Sources of Groundwater Supplying White Lake

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September 18, 2022

SUMMARY OF KEY FINDINGS

1. Sources of water supplying White Lake are precipitation and groundwater from the surficial aquifer. The extent to which the lake gains or loses water from/to groundwater varies with water table elevations/heads in the surficial aquifer surrounding and underlying the lake, and rainfall is the key factor affecting those.

2. Groundwater recharge at the higher land elevations to the northeast of White Lake provides a means for water table elevations to be substantially higher than lake levels. At times following recharge events, deeper flow lines can be expected for groundwater reaching the lake bottom from those elevations/distances versus recharge closer to the lake, such as from the sandy rim.

3. Water level measurements, taken via a temporary well pipe placed about 13 feet into the lake bottom at a known springs site, demonstrated that at times there is a downward hydraulic gradient even in the vicinity of the known springs, with the lake level measured one foot higher than the stabilized water level in the pipe (which represented head levels in the surficial aquifer sands beneath the lake). With a downward hydraulic gradient at this location and depth, seepage losses are likely to occur at times across the entire lake bottom.

4. A clay hardpan layer is well-known to occur in most places around the lake perimeter, typically about 7-feet thick from depths near 5 to about 12 feet and extending some distance into the lake. The hardpan was not encountered at the springs site when the temporary well pipe was installed to a depth of 21 feet below lake level. It was also absent at the site of a deep well drilled east and uphill from Lake White, at an elevation of approximately 78 feet. If the hardpan is largely absent beneath the elevated land areas to the northeast and also absent beneath portions of the lake, the hardpan may act as a “caprock” for a distance in between, preventing underlying groundwater from discharging up into the lake bottom until it reaches the point where the hardpan pinches out or is otherwise breached. This may explain the unusual way in which groundwater discharges at times to the lake bottom in concentrated locations (versus over broader areas of the lake bottom, which is more typical for lakes).

5. The lake (and hardpan) lie entirely within the surficial aquifer sediments. The clay confining unit that underlies the surficial aquifer is deeper in the surrounding region and was encountered at elevations of 10 to 32 feet at three local research sites (versus a typical lake level elevation of 64 feet, with bottom depths of about 8 feet in deeper parts). That would equate to the confining unit being 24 to 46 feet below the lake bottom.

6. The effectiveness of the confining unit as a hydraulic barrier between the surficial aquifer and deeper Black Creek aquifer has been demonstrated by water level differences in monitoring wells at a nearby State research station, with surficial aquifer levels typically about 10 to 12 feet above Black Creek aquifer heads (potentiometric levels). The downward hydraulic gradient means a downward potential for flow. If the confining unit between the aquifers is absent or leaky beneath some area(s) of the lake, which is very unlikely, the surficial aquifer would drain downward into the Black Creek aquifer.

7. Leaks in the Town's sewer system are capturing and transferring groundwater to the wastewater treatment plant. The system underlies most of the sand rim surrounding the lake and separates the lake from the elevated land areas to the northeast. A comparison of numbers for water being pumped from the Town's public water supply wells versus gallons discharged from the treatment plant from 1993 to 2008 shows that the differences averaged 227,644 gallons per month and exceeded 300,000 gallons for 54 months for the 109-month period. Greater differences tended to occur during/following months with higher precipitation and in seasons when the water table is typically higher (winter and spring) versus other times of the year. The current program to repair and replace leaky portions of the sewer system will allow more groundwater to enter the lake. The extent of that impact will be difficult to gauge with future groundwater monitoring, as the repairs/replacements are already underway and because of other variables, primarily rainfall.

8. Another concern regarding the sewer system is whether or not excavation depths, including those for the current replacements/repairs, have removed or otherwise breached portions of the hardpan layer. If the hardpan functions as a caprock as described above, breaches could cause a reduction in groundwater pressure beneath the hardpan (at times when surficial aquifer heads are sufficiently high to impose pressure from higher elevations). This could potentially affect flow at the renowned springs and would mean a larger proportion of groundwater entering the lake/lake bottom from more shallow depths, nearer to the shoreline.

9. The many ponds at the blueberry farms to the northeast and uphill from White Lake are likely to have an overall lowering impact on water table levels because of land drainage and evaporative losses between precipitation events. These higher elevation areas are where water table elevations can be substantially higher at times than lake levels, providing hydraulic gradients for groundwater discharge into the lake bottom. The extent to which hydraulic gradients are lessened by the ponds is difficult to assess without more information about the ponds and without monitoring wells that are nearer to ponds and at deeper depths within the surficial aquifer versus wells utilized for previous studies.

10. For ponds that are pumped for irrigation or freeze protection, water table levels would be further lowered near the ponds during pumping. However, if irrigation ponds are supplied by deep, confined aquifer pumping wells, the impacts to the surficial aquifer would depend upon levels maintained in the ponds, with ponds contributing water to the surficial aquifer when pond levels are higher than the surrounding water table.

11. Impacts from most ditches at the blueberry farms would be similar to ponds, with many appearing (from aerial views) to function as long, narrow ponds, not connected to drainage areas

other than nearby ponds. However, there is a long ditch to the north of White Lake that is an exception, draining to swamps that then flow to Turnbull Creek. The NC Division of Water Resources has considered whether or not the ditch affects groundwater inflow to White Lake, noting that flow in the ditch has appeared to be constant and was measured on one occasion to be flowing at 750 gallons per minute. The topography suggests that land areas being drained by this ditch may be too far north to affect White Lake, but possible impacts could be better assessed with monitoring wells north of White Lake and with ditch monitoring.

12. Well pumping from deep, confined aquifers (the Black Creek aquifer and/or the Upper Cape Fear aquifer) is not likely to have any impact upon groundwater inflow or outflow to/from White Lake. The lake is underlain by the surficial aquifer, which is separated from the deeper, Black Creek aquifer by a confining unit that is well-documented regionally and has an effectiveness that has been demonstrated locally. The Town of White Lake's public water supply wells utilize the Black Creek and Upper Cape Fear aquifers, and wells at the blueberry farms likely do, too. Drawdown impacts in the deeper aquifers, even at these close locations, should not affect White Lake at all.

13. There is an indirect way in which deep, confined aquifer wells could affect groundwater inflow to White Lake. Deep wells could be a source of surficial aquifer drawdown if wells have not been properly sealed at depths of the confining unit. If no bentonite grout has been placed where the confining unit was encountered (and drilled through), the surficial aquifer could drain into the Black Creek aquifer via well gravel packs, lowering surficial aquifer heads and potentially impacting the lake. Unlike the short drawdown cycles that are typical for surficial aquifer wells, drainage from the surficial aquifer to the Black Creek aquifer via leaky, deep wells would have a constant drawdown effect on surficial aquifer levels.

14. The impacts of pumping shallow wells (screened in the surficial aquifer) at properties surrounding the lake is likely to be minor, assuming the wells are for purposes such as residential supply or irrigation and do not have substantial pumping rates/periods. Wells for higher yields will likely be screened in the deeper, confined aquifers, with the only risk being leaky seals, as previously mentioned. If any of the wells at the blueberry farms are screened in the surficial aquifer, there could be seasonal drawdown impacts affecting hydraulic gradients between these higher land areas and the lake, but it is more likely that these wells utilize the deeper, confined aquifers.

BACKGROUND

GeoResources, PLLC was contracted by Lumber River Council of Governments (LRCOG) to review existing hydrogeological information and provide opinions regarding sources of groundwater supplying White Lake and factors affecting groundwater inflow. In addition, GeoResources was asked to outline plans for an additional study with “ballpark” costs that would be helpful toward further characterizing sources of groundwater, the extent to which groundwater comprises overall water input to the lake, and the factors affecting that. Cost estimates provided herein are simply based on the author’s experience with other projects and do not represent a proposal or actual quotes. Opinions that follow are those of Curtis Consolvo, L.G., GeoResources, PLLC. No new data were collected for preparing this report.

Groundwater contributions to White Lake have been the subject of many studies. Some, such as the recent, extensive study by Shank and Zamora (2019), include evaluations of water quality in groundwater and in the lake water to learn more about flow between the two. The report that follows focuses more on groundwater flow in response to the hydraulic head differences/hydraulic gradients that drive flow and the strata through which flow occurs (or does not). Water quality characteristics, especially with respect to surface waters and biological factors, are outside the expertise of this author and are left to be addressed in other parts of the larger LRCOG document in which this report is presented.

SHALLOW GROUNDWATER CONTRIBUTIONS

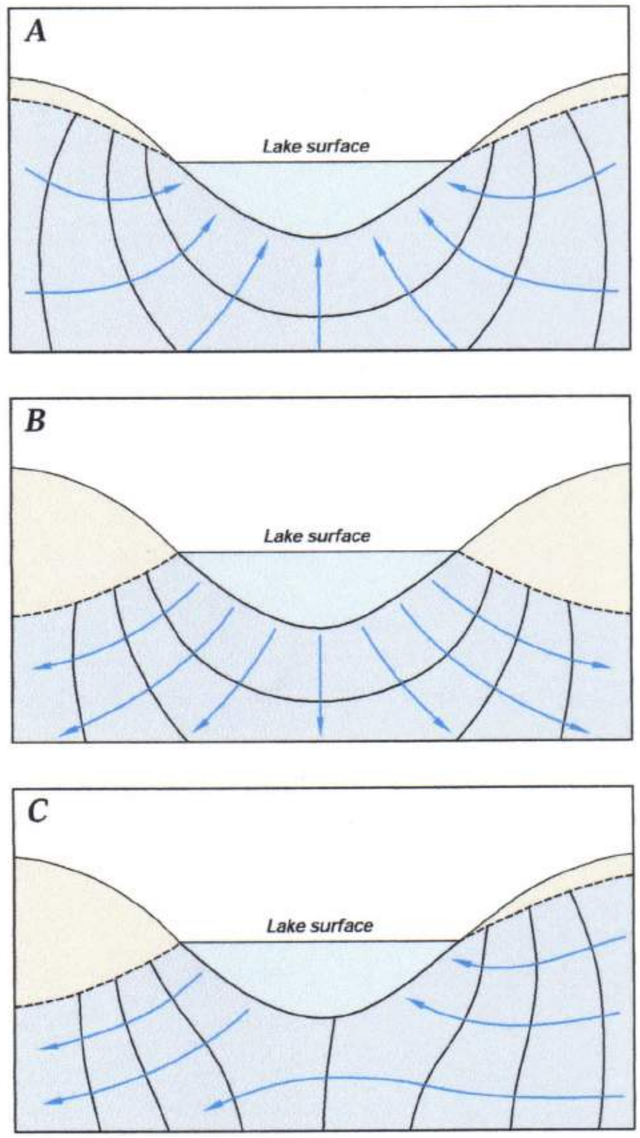
Flow interactions between the lake and groundwater

Sources of water supplying White Lake are precipitation and groundwater from the surficial aquifer. The lake is surrounded and underlain by the surficial aquifer, also known as the water table aquifer. The extent to which the lake gains or loses water from/to the lake bottom varies with the dynamics between lake levels versus water table levels/heads surrounding and underlying the lake. Rainfall is the key factor affecting both levels in the lake and in the surficial aquifer.

At times and in places where water table elevations surrounding the lake are higher than lake levels, hydraulic gradients provide the driving force for groundwater inflow to the lake. The higher the water table, the greater the driving force, so that rainfall and its effect upon water table elevations is the primary variable affecting how much groundwater enters or exits the lake.

Differing types of flow interactions between groundwater and lakes are shown in a generalized diagram (Figure 1) by Winter and others (1999). Flow interactions at White Lake can vary between these, depending primarily upon rainfall. Results of an extensive study by Shank and Zamora (2019) indicate that groundwater inflow to the lake typically occurs from the north and east, with water losses from the lake typically to the southwest, most closely resembling diagram C (Figure 1). They also found that following heavy precipitation, the water table elevation, even at the southwestern edge of the lake, can briefly be elevated above the lake level, more closely resembling diagram A.

Figure 1: Interaction of Groundwater and Lakes



Lakes can receive ground-water inflow (A), lose water as seepage to ground water (B), or both

Source: Winter and others, 1999

Flow variations at the springs

The variability of flow interactions between groundwater and White Lake has also been evident at the known/observed springs, with a long history of being active at times and inactive at other times. Frey (1949) described the springs as being "a number of round clean areas in a region where the sand is thinly covered with fine dark detritus", with "centers about 8 inches lower than edges". He described the location as being offshore about the middle of the northeast side, which coincides with aerial photographs and anecdotal evidence of features that appear to be plumes of light-colored sand suspended in the water. He also described that "the bottoms were hard, no bubbling as reported by other visitors could be observed through a water glass". Wells and Boyce (1953) reported that Wells had observed sand "boiling over a number of orifices" many years earlier, but then later observed that "during times of extended drouth the outlet stream came down to a mere trickle".

In the summer of 2017, the NC Division of Water Resources (NC DWR) placed a temporary well into the lake bottom (from a boat) at a location about 1,175 feet from the northeastern shoreline approximately where springs have been observed at times. The springs were not visible from the boat at the time, and an aerial image showing what appears to be clouds of suspended sand (believed to represent spring sites) was used in combination with triangulating to shoreline features for siting the well (K. White, NC DWR, personal communication, August 1, 2022). The pipe was washed into the sandy bottom to a depth of approximately 21 feet below lake level, or about 13 feet below the bottom of the lake . The water level in the well pipe stabilized at a level approximately one foot below the lake level, indicating a downward hydraulic gradient and that seepage into the lake bottom was occurring at the time.

The 2017 study also found that water table elevations in nested monitoring wells at eastern and western edges of the lake exhibited downward hydraulic gradients throughout the summer/early fall monitoring period. Water levels were consistently higher in the more shallow monitoring wells than in adjacent deeper wells (both depths were within the surficial aquifer). The data suggest that the downward hydraulic gradient evidenced at the springs site and resulting seepage losses to groundwater may occur at times across the entire lake bottom.

Contributing area for groundwater reaching White Lake

When and where water table levels in the land surrounding White Lake exceed lake levels, there is the potential for flow to the lake. As described by Heath (1983), "the water table is usually a subdued replica of the land surface", and simply based on topography, the slightly elevated rim surrounding most of the lake and uphill areas extending to the north and east are the likely source areas for groundwater supplying the lake.

The hydraulic gradients surrounding and underlying the lake vary with lake levels versus water table levels/heads, such that source areas for groundwater inflow will also vary, primarily with rainfall, but attempts can be made to determine the areas (and depths) that most often serve as sources of groundwater supply to White lake. Groundwater from deeper aquifers underlying the surficial aquifer is not a source of lake water, as discussed in the following section (Deeper Groundwater).

Shank and Zamora (2019) conducted an extensive, one-year study and delineated source areas for groundwater contribution to White Lake (Figure 2). These findings were supported by water level monitoring in the lake and in the surficial aquifer, water quality analyses, and hydrologic modeling. Monitoring wells for water levels and quality were placed along transects extending away from the shoreline at multiple locations surrounding the lake. The contributing zone (Figure 2) generally conforms with topography, and Shank and Zamora (2019) incorporated LiDAR data for development of the surface terrain in their model. However, the topography, as it appears on a river basin boundary map, suggests that the contributing area may extend somewhat farther to the east (Figure 3).

Hardpan occurrences and possible explanation for unusual springs

A clay "hardpan" layer is commonly encountered in the subsurface surrounding the lake and underlying portions of the lake bottom extending a distance into the lake. Shank and Zamora (2019) found that it consistently occurred at depths of 5 to 12 feet around White Lake. The NC DWR encountered very hard clay at both east and west well nests (each about 100 feet from the lake). Clay occurrences were similar at both sites, at a depth of 5 feet and continuing to a depth of approximately 13 feet, where it became mixed with sand that increased with depth to the bottom of the holes, at depths near 25 feet (K. White, NC DWR, personal communication, September 8, 2022). The hardpan is well known to pier/dock builders, with anecdotal accounts of encountering it all around the lake and using it as a base for piles (K. White, NC DWR, personal communication, September 8, 2022).

The hardpan is evidently not continuous across the lake bottom, as it was not encountered at the approximate location of the known/observed springs when the NC DWR installed the temporary monitoring well, as previously described. The well pipe was easily advanced to a depth of 21 feet below lake level or about 13 feet below the bottom of the lake (K. White, NC DWR, personal communication, August 1, 2022). With a water depth of about 8 feet to the lake bottom in that location, the bottom elevation of the pipe was below the elevation of common hardpan occurrences near the lake edges. That and the anecdotal accounts of a sandy bottom in other deep areas of the lake suggest that the hardpan is either absent or sharply dips/becomes deeper beneath central portions of the lake.

At a U.S. Geological Survey borehole site approximately 2,100 feet west of White Lake at an elevation of 71 feet along NC Highway 53, clay was encountered at a depth of 39 feet (elevation 32 feet), which was interpreted as being the base of the surficial aquifer (Weems and others, 2011). There apparently was no hardpan, as the only clay reported in the drilling log above 39 feet is a 0.3-foot zone of clayey, silty sand, at a depth of 17 feet.

To the east and uphill of White Lake, at an elevation of approximately 78 feet, the hardpan was not encountered in a deep hole drilled for a Black Creek aquifer production well, with the NC DWR on-site (K. White, NC DWR, personal communication, September 7, 2022).

Figure 2: Shank and Zamora's (2019) Groundwater Contributing Zone (Figure 23 of their report).

Figure 2

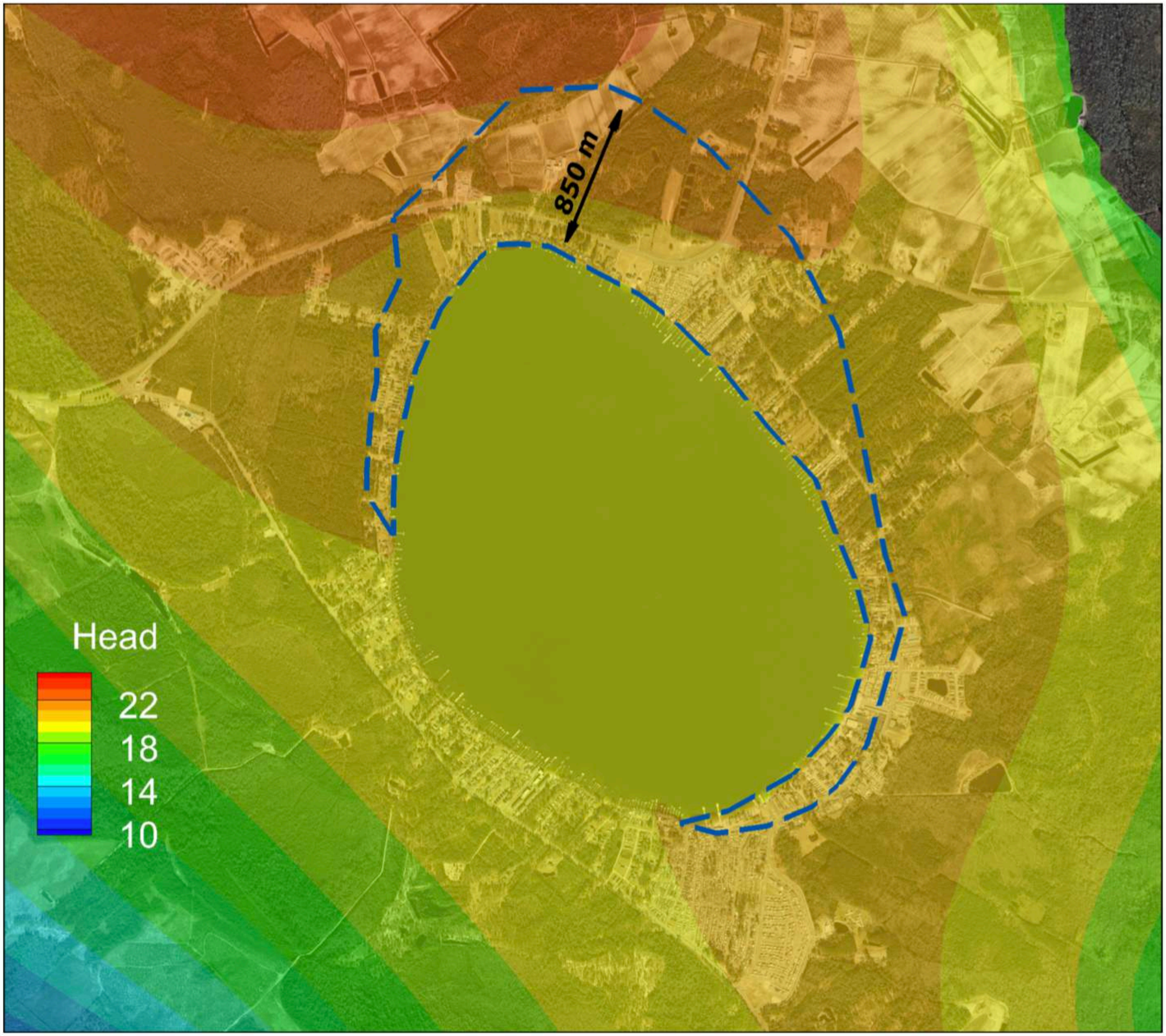
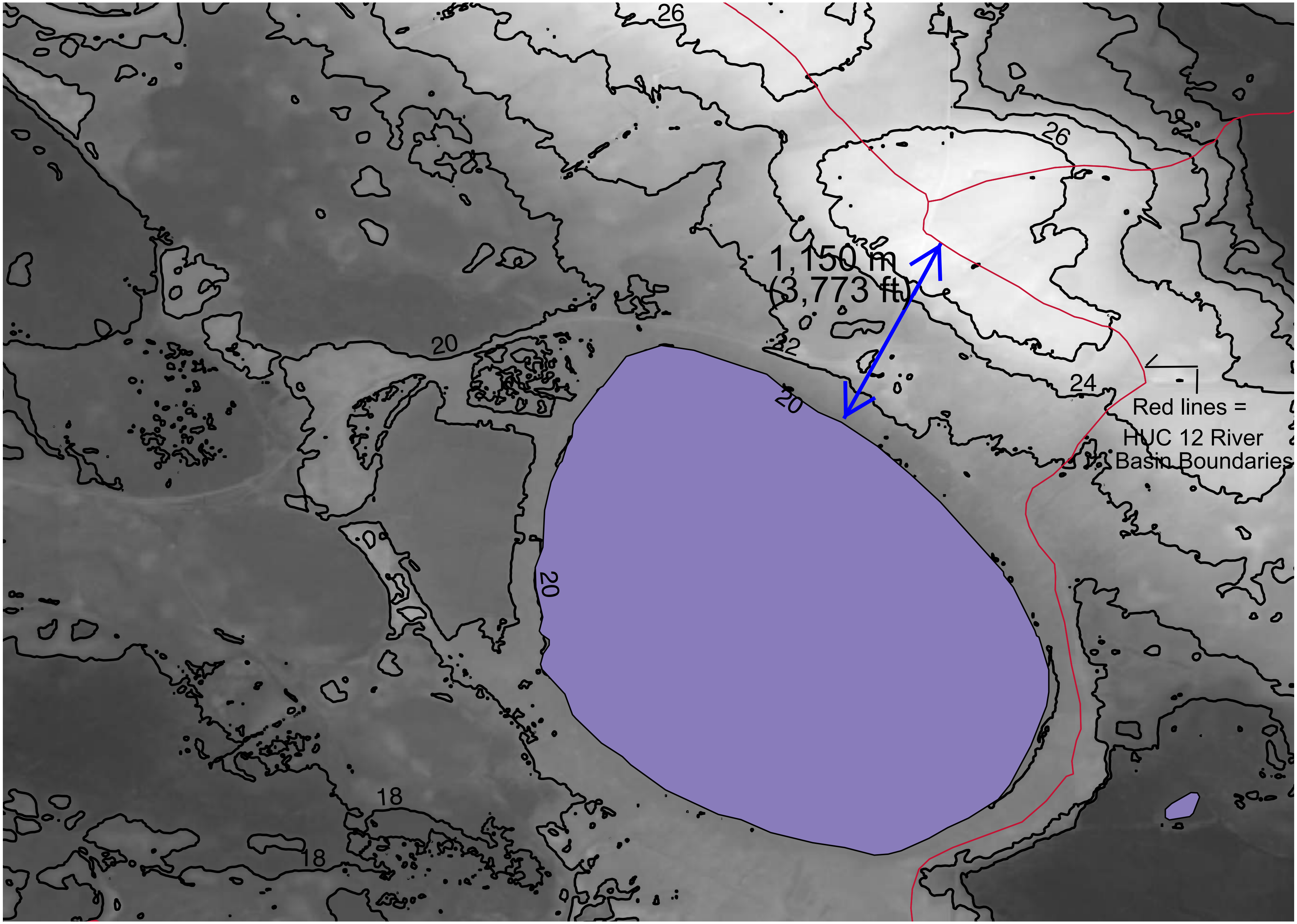


Figure 23. Groundwater contributing zone for White Lake showing the widest section in the northeastern sector.

Figure 3: Widest section of groundwater contributing zone for White Lake based on topography.



Source of base map is a figure prepared by the NC DWR (N. Wilson, personal correspondence, August 2, 2022).

Contours are in meters, with a contour interval of 2 meters.
20 meters = 65.6 feet 26 meters = 85.3 feet

HUC = Hyrologic Units Code (US Geological Survey)

With an apparent absence of the hardpan underlying the lake at the location of known/observed springs and with the hardpan not being encountered at a drill site uphill from the lake to the east, it is likely that groundwater flow from the east/northeast, contributes to White Lake via flow paths both above and below the hardpan. The flow above the hardpan has been documented by Shank and Zamora (2019) for discharging to the lake near the shoreline, but some portion of flow from the more distant, uphill recharge area to the northeast likely reaches the lake via deeper flow beneath the hardpan (along flow lines such as depicted in Figure 1, C).

The flow may be comparable to flow in a pipe, with higher head at the northeast end (via uphill water table elevations) and lower head (lake level) at the southwest end. Groundwater flow for a distance between those endpoints could be trapped between the hardpan and the confining unit at the base of the surficial aquifer, with upward discharge into the lake bottom prevented by the hardpan until flow reaches the point beneath the lake where the hardpan pinches out (or is otherwise breached). Discharge then may finally occur in concentrated areas of the lake bottom, making the "boils" boil at times when surficial aquifer heads are sufficiently higher than lake levels. More typical discharge (springs) at other lakes occurs over broader areas of lake bottoms, such that the discharge is not so distinctly observable.

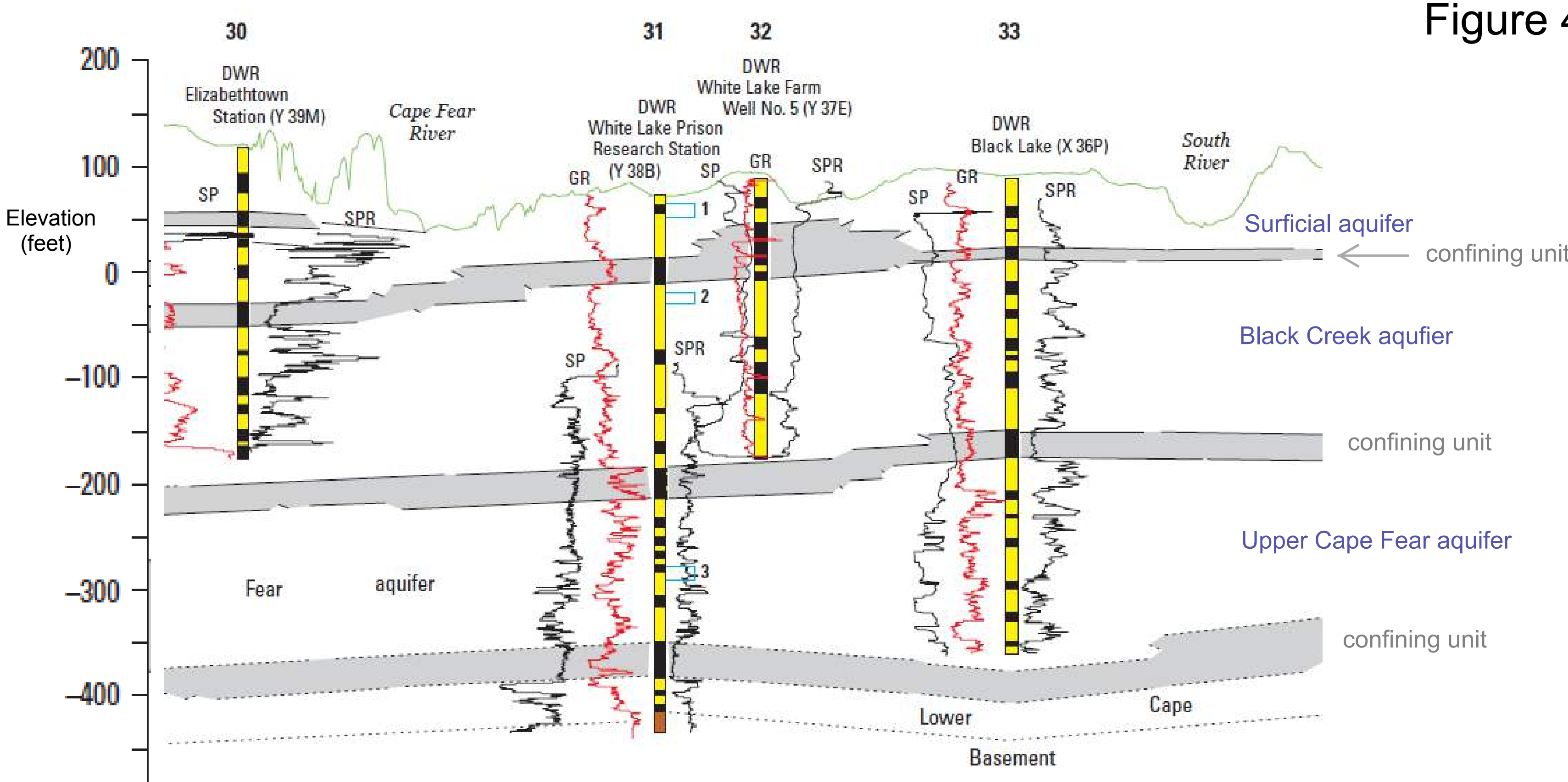
DEEPER GROUNDWATER

The surficial aquifer in the vicinity of White Lake is underlain by a clayey confining unit that separates the aquifer from the deeper, Black Creek aquifer, as evidenced by studies of the regional hydrogeologic framework by Campbell and Coes (2010), GMA and Wooten (2003), and Winner and Coble (1996). A portion of a cross-sectional diagram by Campbell and Coes (2010), Figure 4, shows hydrogeologic framework interpretations at four NC DWR research sites. The two sites nearest to White Lake are the White Lake Prison research station (now a NC DOT facility) and the White Lake Farm site (Figure 5). Water level data are available from the White Lake Prison research station for monitoring wells screened in the surficial, Black Creek, and Upper Cape Fear aquifers, and levels indicate a consistent, downward hydraulic gradient between aquifers (Figure 4).

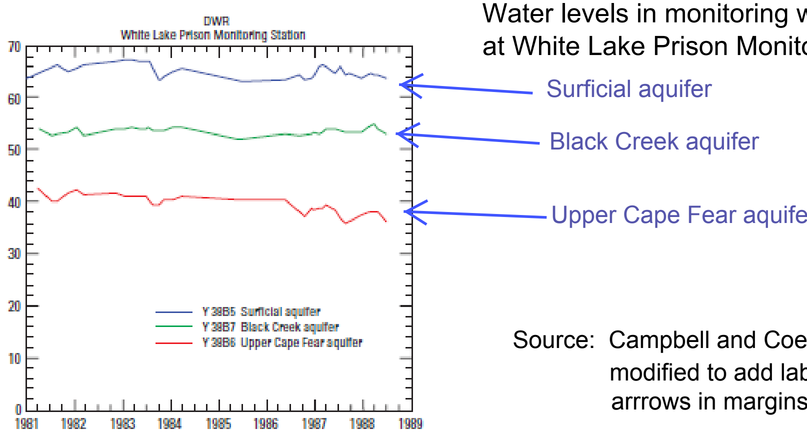
The differing heads between aquifers attest to the effectiveness of the confining units that separate them. Levels in the Black Creek and Upper Cape Fear wells rise above the tops of their confining units (representing the potentiometric surfaces/heads of these aquifers), but levels are still lower than surficial aquifer levels/heads. The downward hydraulic gradient means there is a downward potential for flow. Under these hydraulic conditions, wherever (and to whatever extent) leakance may occur across the confining unit, flow will be downward.

Water levels from Figure 4 for surficial and Black Creek aquifer wells are shown at expanded scales in Figure 6. Elevations for Black Creek aquifer levels remained between 52 to 55 feet from 1981 to 1989, typically about 10 to 12 feet lower than surficial aquifer levels. Recent data from these monitoring wells are not available, with the research station having been abandoned (N. Wilson, NC DWR, personal communication, September 12, 2022). A review of the NC DWR's Groundwater Level database (https://www.ncwater.org/?page=343) indicates that 2022

Figure 4

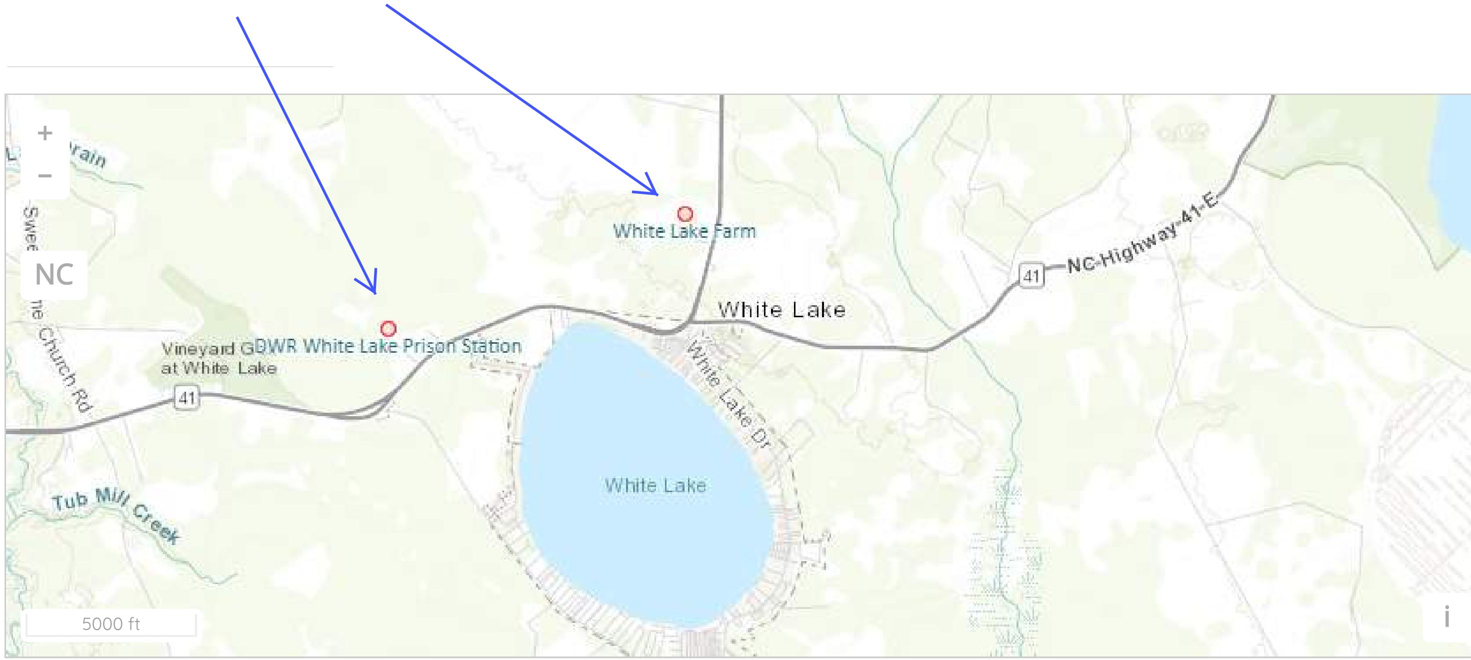


Water levels in monitoring wells
at White Lake Prison Monitoring Station



Source: Campbell and Coes, 2010, modified to add labels and arrrows in margins to the right.

Figure 5: Locations of NC DWR Research Stations nearest to White Lake.

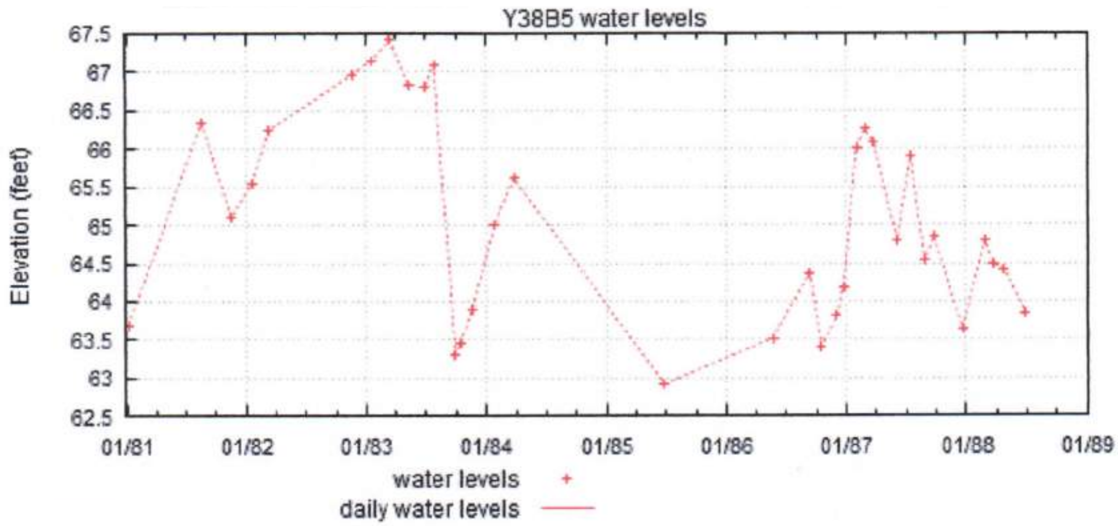


Source: modified from the NC DWR on-line Hyrdogeological Framework database: https://www.ncwater.org/?page=348

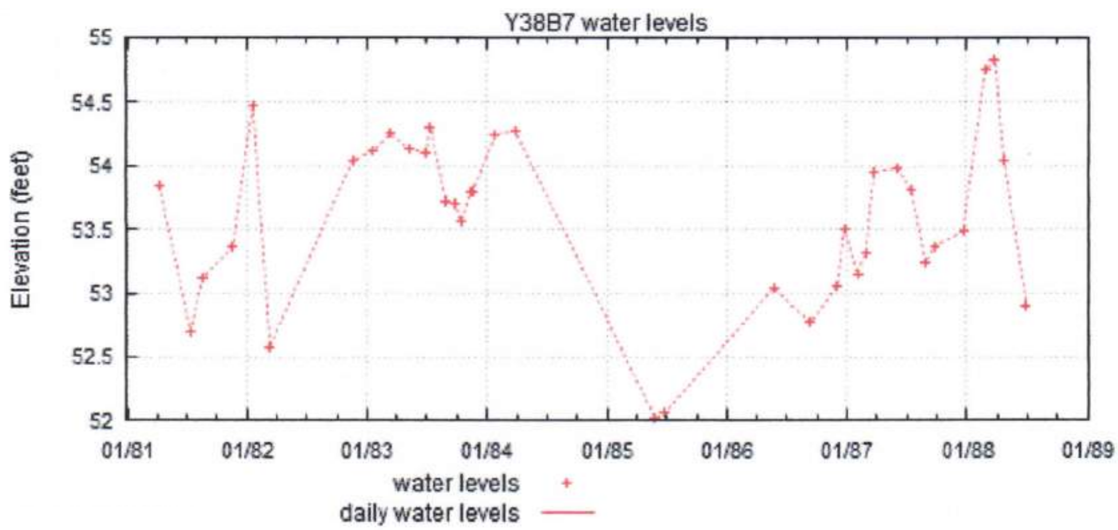
Figure 6

Water levels in monitoring wells at the NC DWR White Lake Prison Station

Surficial aquifer



Black Creek aquifer



Source: Both hydrographs copied from the NC DWR Groundwater
Level Database: ncwater.org/page?343

levels from more distant Black Creek aquifer monitoring wells are lower throughout the general region than levels from 1980s at the NC DWR's White Lake Prison site.

Geophysical logs for the NC DWR's White Lake Prison and White Lake Farm sites are shown with hydrogeologic framework interpretations by the NC DWR on Figures 7 and 8. Depths to the top of the confining unit at the base of the surficial aquifer are approximately 60 feet (White Lake Prison) and 55 feet (White Lake Farm). Both depths equate to an elevation of 10 feet. The thickness of the confining unit is approximately 25 feet at both sites (note that vertical scales differ in Figures 7 and 8, so it is not immediately apparent that thicknesses are approximately identical).

The previously mentioned borehole drilled by the U.S. Geological Survey (Weems and others, 2011) along NC Highway 53, west of White Lake, encountered a clay layer at a depth of 39 feet (elevation 32 feet). The clay was interpreted as being the base of the surficial aquifer, which is equivalent to the top of the confining unit. The 32-foot elevation puts it 22 feet higher than it was encountered at the NC DWR sites. The clay continued to the hole's terminal depth at 56 feet, equating to a confining unit thickness of at least 24 feet.

Elevations for the base of the surficial aquifer (10 feet at both NC DWR sites and 32 feet at the U.S. Geological Survey site) would put it about 32 to 54 feet below typical lake levels, if depths to the confining unit are consistent beneath the lake (and based on a lake level elevation of 64 feet). For an 8-foot depth to the lake bottom (in deeper portions of the lake), the thickness of the surficial aquifer beneath the lake bottom would be 24 to 46 feet.

The likelihood that the confining unit is present and continuous beneath White Lake and the surrounding area is supported by the unit's well-recognized presence on a regional basis and by confirmation of its presence at the local sites described above. Stronger evidence is the differences between water levels in surficial and Black Creek aquifer monitoring wells, demonstrating the effectiveness of the confining unit as a hydraulic barrier in the vicinity of White Lake.

In addition, Shank and Zamora's (2019) evaluations of radon concentrations and also strontium, oxygen and hydrogen isotopes also support that a deeper confined aquifer is not contributing groundwater to White Lake.

If there were an area beneath the lake where the confining unit is absent or especially thin or permeable/leaky, the downward hydraulic gradient would dictate that groundwater flow is from the surficial aquifer to the Black Creek aquifer. The opposite hydraulic gradient (an upward gradient) would be needed for the reverse to occur (Black Creek aquifer flow into the surficial aquifer or somehow directly into the lake bottom). At times when, and at places where, groundwater discharges into White Lake, the source of that groundwater is the surficial aquifer.

DWR Geophysical Log Database Detail for Y 38B, White Lake Prison RS

Figure 7

Field	Data
County	Bladen
Latitude	34.655278
Longitude	-78.522500
Location Accuracy Show Map	Map
Quad	Y 38B
Land Surface	70.00
Dates	02/06/1981
Source	DWAR

White Lake Prison

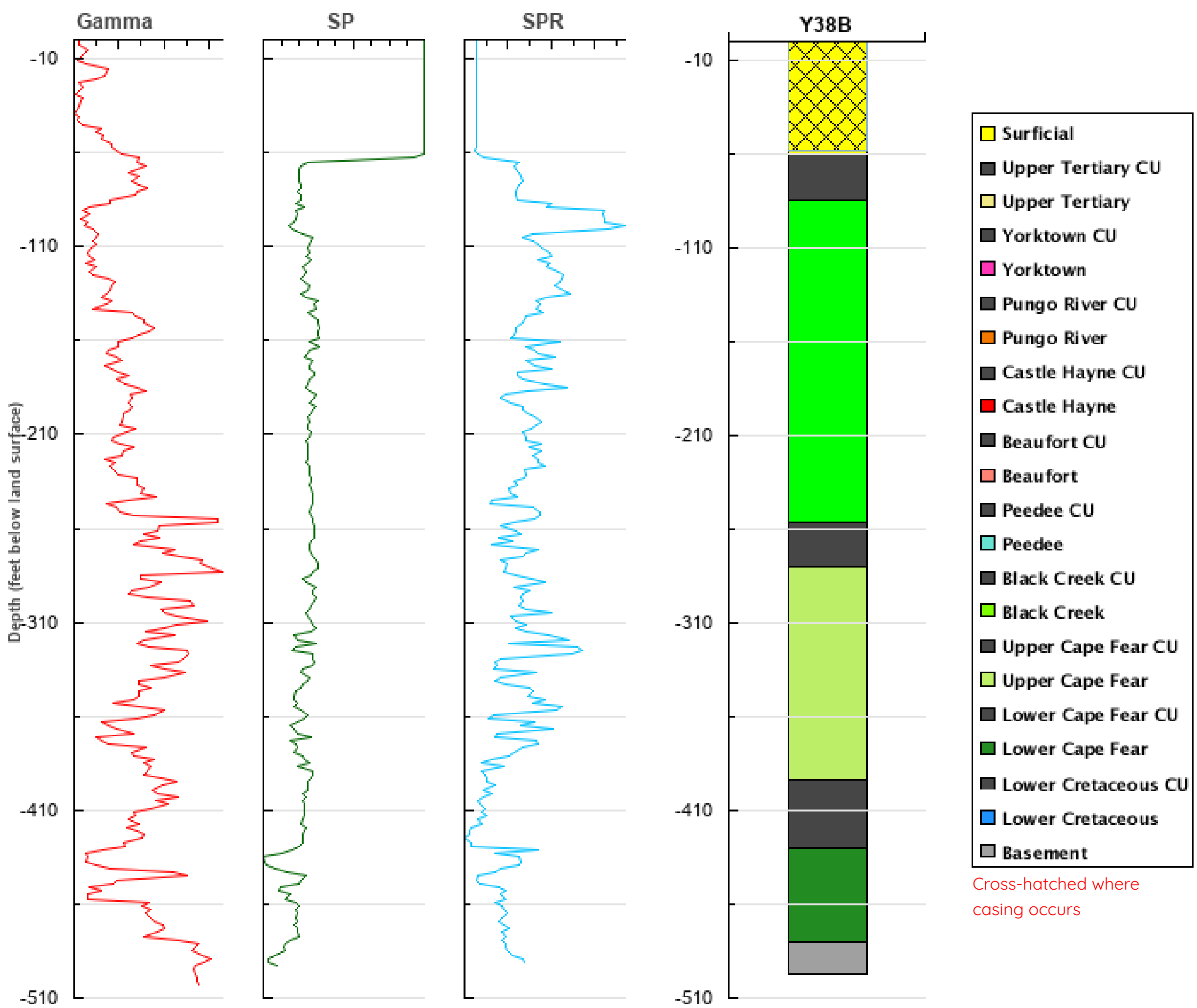
Yellow = Surficial aquifer

Black = Confining unit

Lime Green = Black Creek aquifer

click on each log chart to access complete log

log legend



Source: https://www.ncwater.org/?page=540&quadtype=Y**38B&jmp=1&namex=White*Lake*Prison*RS&e=653369.95&n=100529.11 (modified to add blue text).

DWR Geophysical Log Database Detail for Y 37E, White Lake Farm

Figure 8

White Lake Farm

Yellow = Surficial aquifer

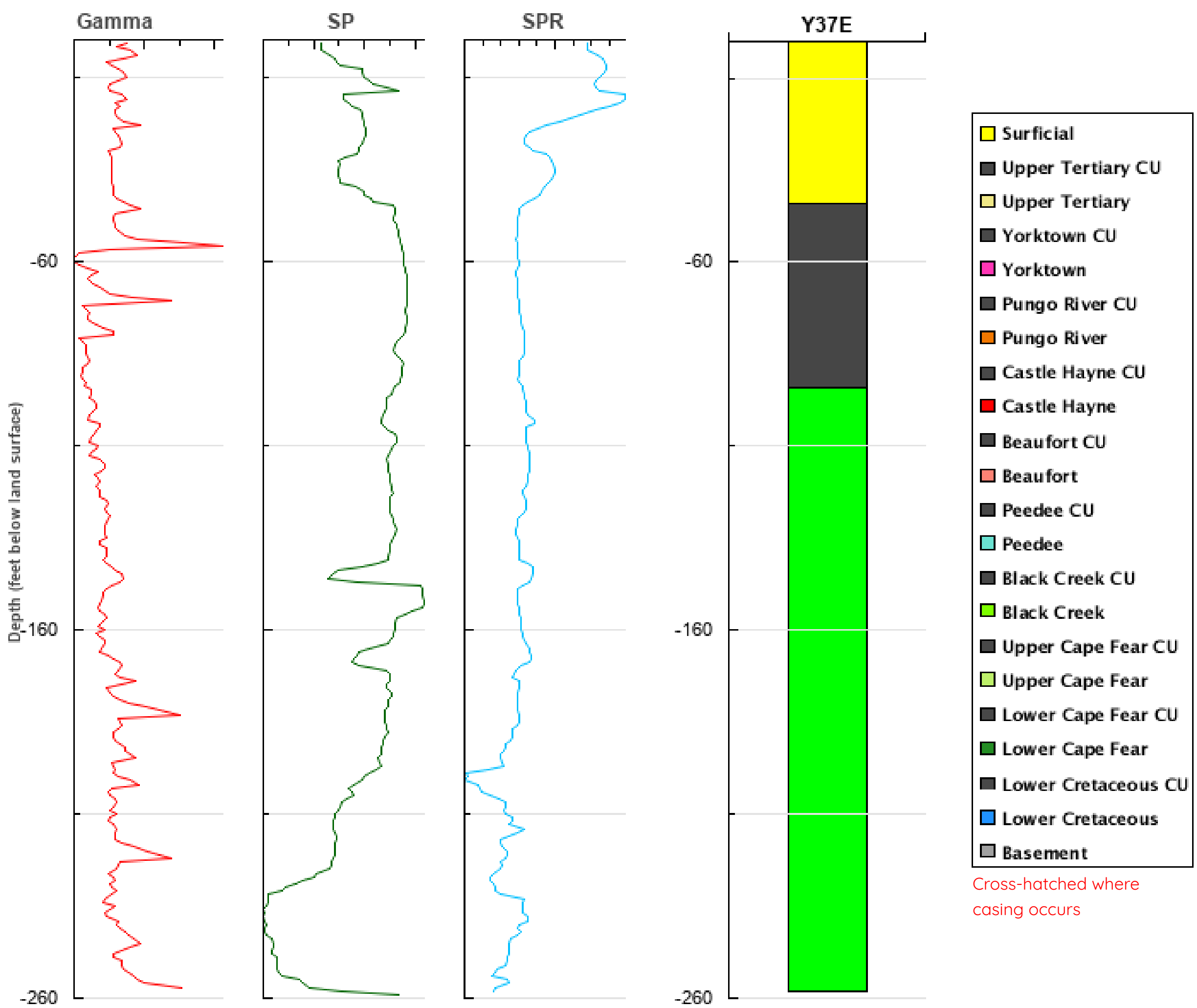
Black = Confining unit

Lime Green = Black Creek aquifer

Field	Data
County	Bladen
Latitude	34.664444
Longitude	-78.493609
Location Accuracy Show Map	Map
Quad	Y 37E
Land Surface	85.00
Dates	01/06/1984
Source	DWAR

click on each log chart to access complete log

log legend



Cross-hatched where casing occurs

Source: https://www.ncwater.org/?page=540&quadtype=Y**37E&jmp=1&namex=White*Lake*Farm&e=656012.96&n=101558.97

(modified to add blue text).

IMPACTS OF DRAINAGE FEATURES AND PUMPING WELLS

Any lowering of the water table within those areas that contribute groundwater at times to White Lake reduces hydraulic gradients, which are the driving forces for surficial aquifer discharge into the lake. In these areas, when water table elevations exceed lake-level elevation, there is potential for groundwater flow into the lake. When water table elevations are lowered, the potential is lowered.

Water table elevations vary primarily with rainfall, but also with the factors discussed below. The extent to which each of these affects water table elevations is unknown and will be difficult to determine or to characterize with much degree of certainty, even with extensive studies and monitoring. They are listed below in order of most-to-least impact based upon this author's opinion from reviewing and considering existing information for preparation of this document.

<u>Sewer system leaks</u>:

Leaks in the Town of White Lake sewer system act as a drain that captures and transfers groundwater to the wastewater treatment plant. This lowers the water table, lessening the hydraulic gradient needed for groundwater flow into the lake. A map of the system by ES Engineering Services (2022) shows that the sewer system encircles most of the lake and underlies the surrounding sand rim that comprises a substantial portion of the groundwater contributing zone delineated by Shank and Zamora (2019). Much of the sewer system lies between the lake and the elevated land areas to the northeast, intercepting some portion of groundwater from this largest area of the contributing zone (Figure 2).

Another concern regarding the sewer system is whether or not excavation depths for installations or repairs have removed or otherwise breached the hardpan layer. The NC DWR found in their 2017 study that the hardpan clay started at a depth of 5 feet and became mixed with sand at 13 feet at both their east and west monitoring well sites, each about 100 feet from the lake shore (K. White, personal communication, September 8, 2022). If the layer has been breached by sewer excavations, a reduction in groundwater pressure from below the hardpan could affect the renowned spring sites (see Shallow Groundwater section, Hardpan subsection).

The groundwater transferred through the gaps from below the hardpan to above the hardpan is still likely to discharge into the lake, joining other groundwater that started off above the hardpan from recharge areas closer to White Lake. This would mean a larger proportion of groundwater entering the lake from more shallow depths and in areas of the lake bottom nearer to the shoreline. In addition to dampening inflow at the renowned springs, the mixing of groundwaters from above and below the hardpan before discharging into the lake and the higher proportion of discharge occurring closer to shore may have lake water quality and biological implications (not addressed herein).

A comparison was made by the NC Division of Water Resources of gallons pumped from Town of White Lake public water supply wells, gallons discharged from the Town's wastewater treatment plant, and precipitation for the period from January 1993 to March 2008 (N. Wilson, personal communication, August 30, 2022). The volume of wastewater exceeded the water being supplied to the town nearly every month (185 months out of the 197 sampled), with the excess water averaging 227,644 gallons per month (based on monthly averages). The difference was more than 300,000 gallons for 54 months for the 109-month period.

It is apparent that the difference represents groundwater draining into sewer system leaks, with greater differences tending to occur during/following months with higher precipitation and in seasons when the water table is typically higher (winter and spring). Sewer system gains tended to be less, and at times even reversed (with wastewater leaking out versus groundwater leaking in) during summer months. This coincides with times when public water use is greatest and the water table is typically relatively low. The reversals only occurred during 5 summers out of the 15 included in the data set. For most summers, groundwater loss to the sewer system appears to have been still occurring. The overall effect of the sewer system throughout the year, and even during most summers, is to drain groundwater, thus lowering the water table and reducing hydraulic gradients needed for groundwater discharge into the lake.

The current program to repair and replace leaky portions of the sewer system will have an overall effect of allowing more groundwater to enter the lake. The extent of that impact will be difficult to gauge with future groundwater monitoring, as the repairs/replacements are already underway and because of other variables, primarily rainfall.

Ponds and ditches:

A large number of ponds and ditches have been excavated at the blueberry farms to the north and east of White Lake (Figure 9). These areas are at higher land elevations (Figure 3), where water table elevations are substantially higher at times than lake levels and provide hydraulic gradients for groundwater discharge into the lake bottom, as exemplified in Figure 1, C. The ponds and ditches appear to be primarily for land drainage, with a fewer number appearing to be equipped with irrigation pumps (simply based on viewing aerial images). Between periods of precipitation, ponds typically cause a lowering of the water table because of evaporation, with responding inflow from the surficial aquifer.

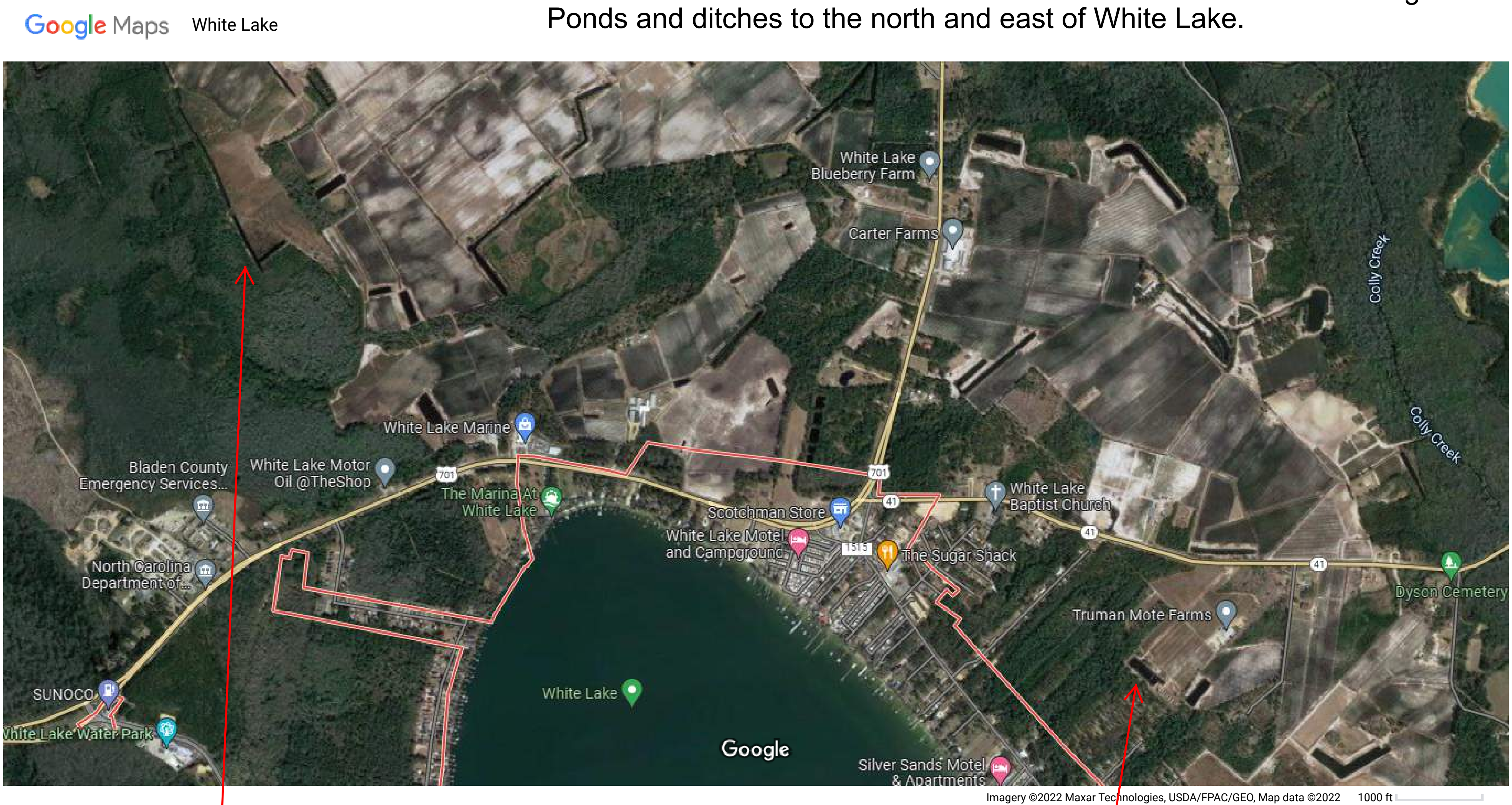
For ponds that are pumped for irrigation or freeze protection, water table levels would be further lowered during pumping; however, if irrigation ponds are supplied by deep pumping wells screened in confined aquifer(s), the impact to the surficial aquifer would depend upon levels maintained in the pond, with ponds losing water to the surficial aquifer when pond levels are higher than the surrounding water table.

The ponds likely have an overall impact of lowering the water table because of land drainage and water table discharge to ponds in response to evaporative losses between precipitation events. During rainy periods, ponds and ditches may temporarily fill to levels above the surrounding water table and contribute water to the surficial aquifer, but not likely any more so than the recharge that the surficial aquifer would have otherwise received.

Ditches in these areas north and east of White Lake (Figure 9) appear to either function as elongated ponds or to flow short distances to nearby ponds. These ditches, like ponds, can be

Figure 9

Ponds and ditches to the north and east of White Lake.



The long ditch that drains to swamps flowing to Turnbull Creek.

Example of one of the many ponds interspersced througout the region uphill from Lake White.

Source of base map: Google maps:

https://www.google.com/maps/place/White+Lake,+NC+28337/@34.6583224,-78.497427,2579m/data=!3m1!1e3!4m5!3m4!1s0x89aa52fa8c651d3d:0x570c103891a9d56d!8m2!3d34.6404489!4d-78.483…

expected to have an overall lowering effect on the water table because of land drainage and evaporative losses between precipitation events.

The long ditch (Figure 9) is outside of Shank and Zamora's (2019) contributing zone, but the NC Division of Water Resources has considered whether or not its drainage has affected groundwater inflow to White Lake. The ditch flows to the swamps to the west, which drain to Turnbull Creek, and flow in the ditch appears to be constant, based on observations by the NC DWR at varying times over a number of years (K. White, personal communication, August 1, 2022). Constant flow would indicate that the ditch receives groundwater discharge even when rainfall and water table elevations are minimal, with the ditch serving to drain shallow groundwater from the upslope areas east of the ditch and north of White Lake. The flow rate in the ditch was estimated to be 750 gallons per minute on one occasion when the NCDWR took measurements at a culvert (K. White, personal communication, August 1, 2022).

Based on topography, the land areas drained by the ditch may be too far north of White Lake for lowering of the water table there to impact groundwater flow to the lake. But monitoring wells between White Lake and the ditch and/or the area that topography suggests is drained by the ditch (east of the ditch) would be helpful toward determining whether or not the ditch affects groundwater inflow to White Lake.

Ditches just west of White Lake are topographically lower than the sand rim that separates the area from the lake and falls outside of the groundwater contributing zone determined by Shank and Zamora (2019). The effect of lowering the water table in this area would be to increase the hydraulic gradient between this area and the lake, potentially increasing the rate of water loss to seepage in western portions of the lake bottom (the left side of diagram C, Figure 1 provides an example of the setting). The extent to which seepage is increased largely depends upon how effectively the ditching is draining land and lowering water table elevations west of White Lake, which may be difficult to determine.

Well Pumping:

Well pumping from deep, confined aquifers (the Black Creek and/or Upper Cape Fear aquifers) is not likely to have any impact upon groundwater inflow to White Lake. The lake lies entirely within surficial aquifer sediments. The base of the aquifer (top of the confining unit) has been identified at nearby NC DWR sites and by Weems (2011) at elevations equating to depths of 24 to 46 feet below deeper parts of the lake bottom (see preceding Deeper Groundwater section). If, contrary to this evidence, the confining unit between the aquifers is absent or leaky beneath some area(s) of the lake, the underlying surficial aquifer would drain downward into the Black Creek aquifer in response to the lower heads at the deeper depths.

More information about depths and thicknesses of the confining unit could be learned from records for the Town's three public water supply wells, if drilling and/or geophysical logs are available. Screen depths for the three wells are listed at depths ranging from 154 to 392 feet on the Town's 2021 Local Water Supply Plan (NC DWR, 2021), so each was drilled through depths where the confining unit occurs at the two NC DWR research sites (Figures 5, 7, and 8) and was encountered by Weems and others (2011) west of White Lake.

Town wells were determined by GMA and Wooten (2003) to utilize the Black Creek and Upper Cape Fear aquifers. Distances from the wells to the lake range from about 700 to 2,750 feet, located to the north, northwest, and south of the lake (distances estimated from a map by GMA and Wooten, 2003 and from Google Maps). Based on the existing evidence of an effective confining unit, Town well pumping does not likely have any impact upon groundwater inflow or outflow to/from White Lake.

Wells for the nearby blueberry farms typically utilize deep aquifers (K. White, NC DWR, personal conversation, September 6, 2022). Like the Town wells, any of these wells screened in the deep, confined, Black Creek or Upper Cape Fear aquifers are not likely to have any impact upon groundwater inflow to White Lake. Wells screened in the surficial aquifer could have an impact by lowering water table elevations, as described for ponds and ditches.

There is an indirect way that deep, confined aquifer wells could affect groundwater inflow to White Lake. Surficial aquifer levels could be drawn down if wells have not been properly sealed at depths of the confining unit. If no bentonite grout has been placed where the confining unit was encountered, the surficial aquifer could drain into the Black Creek aquifer, lowering surficial aquifer heads and thus potentially impacting inflow to the lake.

This can occur through the well's gravel pack, in the annular space between borehole walls and casing. Remnant drilling fluids (drilling "mud") in the gravel pack can act as a seal to some extent for a time, but under the downward hydraulic gradients that are evident near White Lake between the surficial and Black Creek aquifers, the remnant muds may have fully flushed down and out over time, creating a drain. The hydraulic gradient between the aquifers would be amplified in close proximity to the wells because of pumping drawdown in the Black Creek aquifer. Unlike the shallow well impacts discussed below, drawdown effects would be constant, with the surficial aquifer continuously leaking downward. Recommendations (next section) include ways to address this possibility.

Wells screened in the surficial aquifer at properties surrounding the lake likely have some impact to groundwater inflow to the lake. But pumping rates for residential supply or irrigation purposes are typically low and pumping periods typically short, and impacts are likely to be minor. Larger wells screened in the surficial aquifer with more substantial pumping rates/periods, such as for commercial purposes, would be more impactful, but these wells are more likely to be screened in the Black Creek and/or Upper Cape Fear aquifers, so that impacts would not be expected unless wells are improperly sealed at confining unit depths, as discussed above.

RECOMMENDATIONS

These recommendations are specifically regarding groundwater inflow to the lake and are meant to accompany the other recommendations in the larger document in which this report is to be presented. Plans for a study to learn more about groundwater flow and the extent of impacts are presented as an appendix, and the study is listed below as a third recommendation, but the first two are actions that the Town could take in the shorter term to address two of the concerns raised in this report.

Sewer system repairs and hardpan

The Town should meet with sewer system engineers/contractors and discuss concerns about excavations penetrating through the bottom of the hardpan layer, asking if contractors have been breaking through the hard layer and experiencing rising water levels or having to increase dewatering efforts. The rising levels would likely be more evident in winter/spring months and following periods of rainfall. If this has happened or is happening now, possibilities for minimizing excavation depths should be discussed. Where breaches have already happened or are necessary, the feasibility of sealing gaps with an impermeable grout should be explored. Perhaps bentonite grout could be used as a base layer (below otherwise permeable backfill materials) across the bottoms of trenches/other excavations to bridge gaps and recreate a continuous layer of impermeable material.

Check Town well records for drilling/geophysical logs and bentonite seals

The Town's public water supply well records should be checked to see if drilling logs or geophysical logs are available. Those logs would reveal more information about the confining unit between the surficial and Black Creek aquifers at locations closer to the lake versus the research sites discussed herein. Record searches should also target any logs from test wells or older wells that have been replaced. Depths and thicknesses of the confining unit should be evident from the logs. If no logs are available, gamma logging could be conducted inside the casing, with more logging options available if casings are PVC (versus steel).

Records should be checked to see if wells were constructed with bentonite seals in the annular spaces at depths where the confining unit was encountered. Or the wells may have been constructed with outer casings grouted into the top of the confining unit clay. If neither type of seal is present, the surficial aquifer may be draining to the underlying Black Creek aquifer via well gravel packs (as discussed in the preceding section). If no well records are available or the existence of a seal cannot be determined via other means (cement-bond logging inside the well is a possibility), shallow monitoring wells (in the surficial aquifer) could be installed at well sites to check for water table drawdown in the vicinity of the well. If missing seals are evident at a well, the well should be replaced, not only to reduce surficial aquifer drawdown, but as a wellhead protection measure to prevent shallow groundwater from reaching the source aquifers supplying the wells.

Further study considerations

Monitoring would be necessary to learn more about the extent to which factors discussed above (the sewer system, ponds, ditches, and wells) affect surficial aquifer levels and especially to try and quantify how much the impacts lessen inflow or increase outflow to/from White Lake. Plans for a study meant to attempt that are outlined in the appendix and incorporate much more of a vertical component in assessing hydraulic gradients than past studies have, with monitoring wells screened in deeper portions of the surficial aquifer and well locations farther from the lake and nearer to blueberry farms. Plans also include monitoring wells within the lake bottom. Ideally, monitoring would have started before the current program to repair/replace portions of the Town's sewer system had begun to better gauge the effect of those improvements. But there will at least be somewhat of a pre-repairs baseline from the numerous studies done to date.

Further studies can hopefully be done as a cooperative effort with owner/operators of the nearby blueberry farms, north and east of White Lake. If information sharing could be arranged and approvals/access established for conducting monitoring activities on farm properties, far more could be learned about possible impacts to Lake White from the ponds, ditches, and wells at the higher elevations. Study plans in the appendix could proceed without those arrangements, but it is recommended that the Town first explore possibilities for conducting a study as a cooperative effort.

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APPENDIX

STUDY PLAN AND COSTS TO FURTHER EVALUATE GROUNDWATER FLOW

Costs represent rough estimates based on past experiences with other projects. No actual estimates from service providers and equipment suppliers have been obtained.

It is important to point out that this author thinks it is highly unlikely that further studies will alter the general understanding of the sources of groundwater supplying White Lake. The many studies to date and especially the recent one by Shank and Zamora (2019) strongly support that the source of groundwater inflow to White Lake is the surficial aquifer and that the primary variable is rainfall. It has been well established that deeper, confined aquifers are not a source of water to White Lake. The prime suspect for reduced groundwater inflow is the leaky sewer system, and repairs are already underway.

The study plans are designed to learn more about particular aspects of groundwater flow into and out of White Lake that are not as well-established as others to date. **The value of knowing more about these particular aspects needs to be weighed against costs and the feasibility of being able to address/alter sources of impacts as they become better defined.**

The study is designed to expand upon the study completed by Shank and Zamora (2019), focusing on the following aspects:

- Assess vertical hydraulic gradients underlying the lake.
  How: monitoring of groundwater levels (heads) beneath the lake bottom via wells, with well pipes secured to NO WAKE zone pilings. Wells will be placed at two locations, on east and west sides of the lake, with each location having two wells to differing depths and a stilling tube for monitoring lake levels.

- Evaluate flow at deeper depths within the surficial aquifer.
  How: evaluate both vertical and lateral aspects of hydraulic gradients by installing deeper monitoring wells (versus previous studies) within the surficial aquifer. Wells would be nested, with three wells to differing depths at nest locations east and north of the lake (possibly only two wells per nest, if drill logging indicates that three will not be helpful). Proposed well nest locations are shown on Figure 10. Hopefully, locations previously utilized for wells by Shank and Zamora (2019) could be utilized again, and some of the proposed nest locations are placed along their north and east transects. Wells from their study may be incorporated, depending upon status/condition. The nest locations to the east of the lake and deeper wells (still within the surficial aquifer) at those locations, in combination with head monitoring below the lake bottom and at lake level, will provide a better understanding of deeper-running flow lines from topographic highs to below the lake bottom.

Google Maps White Lake

Target locations for monitoring well nests (12 total)

Imagery ©2022 Landsat / Copernicus, Maxar Technologies, USDA/FPAC/GEO, Map data ©2022 2000 ft

Source of base map: Google maps:

https://www.google.com/maps/place/White+Lake,+NC+28337/@34.650631,-78.4964668,5158m/data=!3m1!1e3!4m5!3m4!1s0x89aa52fa8c651d3d:0x570c103891a9d56d!8m2!3d34.6404489!4d-78.483…

- Learn more about the recharge dynamics at the elevated land areas to the east.
  How: The targeted sites for monitoring well nests along NC Hwy 41 (Figure 10) will be farther uphill than previous monitoring wells, and nests will include wells with deeper screen depths (still within the surficial aquifer). This is an area where heads in the surficial aquifer may have a long line of pressure influence to central parts of the lake bottom. The extent to which blueberry farm ponds and irrigation pumping may affect this is a key point of interest. Also, drilling the deeper, surficial aquifer wells will reveal if the lateral extent of the hardpan reaches these areas.

- Further verify that the deeper aquifer does not contribute to springs.
  How: monitor Black Creek aquifer potentiometric levels via the Town's wells (pumping levels and recovery peaks between pumping cycles), with checks against trends in surficial aquifer levels for any correlation. Also, review drilling/geophysical logs for Town wells, or if not available, pull pumps and conduct geophysical logging (as feasible, depending upon casing materials). Pumps would be pulled one well at a time to minimize operational impacts, and if older wells are available (perhaps now serving as backup wells), logging might be done with no disruptions to operational pumping.

- Collect more information farther north and east of the lake at or near to blueberry farms, including whether or not the "long ditch" has any impact upon White Lake.
  How: attempt to establish cooperative arrangements with farm owners/operators in order to: 1) construct and monitor wells for at least a one-year period, 2) open lines of communication to learn more about well depths, pumping activities, levels maintained in irrigation ponds, pond depths, and the availability of well construction records and drilling/geophysical logs, and 3) monitor water levels and flow rates in the long ditch draining to swamps that flow to Turnbull Creek.

Regarding the long ditch, a monitoring well nest placed between the lake and either the ditch or the area east of the ditch, which it apparently is draining to some degree, could help determine whether or not drainage effects of the ditch extend far enough to the south and east to affect areas contributing groundwater to White Lake. Ideally, the well nest could be monitored in combination with a trial period of stopping ditch flow (perhaps during the off-season) by installing a flashboard riser at a culvert. Cost estimates that follow include a monitoring well nest, but not costs for ditch monitoring or alterations.

It appears that the location for the well nest would need to be on blueberry farm property (Figure 10). Possibly arrangements for constructing wells and regularly accessing the nest would need to be explored as a first step toward further developing these study plans. No costs are included for efforts to establish cooperative arrangements with blueberry farm owner/operators.

Two of the nest locations are targeted to be very near to blueberry farms to the northeast/east of White Lake without requiring sites to be on private properties. These are the two along NC Hwy 41 (Figure 10), with the thought that wells could be sited in the Right of Way via arrangements with the NC DOT. No costs are included for making those arrangements. One of those nest locations is adjacent to an irrigation pond and the other (intentionally) is not.

It is proposed that two of monitoring well transects established by Shank and Zamora (2019) be utilized again, with two nests along their north transect and three nests along their east transect (Figure 10). No costs are included for acquiring use of/access to land for those same well sites. Cost estimates assume that the status/condition of the previously utilized wells will warrant all new wells to be constructed (in addition to newly proposed, deeper wells at those sites). Cost savings could be realized if some wells could be utilized again, depending upon status/condition.

The two proposed well nests on the west side of the lake (Figure 10) are not at a previous transect location; instead the sites are about midway between Shank and Zamora's (2019) south and west transects. No costs are included for securing suitable sites, hoping that there may be properties owned by the Town or a cooperative land owner in this area.

Two of the well nests are within the lake (Figure 10), picturing that these could be placed at No Wake zone pilings. No costs have been included for gaining permission from the State, and it is only assumed that that will be possible. Three pipes would be secured to pilings: one stilling tube for lake level monitoring and two wells installed in the lake bottom from boat or barge rig. It should be noted that the NC DWR has demonstrated that well installation can be done from a personal boat, at least for the temporary well that was installed at a spring site, which did not require penetration of the hardpan (K. White, personal communication, July 29, 2022). The proposed wells at the No Wake zone piles are nearer to shore, and it may be necessary to penetrate the hardpan and also place a bentonite seal in the annular space (between the well pipe and borehole walls) at hardpan depths.

Monitoring Wells:

The study includes 12 monitoring well nest sites (Figure 10).

Each nest to have multiple wells in the surficial aquifer at differing depths, as follows, though the number at a number may be altered based on stratigraphy encountered:

3 wells at the	5 east nests =	15 wells
3 wells at the	2 north nests =	6 wells
2 wells at the	1 far north nest =	2 wells
2 wells at the	2 west nests =	4 wells
2 wells at the	2 in-lake nests =	4 wells
Totals:	12 nests	31 wells

Costs:

Drilling and well construction (all wells assumed to be 2-inch diameter):

Land-based wells

$1,000/shallow surficial aquifer well x 10 =	$10,000
$1,300/mid-depth surficial aquifer well x 7 =	$9,100
$1,800/deepest surficial aquifer well x 10 =	$18,000

In-lake wells

$3,500/mid-depth surficial aquifer well x 2 =	$7,000
$5,000/deepest surficial aquifer well x 2 =	$10,000

Drill logging and well design:

Land-based wells

$600/well site x 27 =	$16,200

In-lake wells

$1,200/well x4 =	$4,800

Monitoring equipment:

$1,500/monitoring device (transducer w/data logger) x 31 =	$46,500

Subtotal (Monitoring wells) =	**$121,600**

Costs do not include:

- Land access for well nest locations.
- Security (such as fencing, if warranted) for well nest locations and monitoring equipment.

Precipitation, Lake Level, and Town Public Supply Wells Monitoring Equipment:

One precipitation gauge, two stilling tubes (for lake levels), and three deep transducers for Town public water supply wells (assuming the Town is not already doing this) are proposed. The monitoring equipment will be transducers with data loggers (similar to those utilized in monitoring wells, except that the three for Town wells will be capable of greater pressure ranges and on longer cables).

Costs:

Monitoring equipment for precipitation and lake levels:

$1,000/monitoring device (transducer w/data logger) x3 =	$3,000

Monitoring equipment for Town wells:

$1,800/monitoring device (transducer w/data logger) x 3 =	$5,400

Subtotal (Monitoring equipment) =	**$8,400**

Quarterly Monitoring Services:

Monitoring would be continued through at least one full year. Multiple years would be more ideal to hopefully observe low/high precipitation years. One year will at least presumably include limited periods (days to weeks) of low and high precipitation. Visits to monitoring devices would be made quarterly to download data loggers and also check operational status/perform any maintenance tasks needed. Costs assume a local firm would perform the service, with minimal travel time (30 minutes travel time assumed).

<u>Costs:</u>

Initial setup/installation and data logger programming:	
11 land-based well nests and a precipitation meter:	
$500/site x 11 sites =	$5,500
2 in-lake well nests:	
$900/site x 2 sites =	$1,800
Quarterly visits to download data and maintain equipment:	
10 land-based well nests and a precipitation meter:	
$400/site x 11 sites x 4 quarters/year =	$17,600/year
2 in-lake well nests:	
$800/site x 2 sites x 4 quarters/year =	$6,400/year
Subtotal (Quarterly monitoring services for one year) =	**$31,300**

Reporting:

Monitoring data to be compiled and evaluated to determine hydraulic gradients (lateral and vertical), producing flow-net diagrams in the vicinity of the lake and extending farther to the north and east. The flow-net diagrams are meant to characterize groundwater flow in three dimensions, surrounding and underlying the lake. Costs are based on evaluating one year of data and producing a series of diagrams to represent varying precipitation conditions and to calculate estimated groundwater inflow and outflow to/from the lake, based on hydraulic gradients, areas, and estimated hydraulic conductivities for sediments encountered when installing wells. No computer modeling is included.

Cost:

Data evaluations and reporting (after one year of monitoring)= **$30,000**

Total Cost of Evaluation = **$191,300**