Use of Numerical Modeling to Evaluate the Quantity and Quality of Induced Surface Water Recharge for the City of Dunlap

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The City of Dunlap is located in Harrison County in west-central Iowa. Dunlap has two active public wells (Well #3 and #4) open to both the Boyer River alluvial aquifer and Dakota sandstone. Concerns about the water supply have increased in recent years because of increasing nitrate levels in the well water.

A hydrogeologic study of the Boyer River alluvial aquifer near Dunlap (Figure 1) was initiated in the fall of 2010. A critical component of the study was to generate a groundwater flow model that would quantify the amount of induced recharge received and delineate capture zones for the City of Dunlap wells. The newly generated capture zones can then be used to direct land use changes and best management practices to reduce nitrate levels around the City of Dunlap's wellfield.

The study included the following tasks:

- Eight (8) observation wells were installed around the City of Dunlap wells (Figure 2) to monitor groundwater levels and nitrate concentrations. A transducer was installed in each well to collect a water level measurement every 10 minutes.
- Four (4) piezometers were installed in the streambed of the Boyer River (Figure 2) to calculate the vertical conductivity of the streambed material. A water quality sample was collected from each piezometer and analyzed for nitrate (as N).
- In coordination with the City of Dunlap, a 24-hour pump test was conducted to calculate various aquifer parameters.

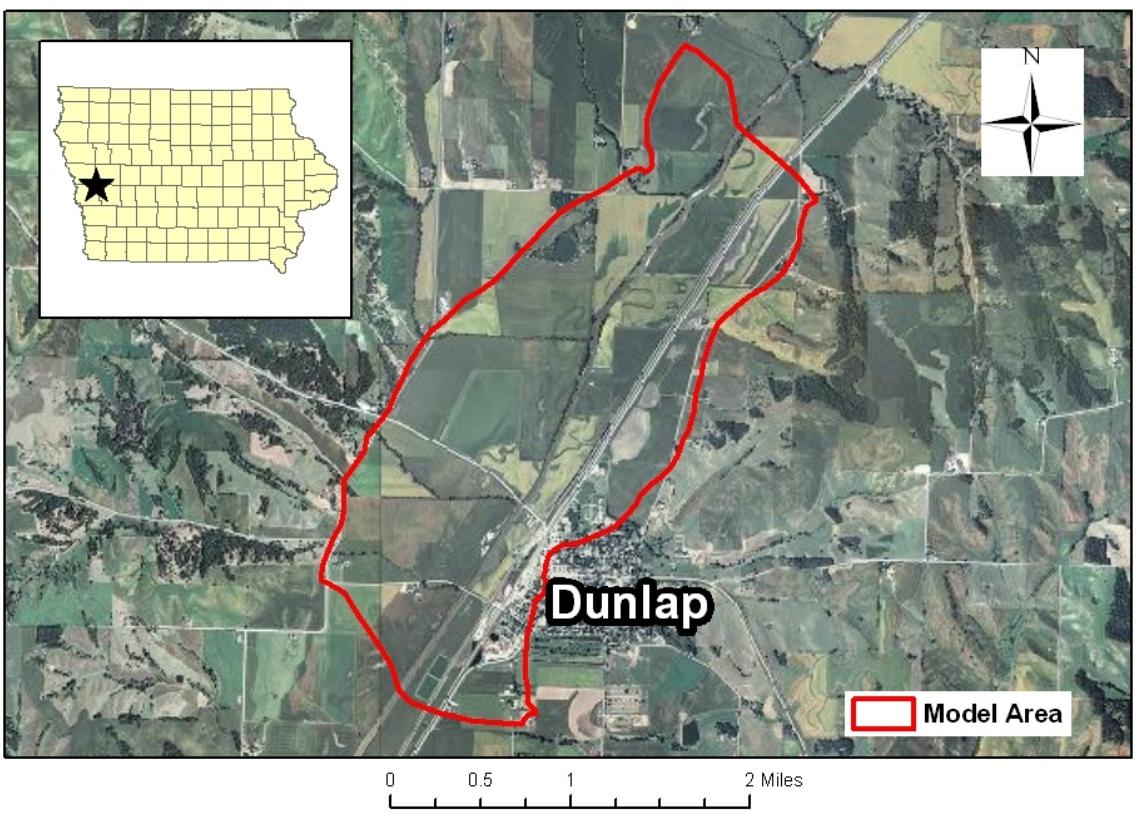

Figure 1. Dunlap model area.

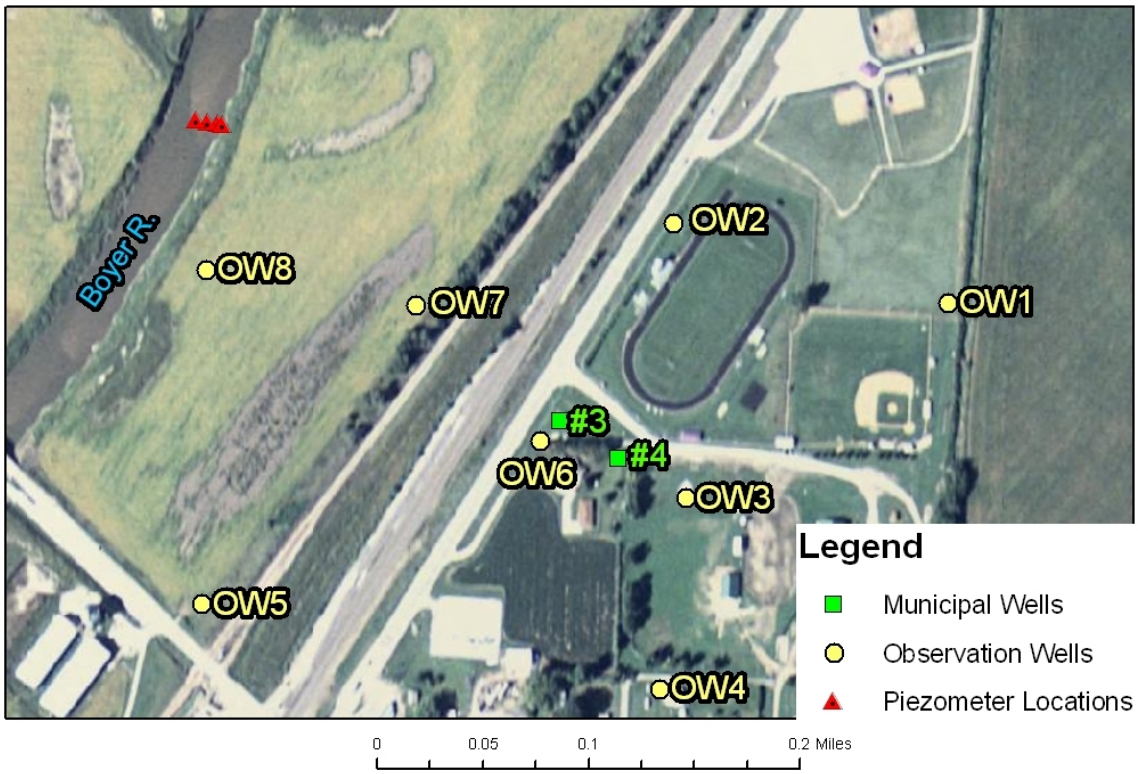

Figure 2. Location of observation wells installed around City of Dunlap's wellfield.

PHYSIOGRAPHY AND CLIMATE

The model area is located within the Southern Iowa Drift Plain landform region. The Southern Iowa Drift Plain is a landscape of steeply rolling hills and incised valleys that has evolved since the end of the pre-Illinoian glaciation (Prior, 1991; Hansen *et al*., 1992). Within the Southern Iowa Drift Plain are well established river systems and associated flood plains. Primary, secondary, and tertiary river terraces are found adjacent to the valley walls along many reaches of the flood plains. These terraces are remnants of earlier alluvial deposits and subsequent erosion and are often hydraulically connected to the more recent alluvial sediments (Gannon and Langel, 2010).

The climate of west-central Iowa is sub-humid. Denison is the closest city to Dunlap that maintains climate records. The long-term average yearly precipitation at Denison is 28.32 inches (Iowa MESONET, 2011). In 2010, precipitation exceeded the long-term average. Rainfall in June, July, and August 2010 greatly exceeded the long-term averages for those months.

SURFACE WATER

The City of Dunlap is located within the Boyer River watershed. At Dunlap, the Boyer River watershed drains 680 square miles and includes portions of Buena Vista, Carroll, Crawford, Harrison, Ida, and Sac counties.

The closest United States Geological Survey (USGS) streamgage, Boyer River at Logan (USGS site number 06609500), is approximately 18 miles downstream from Dunlap. Daily

average streamflow during 2010 was higher than the long-term average streamflow for most days, especially during the summer months (Figure 3).

GEOLOGY AND HYDROGEOLOGY

The Boyer River alluvial aquifer consists of alluvial and some terrace deposits associated with the Boyer River. The Boyer River alluvial aquifer ranges from less than 0.25 to 2 miles wide and has an areal extent of 79 square miles from the headwaters to the mouth (Runkle, 1985). In the Dunlap area, the Boyer River alluvial aquifer ranges from 1 to 1.5 miles wide.

The Boyer River alluvial aquifer is overlain by fine-grained silt and clay. Regionally, the silt and clay range from 7 to 51 feet thick (Runkle, 1985). Data from 23 test holes and wells in the Dunlap area found that the silt and clay range from 11 to 45 feet thick, with an average thickness of 27 feet.

The Boyer River alluvial aquifer consists of sand and gravel deposited by the modern river system and is highly variable in both thickness and grain size. Regionally, the aquifer ranges from 3 to 57 feet thick (Runkle, 1985). Data from 17 test holes and wells in the Dunlap area found that the aquifer ranges from 11 to 41 feet thick, with an average thickness of 27 feet.

The Boyer River alluvial aquifer is underlain by glacial till or the Cretaceous age Dakota sandstone or shale. Where the aquifer is underlain by the Dakota bedrock, the water levels in the Dakota aquifer wells are slightly higher than water levels in the alluvial aquifer, indicating that the Dakota aquifer is hydraulically connected to and discharging into the Boyer River alluvial aquifer (Runkle, 1985).

Regional groundwater flow in the Boyer River alluvial aquifer is generally directed toward the Boyer River. Groundwater recharge sources are precipitation and infiltration, induced recharge

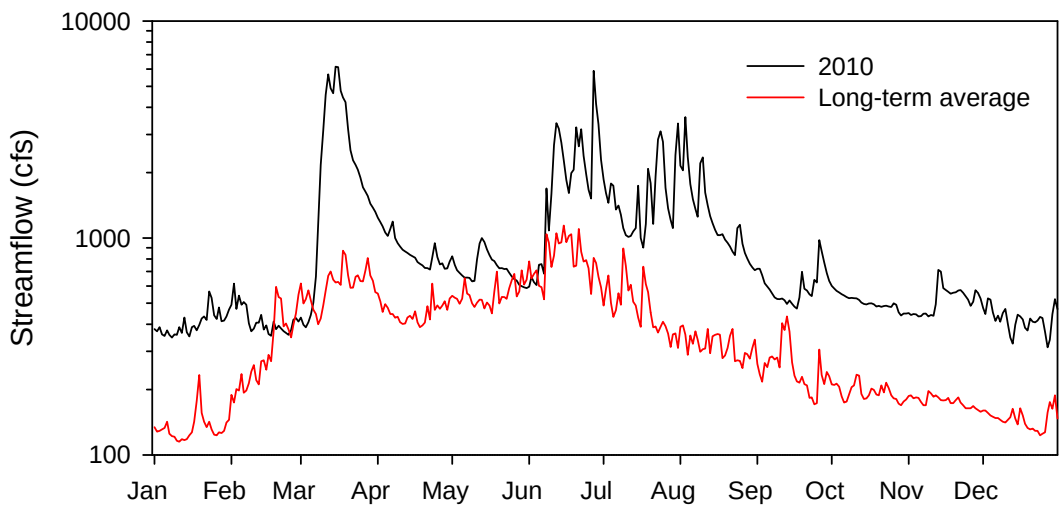

Figure 3. Daily average streamflow for the Boyer River at Logan.

from surface water, and discharge from glacial drift and terraces along the valley wall. The Boyer River can be either a gaining or losing stream. During most of the year when the stream stages are low, the Boyer River is a gaining stream. Exceptions to this occur during high river stage when temporary bank storage may cause a reversal in flow direction.

Aquifer Test Results

Hydraulic properties are used to define and characterize aquifers and include specific yield or storage, transmissivity, and hydraulic conductivity. The most reliable aquifer properties are those obtained from controlled aquifer tests with known pumping rates, pumping duration, accurate well locations, and accurate water level measurements. In conjunction with the City of Dunlap, the Iowa Department of Natural Resources (IDNR) conducted an aquifer test in the Dunlap wellfield. The test occurred Oct. 6-7, 2010.

Based on aquifer test results, the transmissivity of the Boyer River alluvial aquifer ranged from 4,900 feet^2/day to 31,200 feet^2/day (Table 1). The arithmetic mean transmissivity value is 17,436 feet^2/day. Transmissivity values in the aquifer may be higher or lower than those reported due to heterogeneities found in the alluvial sand and gravel units.

Hydraulic conductivity is considered an intrinsic parameter, which means that it is independent of the thickness of the formation, and is calculated by dividing the transmissivity by the overall aquifer thickness. Horizontal hydraulic conductivity was found to range from 140 to 891 feet/day, with an arithmetic mean of 498 feet/day (Table 1).

The vertical hydraulic conductivity of streambed material was calculated using four piezometers installed in the Boyer River. The vertical hydraulic conductivity ranged from 6 feet/day to 22 feet/day (Figure 4). The vertical hydraulic conductivity at P1 was not calculated.

Table 1. Aquifer characteristics in observation wells and piezometers.

Well	Transmisivity (ft^2/day)	Hydraulic Conductivity (ft/day)	Storage Coefficient
OW1	31,200	891	0.0007
OW2	12,000	344	0.02
OW3	26,900	768	0.00002
OW4	24,300	695	0.00004
OW5	5,190	148	0.1
OW6	18,700	534	0.001
OW7	4,900	140	0.1
OW8	16,300	466	0.06
P2		22	
P3		6	
P4		17	

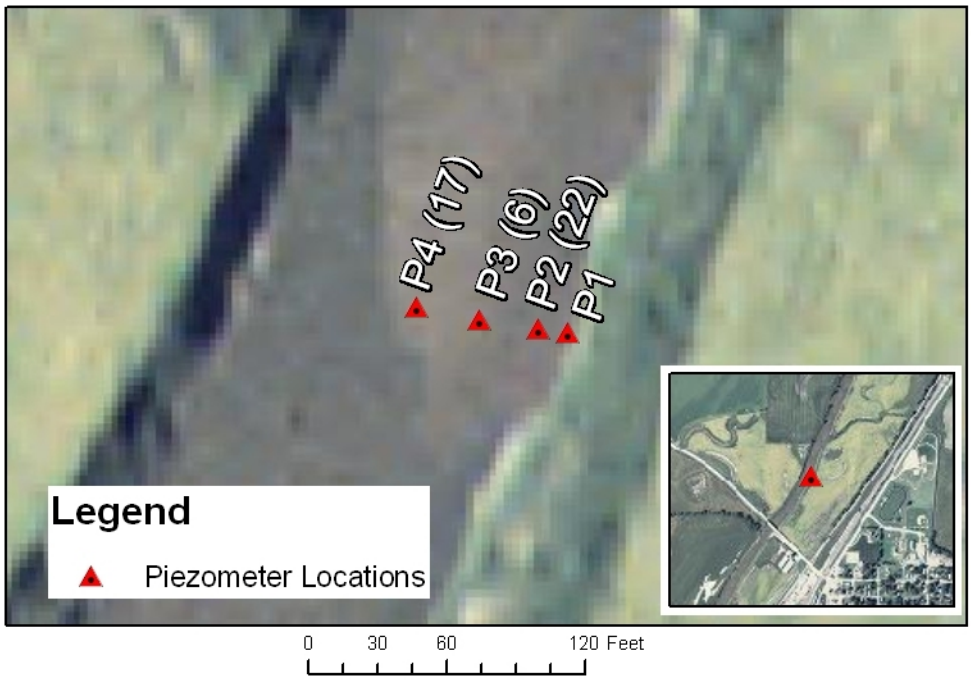

Figure 4. Location of piezometers. Hydraulic conductivity of streambed material is shown in parenthesis (units are ft/day).

While sand comprised the stream substrate at the other piezometers, clay dominated the substrate at P1. The water level in P1 recovered only a few hundredths of a foot during the hour-long slug test. The water levels in the other piezometers recovered to their original level in approximately 30 minutes.

WATER QUALITY

Nitrate (as N) water samples were collected three (3) times from the observation wells. Nitrate levels in these wells ranged from 0.15 mg/L to 19.9 mg/L (Table 2). Relatively low nitrate concentrations in the aquifer were found in the observation wells to the south and southwest of the city wells. Relatively high nitrate concentrations, in excess of the drinking water standard of 10 mg/L were found in the observation wells to the north and northeast of the city wells in the city and school sports complexes.

Nitrate concentrations in all wells except OW4 increased after the aquifer pump test. Figure 5 shows the nitrate concentrations before the pump test on September 28. Figure 6 shows the nitrate concentrations shortly after the pump test ended on October 11. Nitrate concentrations exceeded the drinking water standard of 10 mg/L over a larger area at the conclusion of the aquifer pump test. Vertical leakage of nitrate from the silts and clays overlaying the alluvial aquifer is believed to be responsible for the increase in observations well nitrate concentrations.

Lower nitrate concentrations in the piezometers compared to the Boyer River suggest that the streambed sediments along the bottom of the Boyer River are removing nitrate from the water. The Boyer River had nitrate levels of approximately 8 mg/L. Nitrate levels in the three

Table 2. Nitrate as N concentrations in the Dunlap area. Units are mg/L.

Site	September 28, 2010	October 11, 2010	October 20, 2010
OW1	4	11.9	6.12
OW2	16.7	19.9	17.6
OW3	5.05	6.09	5.72
OW4	0.36	0.22	0.15
OW5	0.79	1.18	0.7
OW6	7.85	14.3	8.82
OW7	2.46	8.27	7.8
OW8	1.7	4.04	
P1		3.82	
P2		0.73	
P3		1.46	
P4		1.77	
Boyer River		8.23	8.39

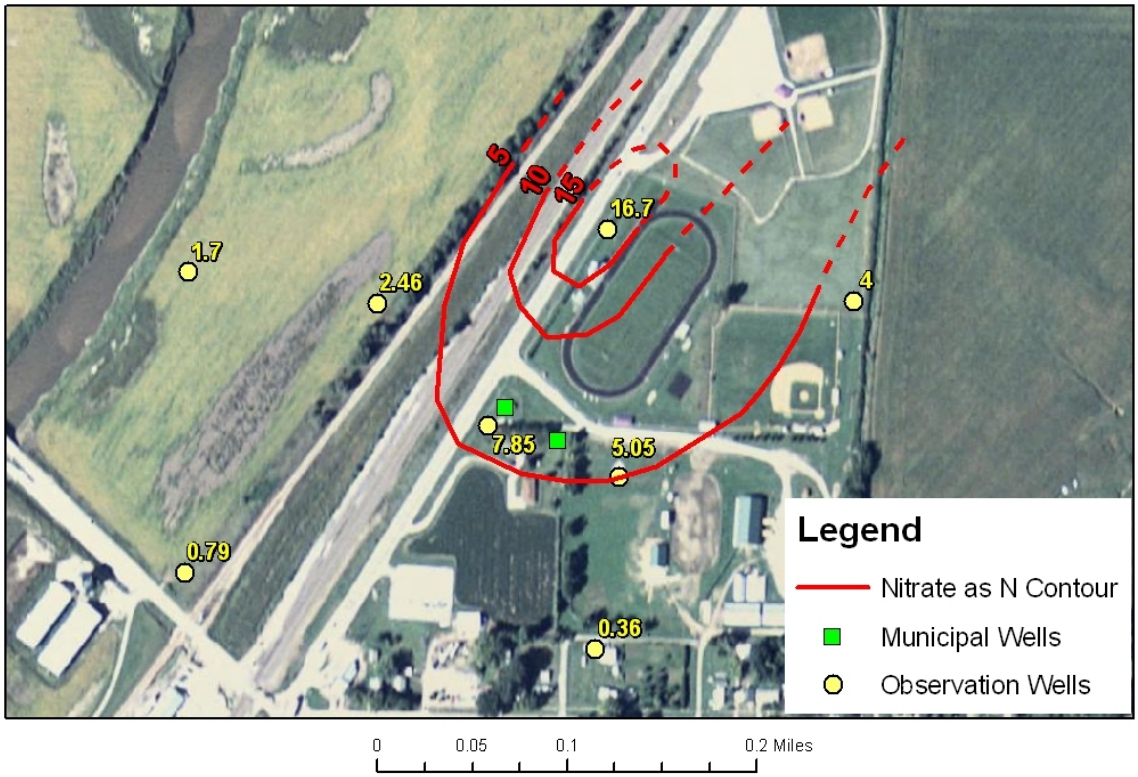

Figure 5. Nitrate as N concentrations in the Boyer River alluvial aquifer on September 28, 2010.

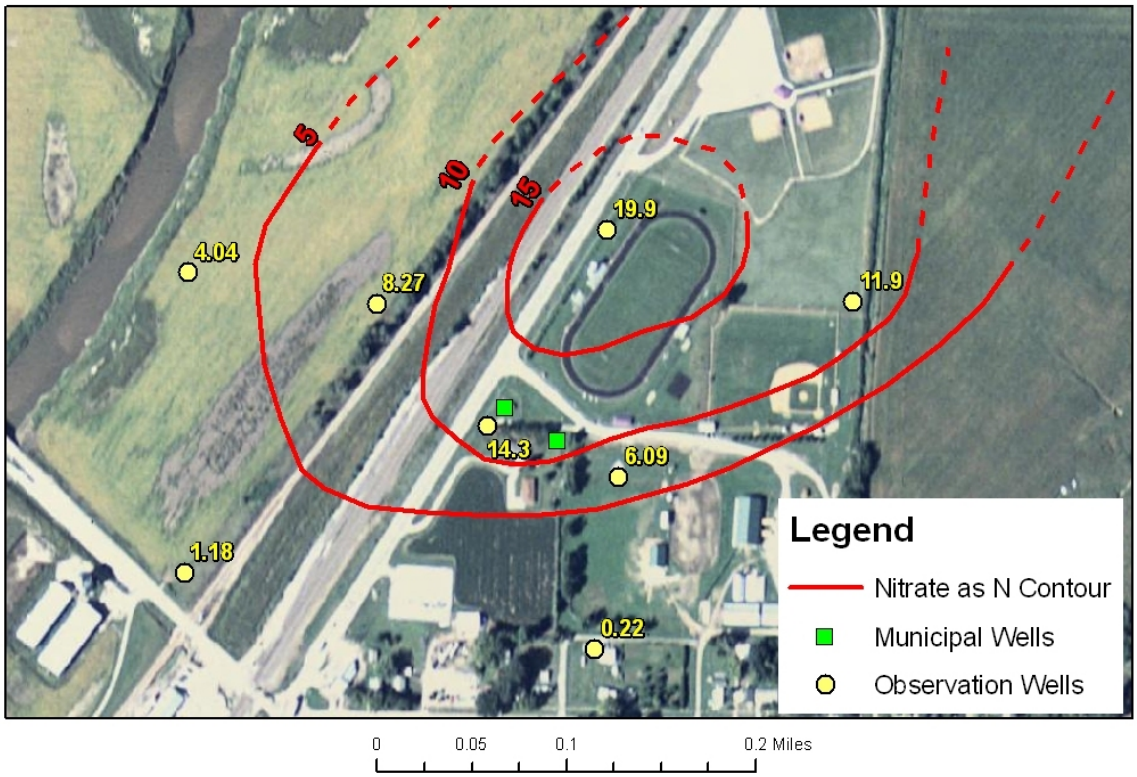

Figure 6. Nitrate as N concentrations in the Boyer River alluvial aquifer on October 11, 2010.

piezometers, P2, P3, and P4, installed into sand ranged from 0.73 to 1.77 mg/L. The nitrate level in P1, which was installed in clay, was 3.82 mg/L.

GROUNDWATER MODELING

Groundwater flow in the Boyer River alluvial aquifer was simulated using Visual MODFLOW Ver. 2010.1 (Schlumberger Water Services, 2010). MODFLOW is a widely used finite difference groundwater modeling program originally developed by the USGS. The Boyer River alluvial aquifer was simulated using a three-layered model (Figure 7). The model layers included:

- Model layer 1 is the fine-grained silt and clay that overlie the aquifer. The thickness of layer 1 is variable and is based on data from 23 local wells and borings. The horizontal hydraulic conductivity was assigned a value of 0.3 feet/day. The vertical hydraulic conductivity value was assigned a value 1/10 of the horizontal hydraulic conductivity.
- Model layer 2 is the sand and gravel deposits of the Boyer River alluvial aquifer. The thickness of layer 2 is variable and is based on data from 19 local wells and borings. The horizontal hydraulic conductivity, which was based on the results of an aquifer pump test, was variable and assigned values as shown in Figure 8. The vertical hydraulic conductivity value was assigned a value 1/10 of the horizontal hydraulic conductivity.

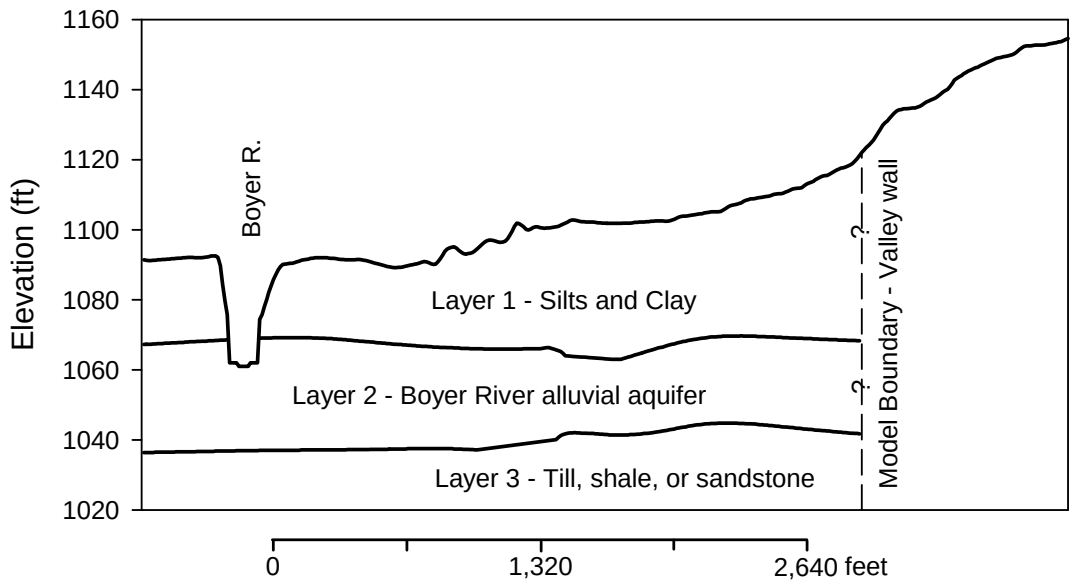

Figure 7. Generalized conceptual model of the Boyer River alluvial aquifer.

- Model layer 3 is the till, shale, or sandstone that underlies the Boyer River alluvial aquifer. The horizontal hydraulic conductivity was assigned a value of 0.03 feet/day. The vertical hydraulic conductivity value was assigned a value 1/10 of the horizontal hydraulic conductivity.

The main water source for the City of Dunlap's wells is assumed to be the Boyer River alluvial aquifer despite the fact the wells are also open to the Dakota aquifer. The geology and aquifer characteristics of layer 3, which includes portions of the Dakota aquifer, are largely unknown because of the lack of wells and well information. In the few wells that exist, tills, shales, and sandstones all underlie the Boyer River alluvial aquifer in the model area. The lack of wells makes mapping the geology difficult. The lack of wells with pump test data makes calculation of aquifer parameters nearly impossible.

Other model parameters included in the groundwater flow model are:

- The model was divided into a grid containing 141 rows and 149 columns. Individual cells varied in size, with the smallest cells located in the City of Dunlap and increasing in size outward.
- The uplands on the east and west sides of the model area were considered no-flow boundaries. This was represented by de-activating the grids outside the alluvial aquifer boundary.
- General head boundaries were used on the northern and southern ends of the model area to represent flow-through conditions.
- A general head boundary was used on the eastern edge to simulate terrace recharge.

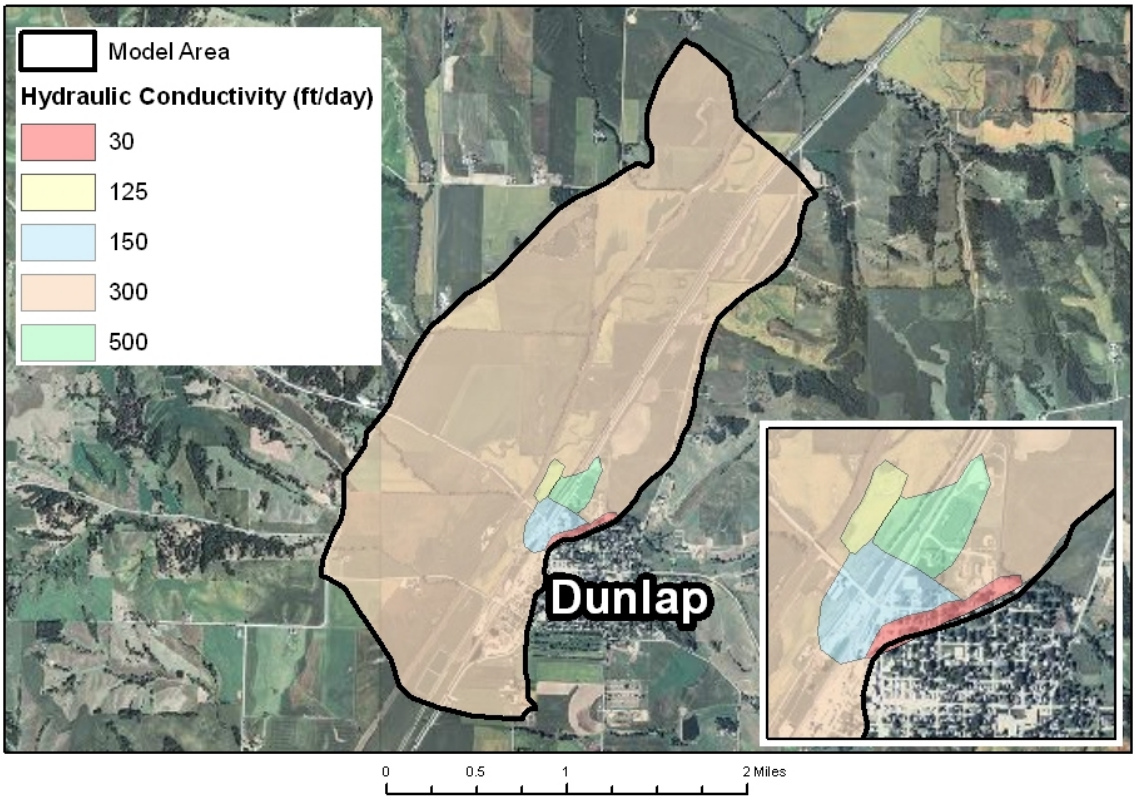

Figure 8. Hydraulic conductivity distribution in the Boyer River alluvial aquifer.

- The Boyer River and an unnamed tributary to the Boyer River on the northern edge of Dunlap were represented as river boundaries. The streambed and surface water elevation were estimated using LiDAR data. A water level depth of 1 m (3.28 ft) and 0.3 m (1 foot) were used for the Boyer River and the unnamed tributary, respectively. The vertical conductivity of the streambed was estimated at 1/10 the average horizontal conductivity of the alluvial aquifer.
- Average annual recharge was calibrated to be 5 inches/year.

Calibration Results

The model initially simulated non-pumping conditions. The model was calibrated using water level measurement made on September 28, 2010, when the city wells were not pumping. Figure 9 and Table 3 compare the simulated water table map with observed data.

A transient model was then developed to simulate the effects of the aquifer pump test on October 7, 2010. A pumping rate of 560 gallons per minute (gpm), which was divided equally between wells 3 and 4, was used in the simulation. The sand and gravel aquifer was believed to be discharging 500 gpm, while the sandstone was discharging 60 gpm. Figure 10 and Table 4 compare the simulated water table map with observed data. The water level drawdown simulated with the computer model was within ±0.1 ft for most wells.

Table 3. Simulated versus observed elevation during non-pumping conditions.

Site	Groundwater Elevation (ft)		Difference (ft)
	Observed	Simulated	
OW1	1078	1077.2	0.8
OW2	1076.2	1076	0.2
OW3	1076.8	1076.3	0.5
OW4	1076.3	1076.7	-0.4
OW5	1075.1	1073.8	1.3
OW6	1075.4	1075.6	-0.2
OW7	1075.4	1075.1	0.3
OW8	1074.6	1073.6	1

Figure 9. Simulated versus observed groundwater elevations for the non-pumping (steady-state) model.

Table 4. Simulated versus observed drawdowns during aquifer pump test.

Site	Drawdown (ft)		Difference
	Observed	Simulated	(ft)
OW1	1.31	1.3	0.01
OW2	1.41	1.5	-0.09
OW3	1.41	1.5	-0.09
OW4	2.39	2.4	-0.01
OW5	0.79	0.64	0.15
OW6	3.38	4.1	-0.72
OW7	1.38	1.5	-0.12
OW8	0.59	0.56	0.03

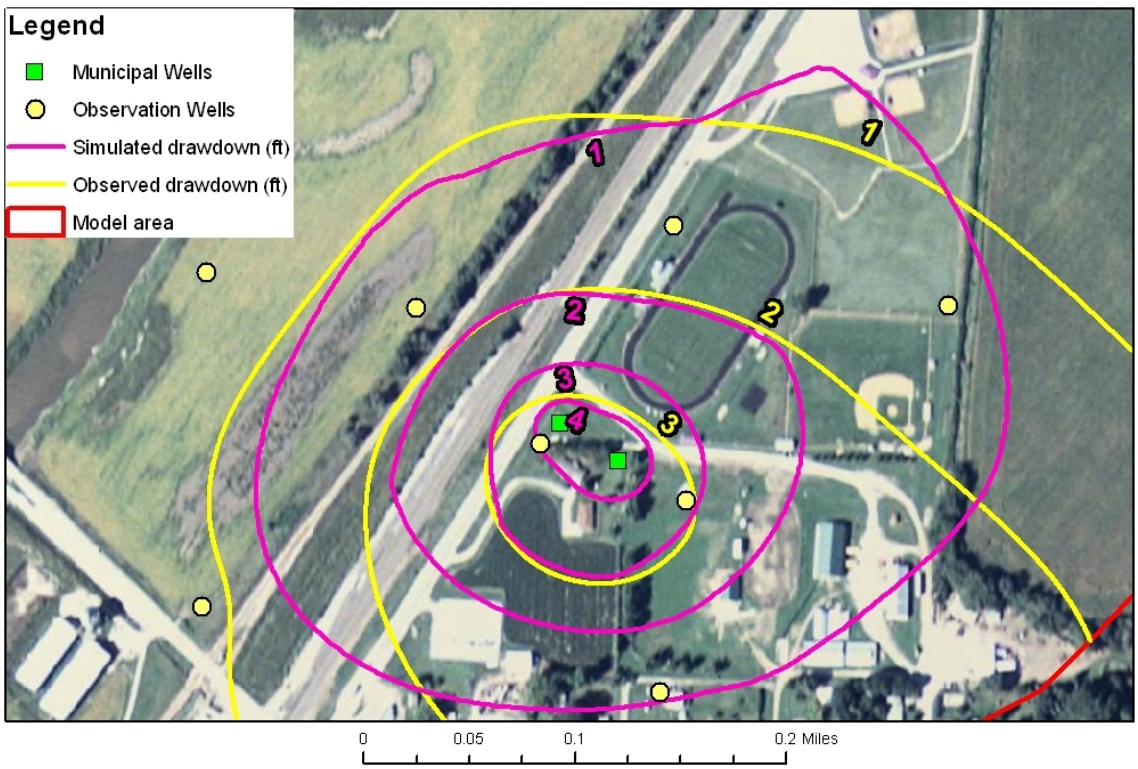

Figure 10. Simulated versus observed groundwater drawdowns at the end of the aquifer pump test.

Capture Zone Model Simulation

Using the calibrated transient model, real time pumping rates were entered into the model for city wells 3 and 4. The real time pumping rates were estimated using the combined pumping rates of the two city wells multiplied by the cumulative time each pump was on each day. The pumping rates were provided by the City of Dunlap, and the cumulative time was calculated by dividing the known pumping rate by the daily water usage. The combined pumping rate for city wells 3 and 4 was approximately 560 gpm (500 gpm was estimated from the alluvial aquifer).

The average daily water usage from 2000 to 2009 was found in the IDNR water use database. The total time the wells were on each day varied from 5 to 10 hours over the 10-year time period.

The particle tracking subroutine found in Visual MODFLOW 2010.1 was used to estimate the 2-, and 5-year capture zones. The backward method of particle tracking was used over a 3,650 day time period. Particles were tracked yearly along simulated flowlines. Two-year and five-year capture zones were then estimated by drawing a line connecting the corresponding particles. Ten-year capture zones were not drawn since the backward simulation (movement) of particles terminated within five years of run time.

The river stage was assumed to be constant (based on LiDAR elevations) over the ten-year time period. This assumption was used due to the lack of local river stage and groundwater level data. In reality, the river stage and the corresponding groundwater levels could vary considerably over time. The lack of time series groundwater level data and river stage data are the biggest limitations of the model.

RESULTS

Based on conditions that existed in the fall of 2010, groundwater capture zones for the City of Dunlap's wells were created. The total capture zone is 106 acres, 82 acres of which are in the two-year capture zone (Figure 11). The capture zone includes:

- 4.7 acres in sports complexes, baseball and football field, owned by the Boyer Valley school district. This area was identified as having nitrate levels in excess of the drinking water standard after the aquifer pump test concluded.
- 10.7 acres sport complex managed by the City of Dunlap.
- 39 acres of agricultural land in three different parcels. The largest parcel, 26.3 acres, is located to the east of the city's wells.

Five agricultural cooperatives, potential nitrate point sources located to the south and west of the city wells, were not within the city's wells capture zones and have no impact on the water quality in the city's wells.

During the study, the city wells did not receive induced recharge from the Boyer River. The elevation of the Boyer River was approximately two (2) feet lower than the elevation of the water table in the observation well closest to the river, OW8. The elevation of the Boyer River was lower even during the aquifer pump test when the water level in OW8 dropped ~0.5 feet. The groundwater flow model similarly indicated that the city's wells were not receiving induced recharge.

Despite not receiving induced recharge during this study, the city wells can receive induced recharge under certain conditions. The Boyer River elevation needed to be ~2 feet higher during this study for induced recharge to occur. Spring snowmelt and early summer thunderstorms produce conditions that would increase the Boyer River's elevation. The Boyer River elevation was three (3) feet higher than elevations during this study for 55 days in 2010. During these high flow periods, the city wells can receive induced recharge.

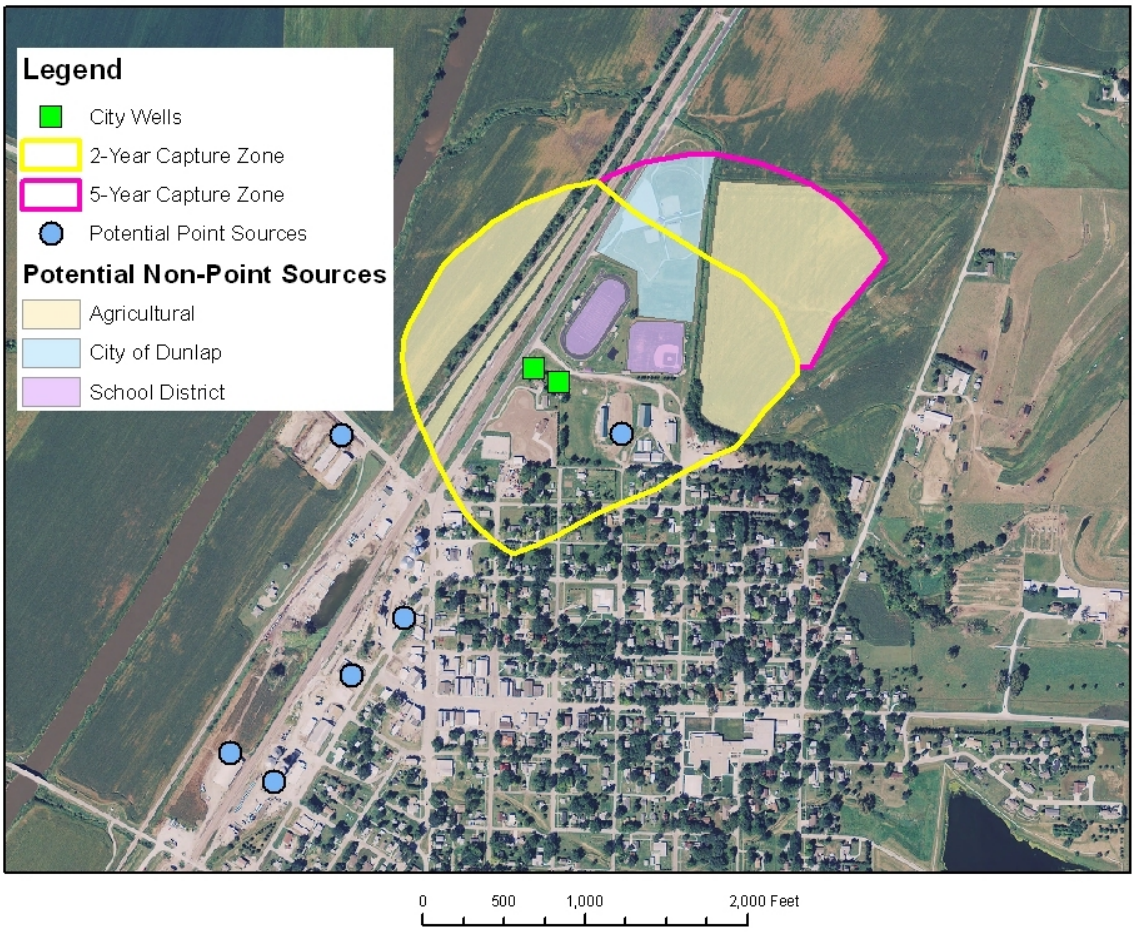

Figure 11. Two (2) and five (5) year capture zone for City of Dunlap's wells.

Water Quality Improvements

The City of Dunlap itself has two options to improve water quality in the short term. If the city continues not applying nitrogen fertilizer to the city's sports complex and other city-owned lands, a source of nitrate is eliminated. Reducing the pumping rate for the city wells will decrease the size of the capture zone and may result in better water quality. The groundwater flow model simulated the effects of reducing the pumping rates in half. The resulting capture zone is 27 acres, roughly ¼ of the original size (Figure 12). Additionally, this capture zone pulls water from areas observed to have lower nitrate concentrations.

Reducing the sources of nitrate within the capture zone may help improve water quality. The highest nitrate levels observed in this study were associated with the Boyer Valley school district's sports complexes, particularly the football field. If the school is applying nitrogen fertilizer on their property, any reductions they can make should lower nitrate concentrations in the aquifer. During fair season, manure is temporarily stored on the Harrison County fairgrounds. Ensuring that this manure is disposed outside of the capture zone eliminates another potential source of nitrate. Three tracts of agricultural land were found within the capture zone. Establishing nitrogen management plans, if they do not already exist, may further reduce nitrate concentrations in the aquifer.

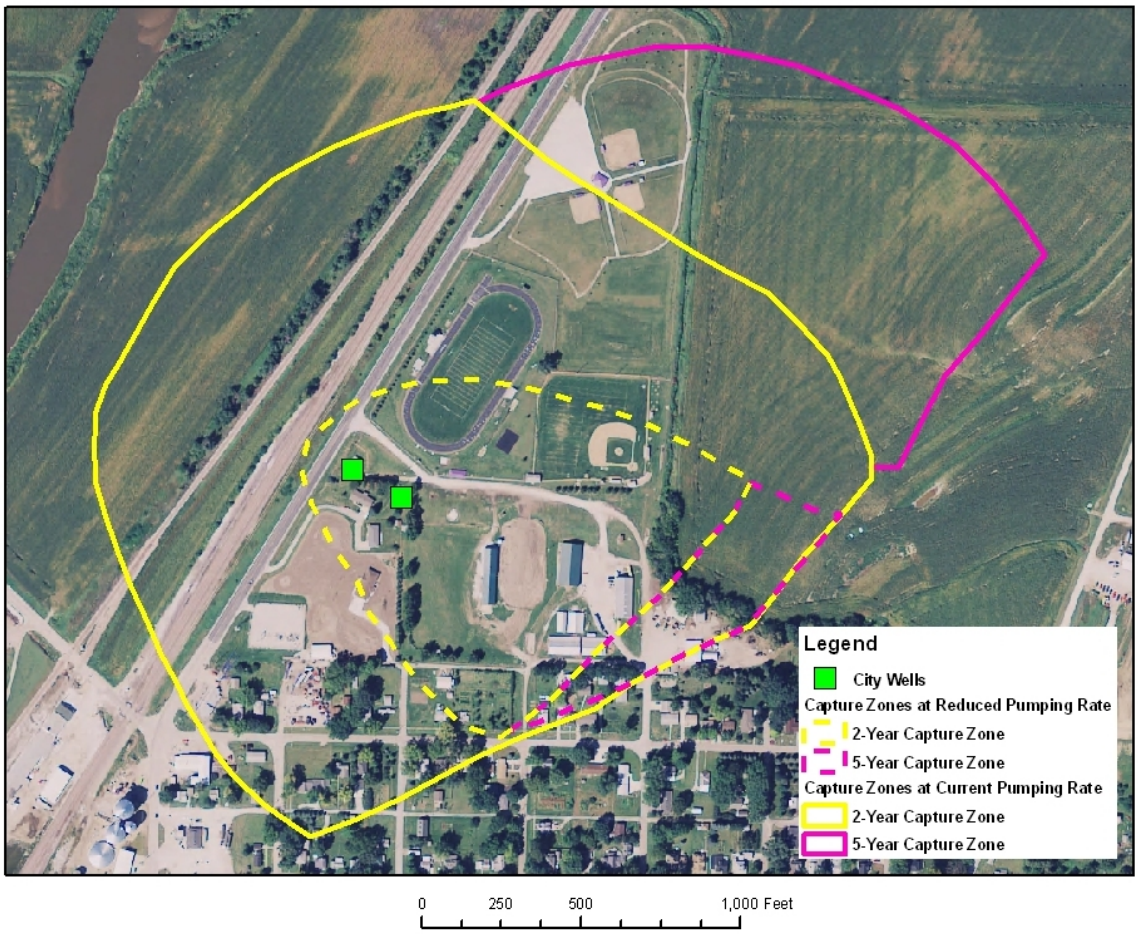

Figure 12. Comparison of capture zone for City of Dunlap's wells based on current pumping rate and a reduced rate.

The location of future wells may further reduce nitrate concentrations in the city's water supply. Increasing the spacing between future wells should help lessen the vertical leakage of nitrate from the overlying units into the aquifer. Installing new wells closer to the Boyer River may allow the wells to capture more induced recharge, which has a significantly lower nitrate concentration.

CONCLUSIONS

A hydrogeologic study of the Boyer River alluvial aquifer near Dunlap was initiated in the fall of 2010. A critical component of the study was developing a groundwater flow model that would generate capture zones for the City of Dunlap wells and quantify the amount of induced recharge the city wells receive from the Boyer River. The capture zone generated from the groundwater flow model is 106 acres in size and includes Boyer Valley school district's football and baseball field, the City of Dunlap's sports complex, the Harrison County fairground, and three different parcels of agricultural land.

Nitrate concentrations were variable throughout the Boyer River alluvial aquifer. Nitrate levels in observation wells ranged from 0.15 mg/L to 19.9 mg/L. Relatively high nitrate

concentrations, in excess of the drinking water standard of 10 mg/L were generally found in the observation wells to the north and northeast of the city wells in the city and school sports complexes. Nitrate concentrations in all of the observation wells, except OW4, increased due to pumping stress. This suggests that pumping stress increases the vertical leakage of nitrate-rich groundwater into the alluvial aquifer from the overlying silt and clay unit.

During the study, the city wells did not receive induced recharge from the Boyer River. Water level elevations in observations wells in the alluvial aquifer remained higher than the elevation of the Boyer River. However, induced recharge is possible during short-term durations when the elevation of the Boyer River is higher during flood events.

Many options exist to lower the nitrate concentrations in the city's wells. The city can lower the pumping rates in the city wells, which would reduce the vertical leakage of nitrate from the overlying silt and clay units. Reducing the pumping rates would also decrease the size of the capture zone, and pull groundwater from areas with lower nitrate concentrations. Reducing the application of nitrogen fertilizer on the Boyer Valley school district's sport complexes or agricultural land in the current capture zone may help lower nitrate concentrations. Locating new wells closer to the Boyer River may improve the water quality by capturing more induced recharge

ACKNOWLEDGEMENTS

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