from the underlying Bighorn Dolomite or from the overlying Minnelusa Formation? Would it be possible for some ground-water users to circumvent the intent of a ground-water compact by producing from adjacent hydraulically connected formations? How would the effects of oil and gas development be considered? Hydraulically, the ground-water head responds to the effects of oil and gas withdrawals in the same manner as it responds to ground-water withdrawals. At present, oil and gas is produced from the Madison in North Dakota, as well as from formations overlying the Madison in Wyoming and Montana. Would the compact, therefore, attempt to regulate oil and gas development activities or even to monitor the effects of oil and gas production on the head or pressure in the Madison?

Discharge to Surface Water

Another major area of interest that a compact should focus on is the possible effects of ground-water development on streamflow and spring discharge. Again we are faced with technical problems that primarily relate to our inability to define precisely and accurately the relationship between changes in head in the Madison aquifer and changes in ground-water discharge to streams and springs.

Many springs and gaining reaches of streams are believed to derive all or part of their flow from ground-water discharge from the Madison. However, the exact percentages of flows derived from the Madison are uncertain and would be difficult to compute. Thus, if a major spring, for example Cascade Spring, which is south of the Black Hills in South Dakota, were to exhibit a 20-percent reduction in discharge during a given year, we may or may not be able to determine whether the decrease was caused by ground-water withdrawals from the Madison, from the Minnelusa, or from the Minnekhata, or was caused by below averge precipitation and recharge in the vicinity of the spring a year or two earlier.

Ground-water Quality

Perhaps water quality is another factor that should be considered in a ground-water compact. The natural quality of ground water in the Madison varies considerably within the area of interest. In the Williston Basin in North Dakota, the Madison contains a brine; whereas near the recharge areas in the Black Hills and Bighorn Mountains, the dissolved-solids concentration is relatively low. Major ground-water withdrawals could eventually affect water quality in the Madison. For example, in some areas the quality of water in the Madison is better than that in underlying or overlying formations. A significant head decline in the Madison caused by ground-water withdrawals could induce the leakage of poorer quality water from adjacent formations into the Madison. However, the effects of ground-water development on water quality will be more difficult to assess than the hydraulic effects. Despite the difficulty, it may still be desirable for a ground-water compact to consider changes in ground-water quality.

CONCLUSION

I have mentioned what I believe to be some serious obstacles to developing an interstate ground-water compact for the Madison aquifer that is hydrologically sound, logical, and equitable. I do not mean to imply that these obstacles (or technical considerations) will necessarily preclude the development of a viable ground-water compact, but they certainly will have to be faced with some very innovative thinking. When the possible objectives of the compact become better defined, their compatibility with the hydrogeology of the Madison aquifer should be evaluated in a more detailed and comprehensive technical investigation than was possible for this report. An interstate ground-water compact may require very precise, legally acceptable definitions that may imply a degree of measurement accuracy that cannot be technically or economically provided. My main conclusion is that the designers of the compact should carefully evaluate the long-term implications of any proposed rules before they become legally binding.

REFERENCES CITED

U.S. Geological Survey, 1975, Plan of study of the hydrology of the Madison Limestone and associated rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming: U.S. Geol. Survey Open-File Rept. 75-631, 35 p.