Geostatistical Assessment of Shallow Groundwater Risk in Urban Coastal Virginia: A Case Study from Virginia Beach

Guiselle Valderrama Vizcarra
Independent Researcher, Newport News, Virginia, USA
Email: guiselle.valderramaviz@gmail.com

ABSTRACT

Urban groundwater assessments in coastal cities often rely on public monitoring datasets that are spatially uneven and temporally discontinuous. This study evaluates shallow groundwater risk in Virginia Beach, Virginia, using 30 years of records (1991–2020) from 121 monitoring wells for groundwater levels and 55 wells with groundwater-quality data for chloride (Cl), iron (Fe), and manganese (Mn). The analysis is restricted to the NLCD 2024 urban land-cover class, which provides sufficient data density for spatial modeling.

Groundwater levels and a Composite Contamination Index (CCI) were analyzed within a three-dimensional block model (50 × 50 × 5 m) using Sequential Gaussian Simulation (50 conditional realizations per variable). Simulation outputs were summarized using E-type estimates, uncertainty metrics, and conservative percentile scenarios to characterize spatial patterns under data limitations.

The results indicate that groundwater conditions suitable for new abstraction are extremely limited. More than 94 % of the urban domain is classified as not recommended, while less than 1 % exhibits moderate to favorable conditions. Shallow groundwater levels, elevated uncertainty, and groundwater-quality stress overlap most strongly in urban–wetland transition areas south of the Green Line, previously identified as hydrogeologically sensitive.

The analysis provides screening-level support for urban groundwater management. Incorporating groundwater depth, quality, and spatial uncertainty into a unified assessment offers a practical basis for monitoring prioritization and precautionary decision-making in Virginia Beach and in similar coastal cities that rely on public groundwater data.

TABLE OF CONTENTS

1. INTRODUCTION

Groundwater is a strategic component of water supply in Virginia Beach and in many coastal urban areas of the United States, where it provides flexibility and resilience during periods of high demand and climatic variability. In this region, usable freshwater resources are largely restricted to shallow aquifer systems within the upper 30–60 m, while deeper units (> 45–60 m) are affected by naturally elevated salinity that limits their use without treatment (Johnson, 1999; Smith, 2003). This vertical constraint places strong limits on groundwater availability and increases the vulnerability of urban water supply systems.

Urban development has progressively altered surface and subsurface hydrological processes in coastal settings. Increased impervious cover reduces natural recharge and enhances runoff, modifying surface–subsurface connectivity and increasing the susceptibility of shallow aquifers to diffuse contamination. Regional assessments for the Chesapeake Bay watershed document sustained losses of forest cover and expansion of impervious surfaces in suburban corridors, including the Hampton Roads region, with measurable impacts on groundwater recharge and water quality (Chesapeake Bay Program, 2023; USGS, 2024).

Seasonal water demand further stresses the system. During summer months, residential outdoor water use in Virginia Beach has been estimated at average rates of 10.8 $\mathrm{Mgal\,d^{-1}}$, with peak demands reaching 21.5 $\mathrm{Mgal\,d^{-1}}$, producing localized declines in groundwater levels that can facilitate saline mixing in vulnerable areas (Eggleston, 2010). Numerical simulations using MODFLOW show that concentrated pumping particularly within the Transition Zone between Back Bay and the North Landing River can generate drawdowns of 3–4.6 m and propagate low-head contours more than 1 km from pumping centers (Smith, 2005). These results highlight the sensitivity of the shallow aquifer system to short-term pumping stresses.

Although extensive groundwater, land-use, and water-quality datasets are publicly available for Virginia Beach, their spatial and temporal heterogeneity complicates deterministic assessment. Monitoring density is uneven, water-quality records are discontinuous, and many areas of management interest are poorly constrained by data. Under these conditions, spatial assessments based solely on single best-estimate surfaces can underestimate risk, particularly in transition areas where uncertainty is high.

This study applies a geostatistical approach to examine the relationship between land use, groundwater levels, and groundwater quality in Virginia Beach using publicly available data. The analysis integrates groundwater-level records from 121 monitoring wells and groundwater-quality data from 55 wells measuring Cl, Fe, and Mn, restricted to the urban land-cover class of the NLCD 2024, which contains sufficient data density for spatial modeling. Sequential Gaussian Simulation is used to represent spatial variability and uncertainty in both groundwater levels and a Composite Contamination Index, and the results are translated into an operational zoning framework.

The objective of this work is to support screening-level groundwater management in a coastal urban setting. By combining expected conditions with explicit measures of uncertainty and groundwater quality, the analysis provides a practical basis for identifying vulnerable areas, prioritizing monitoring efforts, and informing precautionary groundwater management in Virginia Beach and similar coastal cities that rely on public monitoring data.

2. STUDY AREA

The study area corresponds to the City of Virginia Beach, located along the southeastern coast of Virginia, United States, within the lower portion of the Chesapeake Bay watershed (Figure 1). The city lies on the Atlantic Coastal Plain, a low-relief physiographic province characterized by unconsolidated sediments and shallow aquifer systems that are hydraulically connected to coastal and estuarine environments.

Groundwater resources in Virginia Beach are primarily contained within shallow aquifers, with freshwater typically confined to the upper 30–60 m. At greater depths, naturally elevated salinity limits groundwater use without treatment, placing structural constraints on long-term groundwater availability (Johnson, 1999; Smith, 2003). These constraints are particularly relevant in urban settings where water demand is high and opportunities for alternative supply are limited.

Virginia Beach is predominantly urbanized, with extensive residential development, transportation infrastructure, and recreational land use. Progressive expansion of impervious surfaces has reduced natural recharge and altered surface–subsurface hydrological connectivity. In the northern portion of the city, most residential supply is provided by surface-water imports, whereas the southern and transitional areas rely largely on groundwater, increasing their sensitivity to both water-level decline and groundwater quality degradation.

A critical feature of the study area is the Transition Zone, located south of the Green Line established in 1979 to control urban expansion. This zone represents a buffer between highly urbanized areas and rural or natural landscapes and includes wetlands, low-density residential development, agricultural land, and borrow pits. From a hydrogeological perspective, the Transition Zone has been identified by the USGS as particularly vulnerable due to limited recharge, partial confinement, and proximity to tidal creeks and estuarine systems, including West Neck Creek and Back Bay (Smith, 2005). Numerical groundwater flow simulations indicate that concentrated pumping in this zone can produce drawdowns of several meters and promote landward migration of saline water.

The spatial analysis presented in this study focuses on the urban land-cover class derived from the NLCD 2024, which contains sufficient groundwater monitoring density for geostatistical modeling. This domain includes 121 monitoring wells with groundwater-level records and 55 wells with groundwater-quality data (Cl, Fe, Mn). Restricting the analysis to this functional urban domain ensures spatial consistency between point observations and land-use data while avoiding over-interpretation in areas with sparse or discontinuous monitoring.

The geographic context of the study area, including the urban modeling domain, the Transition Zone, the Green Line, and the distribution of groundwater monitoring wells, is shown in (Figure 1).

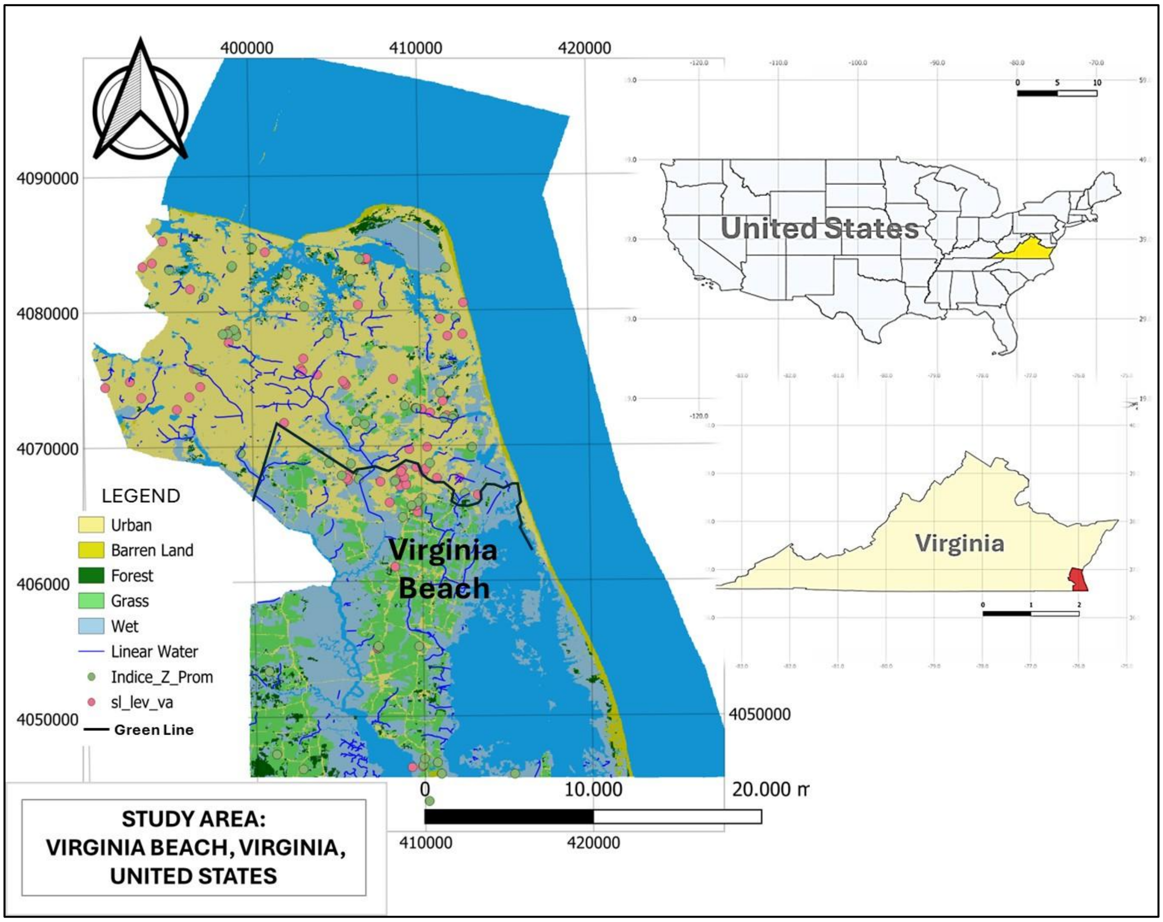

Figure 1. Location of the study area in Virginia Beach, Virginia, United States, showing the NLCD 2024 urban modeling domain, the Transition Zone and Green Line, and the distribution of groundwater monitoring wells used in this study.

3. GEOSTATISTICAL MODELING

The geostatistical modeling was developed to characterize spatial variability and uncertainty in urban groundwater conditions using heterogeneous public datasets. The methodology combines specialized geostatistical software with statistical analysis and three-dimensional visualization tools, reflecting a practical workflow commonly used in applied urban hydrogeological studies.

3.1 Data preparation and spatial support

The analysis integrates groundwater-level and groundwater-quality information derived from publicly available monitoring records. Groundwater levels are represented by the variable sl_lev_va, converted to meters above the vertical datum NAVD88 using NOAA VDatum v4.7.1 to ensure vertical consistency across the study area. The final dataset includes 121 monitoring wells with multiyear groundwater-level records spanning 1991–2020.

Groundwater quality is represented through a Composite Contamination Index (CCI) constructed from chloride (Cl), iron (Fe), and manganese (Mn) concentrations measured at 55 monitoring wells. These parameters were selected due to their relevance to saline influence, redox processes, and urban groundwater quality constraints documented in coastal Virginia aquifers. The apparent difference between the number of groundwater-level wells (121) and groundwater-quality wells (55) reflects the limited availability and temporal continuity of water-quality data relative to water-level monitoring. To ensure spatial coherence between point observations and land-use information, the geostatistical domain was restricted to the urban land-cover class defined by NLCD 2024. This domain concentrates more than 90 % of the available groundwater-level observations and provides sufficient data density for stochastic modeling, while avoiding interpretation in areas with sparse or discontinuous monitoring.

A three-dimensional block model was defined as the spatial support for all simulations, with block dimensions of 50 × 50 × 5 m. This resolution aligns with the NLCD raster grid and balances spatial detail against data density. Smaller blocks would increase the proportion of unsampled cells, whereas larger blocks would smooth urban-scale gradients relevant for groundwater management. Spatial support and data coverage for the geostatistical analysis are provided by the three-dimensional block model and the distribution of monitoring wells within the urban domain (Figure 2).

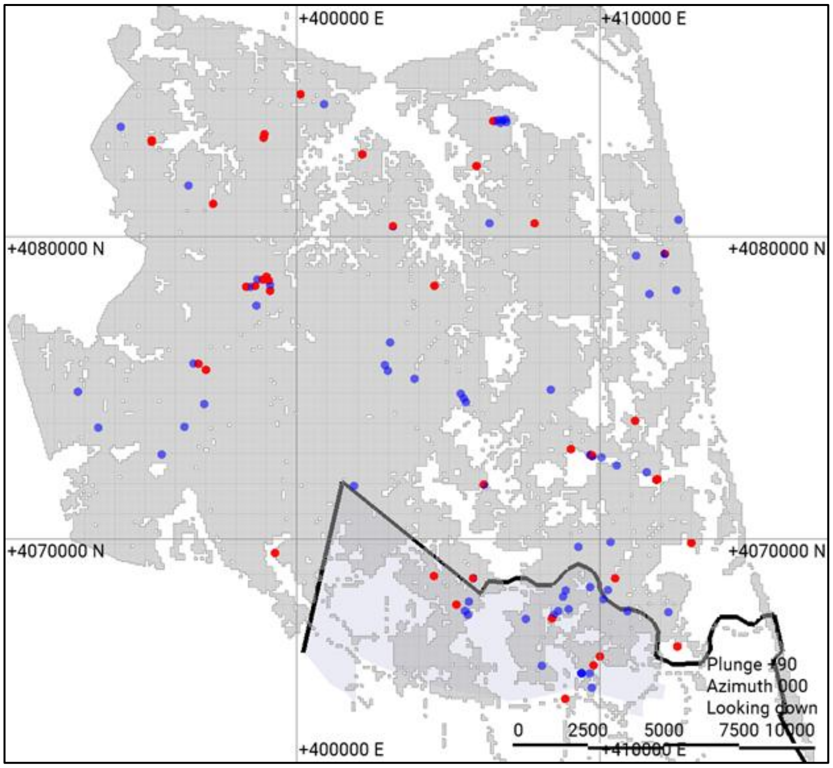

Figure 2 . Block model (50 × 50 × 5 m) and spatial distribution of groundwater monitoring wells within the NLCD 2024 urban domain of Virginia Beach.

3.2 Exploratory analysis and transformations

Exploratory data analysis (EDA) was performed in RStudio to evaluate data ranges, dispersion, and distributional properties prior to geostatistical modeling. Groundwater levels (sl_lev_va) exhibit moderate variability within the urban domain, with values ranging from approximately −3.904 m to 4.307 m NAVD88, a mean of 0.661 m, a median of 0.838 m, and a standard deviation of 1.635 m. Slight negative skewness (−0.563) reflects asymmetry toward lower water-level values, consistent with localized drawdown effects in shallow coastal aquifers. Summary statistics for sl_lev_va are reported in Table 1.

Table 1. Descriptive statistics for sl_lev_va (NAVD88, m).

Metric	Value
Number of records	121
Mean (m)	0.661
Median (m)	0.838
Standard deviation (m)	1.635
Minimum (m)	−3.904
Maximum (m)	4.307
Range (min–max, m)	−3.904 to 4.307
IQR (m)	1.566
Skewness	−0.563
Kurtosis (excess)	0.686
% outliers (1.5×IQR)	8.26%

The CCI shows stronger dispersion and pronounced right-skewed behavior, reflecting the localized and heterogeneous nature of groundwater-quality impacts in urban environments. Concentration ranges differ markedly among Cl, Fe, and Mn, further justifying the use of a composite index for integrated spatial analysis. Summary statistics for the CCI are reported in Table 2.

Table 2. Descriptive statistics for the Composite Contamination Index (CCI).

Metric	Value
Number of records	55
Mean (m)	0
Median (m)	−0.229
Standard deviation (m)	0.624
Minimum (m)	−0.655
Maximum (m)	2.119
Range (min–max, m)	−0.655 to 2.119
IQR (m)	0.94
Skewness	1.26
Kurtosis (excess)	1.145
% outliers (1.5×IQR)	1.82%

Because both kriging and Gaussian simulation require approximate normality, sl_lev_va and CCI were transformed to a normal-score domain using non-parametric rank-based transformations. Extreme values were retained to preserve spatial signal, and reversibility was ensured through lookup tables for back-transformation. No truncation or winsorization was applied, as outliers reflect real hydrogeological and geochemical variability rather than measurement error.

Composite Contamination Index (CCI)

Groundwater quality was integrated through a Composite Contamination Index (CCI) derived from chloride (Cl), iron (Fe), and manganese (Mn) concentrations. These parameters were selected because they are routinely monitored in coastal Virginia aquifers and are directly associated with saline influence, redox processes, and operational or aesthetic limitations of shallow urban groundwater systems.

The use of a composite index is appropriate in this context for two reasons. First, individual groundwater-quality parameters differ substantially in units, ranges, and statistical behavior ($\mathrm{mg\,L^{-1}}$ for Cl versus $\mathrm{\mu g\,L^{-1}}$ for Fe and Mn), which prevents direct combination without normalization. Second, modeling each contaminant independently would increase dimensionality and complexity without improving interpretability for a screening-level groundwater assessment, where the objective is to identify areas of relative groundwater-quality stress rather than predict individual concentrations with regulatory precision.

To place all parameters on a comparable statistical basis, each variable was first normalized using a Z-score transformation:

$$Zi = (xi - \mu i) / \sigma i$$

where xi is the observed concentration, and μi and σi correspond to the sample mean and standard deviation of the respective parameter. This normalization eliminates unit effects, preserves relative deviations from background conditions, and prevents dominance by a single contaminant—particularly chloride, which exhibits larger absolute ranges.

The Composite Contamination Index was then computed as the arithmetic mean of the normalized values:

$$CCI = \frac{Z_{Cl} + Z_{Fe} + Z_{Mn}}{3}$$

No weighting scheme was applied in order to retain transparency and minimize subjective assumptions regarding the relative importance of individual contaminants. This formulation is consistent with the screening-level objective of the study and remains fully compatible with subsequent normal-score transformation, variogram modeling, and Sequential Gaussian Simulation. The resulting CCI provides a single continuous variable suitable for spatial analysis of groundwater-quality patterns under data limitations.

3.3 Variogram modeling

Spatial continuity was evaluated through experimental variograms computed in ISATIS. For groundwater levels (sl_lev_va), omnidirectional variograms were calculated using lag distances up to 10 km and 20 lag classes. The experimental structure is well described by a spherical variogram model with a nugget effect, indicating moderate spatial continuity combined with local-scale variability.

The fitted model parameters for sl_lev_va include:

- nugget ≈ 0.41,
- sill ≈ 1.25, and
- principal ranges of approximately 514 m and 2001 m,

consistent with anisotropy imposed by urban layout, drainage patterns, and coastal hydrogeological controls. Groundwater levels exhibit moderate spatial continuity with local-scale variability, as reflected in the experimental variogram and fitted spherical model (Figure 3), while numeric parameters are summarized in Table 3.

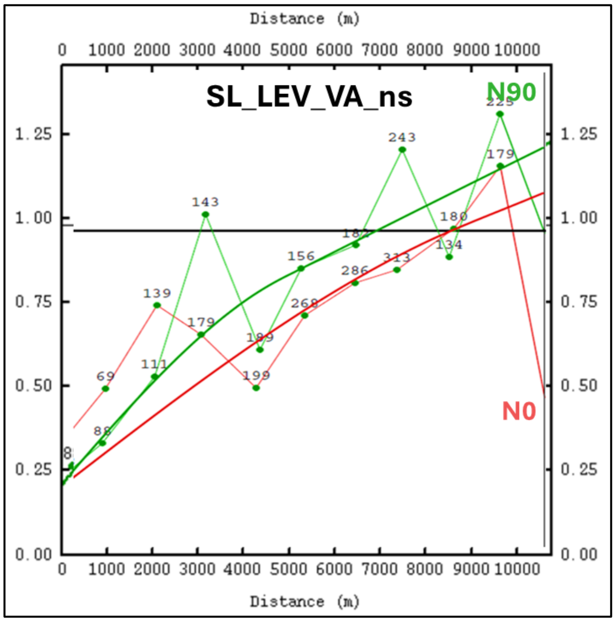

Figure 3. Experimental omnidirectional variogram and fitted spherical model for groundwater levels (sl_lev_va) within the urban domain.

Variogram behavior for the CCI differs markedly from that of groundwater levels. The experimental variogram shows rapid loss of spatial correlation and high variability at short distances. A spherical model with a high nugget relative to sill (nugget ≈ 0.92, sill ≈ 0.82) was adopted, with principal ranges of approximately 300 m and 6000 m. This structure indicates that groundwater-quality patterns in the urban domain are dominated by local-scale processes rather than smooth regional gradients, a result consistent with diffuse urban contamination sources, site-specific geochemical conditions, and heterogeneous subsurface environments.

All variogram models were evaluated and validated in ISATIS prior to simulation. Parameters for both variables are reported in Table 3, providing a transparent basis for reproducibility and interpretation.

Table 3. Variogram model parameters (sl_lev_va and CCI).

Variable	sl_lev_va_ns	CCI_ns
Directions	2	2
Direction 1 (D1)	N0	N210
D1_Angular_tolerance	45	45
D1_Lag	1086.24 m	800.00 m
D1_Count	10 lags	10 lags
D1_Tolerance	50.00%	50.00%
Direction 2 (D2)	N90	N300
D2_Angular_tolerance	45	45
D2_Lag	1086.24 m	800.00 m
D2_Count	10 lags	10 lags
D2_Tolerance	50.00%	50.00%
Structural_Models	3	2
Global_rotation	Azimuth = N0.00 (Geologist Plane)	Azimuth = N210.00 (Geologist Plane)
S1_Nugget_effect	Sill = 0.2081	Sill = 0.8203
S2_Spherical_Range	600.00 m	300.00 m
S2_Sill	0.2901	0.3618
S2_Directional_Scales	9000.00 m, 5000.00 m, 600.00 m	3000.00 m, 6000.00 m, 300.00 m
S3_Spherical_Range	65000.00 m	
S3_Sill	2.964	
S3_Directional_Scales	80000.00 m, 65000.00 m, 80000.00 m	

3.4 Sequential Gaussian Simulation

Spatial uncertainty in groundwater levels and groundwater quality was quantified using Sequential Gaussian Simulation (SGS) implemented in ISATIS. Separate simulations were performed for sl_lev_va and CCI, generating 50 conditional realizations per variable over the three-dimensional block model.

Simulations honor the normal-score-transformed data and the fitted variogram models. Simple kriging (SK) with a constant mean was used as the conditioning estimator. Independent simulation paths were generated using a fixed random seed (423141) to ensure reproducibility. After simulation, all realizations were back-transformed to the original measurement units using the transformation lookup tables described above.

This simulation strategy allows explicit representation of spatial uncertainty while preserving observed data values and modeled spatial structure.

3.5 Post-processing, uncertainty analysis, and visualization

Post-processing and uncertainty analysis were carried out in RStudio, where simulation ensembles were summarized to derive the E-type estimate (conditional mean), standard deviation, and selected percentiles (P05, P10, P50, P90) for each variable. These metrics provide complementary perspectives on expected conditions and spatial uncertainty.

Model performance was evaluated by comparing simulated values and E-type estimates against observed data using RMSE, MAE, and R^2. For groundwater levels, the E-type prediction achieved RMSE = 0.559 m and $R^2 = 0.913$, indicating strong internal consistency and spatial coherence. Validation metrics for groundwater levels and the CCI are reported in Table 4.

Table 4. Validation metrics comparing simulated results and E-type estimates (RMSE, MAE, R^2).

Variable	Metric	Simulations (min–max)	E-type
sl_lev_va	RMSE	0.6197 – 0.8115	0.5590
	MAE	0.4336 – 0.5484	0.3432
	R^2	0.7578 – 0.8740	0.9134
CCI	RMSE	0.4648 – 0.6658	0.4520
	MAE	0.3415 – 0.5123	0.3490
	R^2	0.1090 – 0.4401	0.5524

Three-dimensional visualization of simulation outputs was conducted in Leapfrog to inspect vertical gradients, urban–coastal transitions, and hydrogeologically sensitive zones. These visual checks supported assessment of spatial realism and guided the selection of representative outputs presented in the Results section.

3.6 Role of geostatistical modeling in the study

The geostatistical framework applied in this study is screening-level and exploratory. Its purpose is to identify spatial patterns, uncertainty, and relative groundwater risk under data limitations, not to replace site-specific investigations, regulatory assessments, or engineering design. By integrating groundwater levels, groundwater quality, and explicit uncertainty within a unified spatial framework, the modeling provides the analytical foundation for the groundwater risk mapping and operational zoning presented in the following section.

4. RESULTS

The results summarize spatial patterns of groundwater levels, groundwater quality, and associated uncertainty within the urban domain of Virginia Beach. Outputs derived from Sequential Gaussian Simulation are presented through expected values (E-type), uncertainty metrics, conservative percentiles, and an integrated risk-based zoning. The results are interpreted at a screening level, with emphasis on spatial contrasts relevant for groundwater management rather than site-specific prediction.

4.1 Expected Groundwater Conditions (E-type)

The E-type map for groundwater levels represents the conditional mean of 50 Sequential Gaussian Simulation (SGS) realizations of the variable sl_lev_va within the urban domain. The results reveal a clear north–south spatial contrast, with deeper groundwater levels concentrated in the northern and northwestern sectors of the city and shallower conditions dominating central and southern areas, particularly south of the Green Line.

These shallow conditions coincide with low-relief zones and areas in closer proximity to wetlands and tidally influenced water bodies. Within the Transition Zone, shallow groundwater levels show strong spatial continuity, indicating increased sensitivity to pumping and reduced recharge capacity. This pattern is consistent with regional hydrogeological interpretations and with previous numerical modeling studies conducted in the area.

The spatial distribution of expected groundwater levels at the urban-domain scale is presented in (Figure 4).

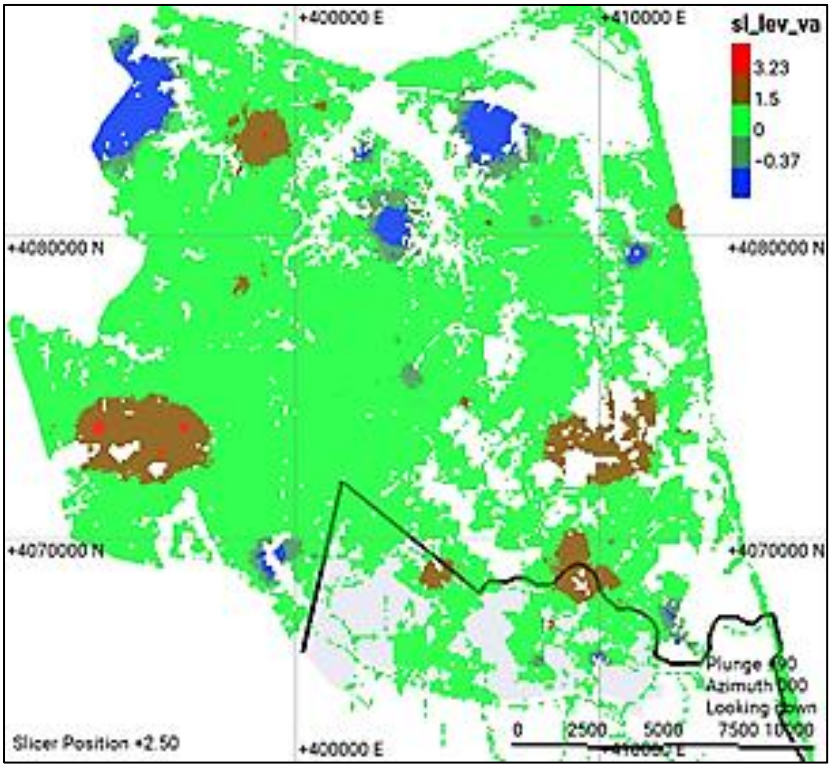

Figure 4. E-type groundwater-level map (mean of 50 SGS realizations) for sl_lev_va within the NLCD 2024 urban domain, Virginia Beach.

4.2 Spatial Distribution of Uncertainty

Uncertainty, quantified by the standard deviation of the simulated groundwater levels, exhibits strong spatial heterogeneity across the urban domain. Lower uncertainty values are observed in areas with dense monitoring coverage, particularly within consolidated urban sectors. In contrast, higher uncertainty is concentrated along the urban–wetland interface and in peripheral areas where monitoring density decreases.

The Transition Zone stands out as an area of elevated uncertainty, reflecting both hydrogeological complexity and limited data support. This result indicates that groundwater conditions in these areas are less constrained by observations and should be interpreted with greater caution.

Spatial uncertainty varies markedly across the urban domain, with highest values concentrated in transition and wetland-adjacent areas (Figure 5).

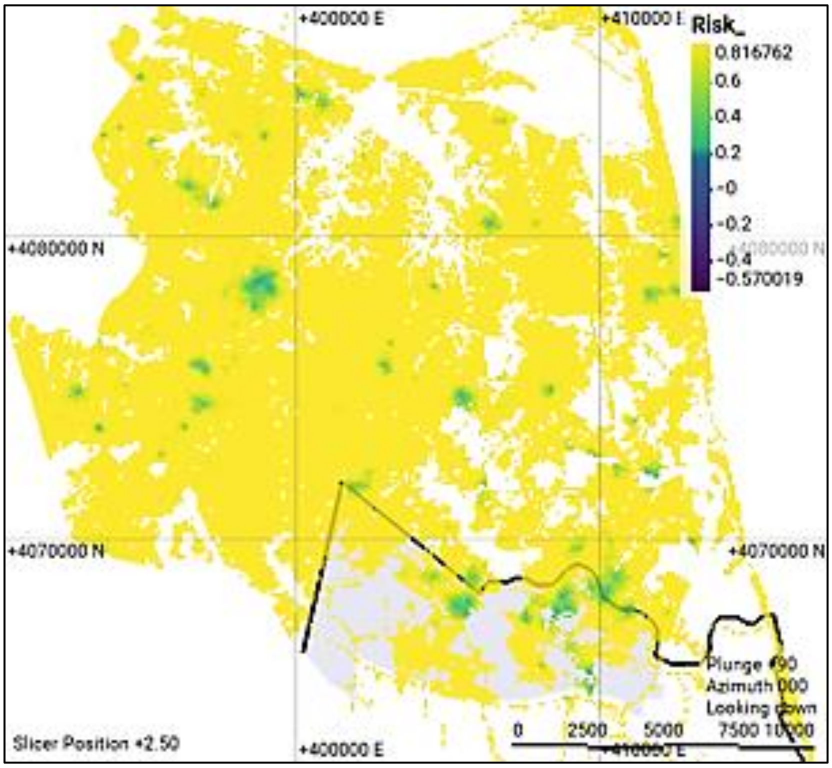

Figure 5. Spatial distribution of groundwater-level uncertainty expressed as standard deviation (SD). Higher uncertainty is concentrated along the urban–wetland transition zone.

4.3 Conservative scenarios and percentile representation

Percentile maps derived from the simulation ensemble provide insight into conservative groundwater conditions. Low-percentile maps (P05–P10) indicate relatively stable conditions in deeper northern sectors, whereas high-percentile maps (P90) reveal a substantial expansion of shallow groundwater conditions into central and southern urban areas.

The P90 scenario highlights zones where shallow water tables may occur under plausible but unfavorable configurations, extending beyond the areas suggested by the E-type map alone. These results demonstrate how reliance on average conditions can underestimate potential groundwater risk.

Conservative scenarios reveal an inland expansion of shallow groundwater conditions beyond those suggested by the E-type map (Figure 6).

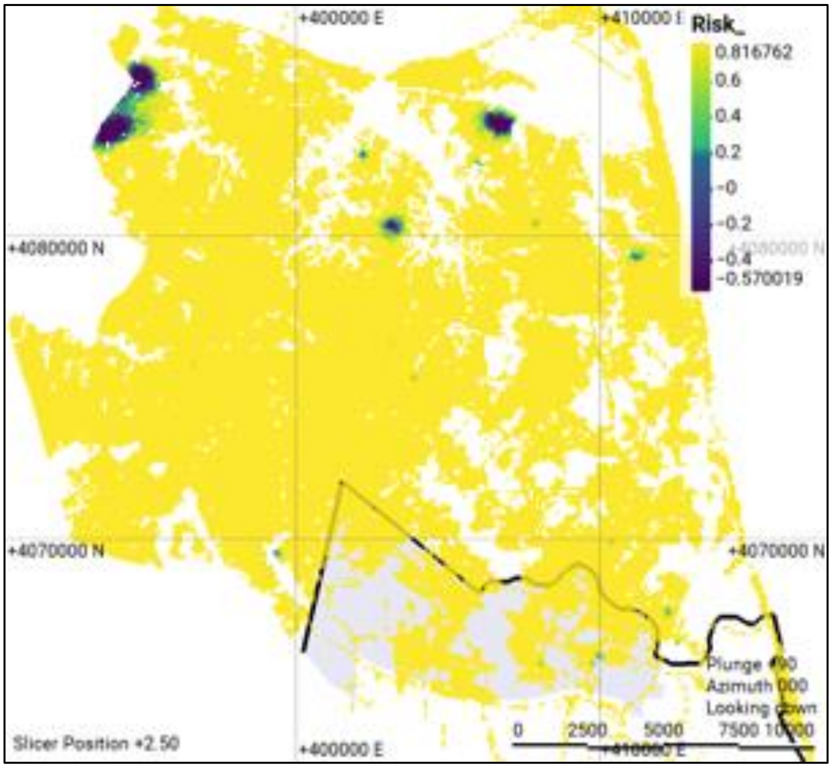

Figure 6. P90 groundwater-level map illustrating conservative scenarios with expanded shallow conditions in central and southern urban areas.

4.4 Groundwater quality patterns (CCI)

The E-type map of the Composite Contamination Index (CCI) reveals heterogeneous groundwater-quality conditions within the urban domain. Lower CCI values, indicating relatively better water quality, are more prevalent in less densely developed southern sectors, whereas higher CCI values cluster in densely urbanized areas and near the coast.

CCI spatial continuity is markedly weaker than that of groundwater levels. The fitted variogram model shows a dominant nugget effect, indicating that contamination patterns are governed primarily by local-scale processes rather than smooth regional gradients. This behavior is consistent with urban groundwater systems influenced by diffuse sources, site-specific infrastructure, and heterogeneous subsurface conditions.

Groundwater-quality stress displays a heterogeneous spatial pattern, with higher CCI values clustered in densely urbanized sectors (Figure 7).

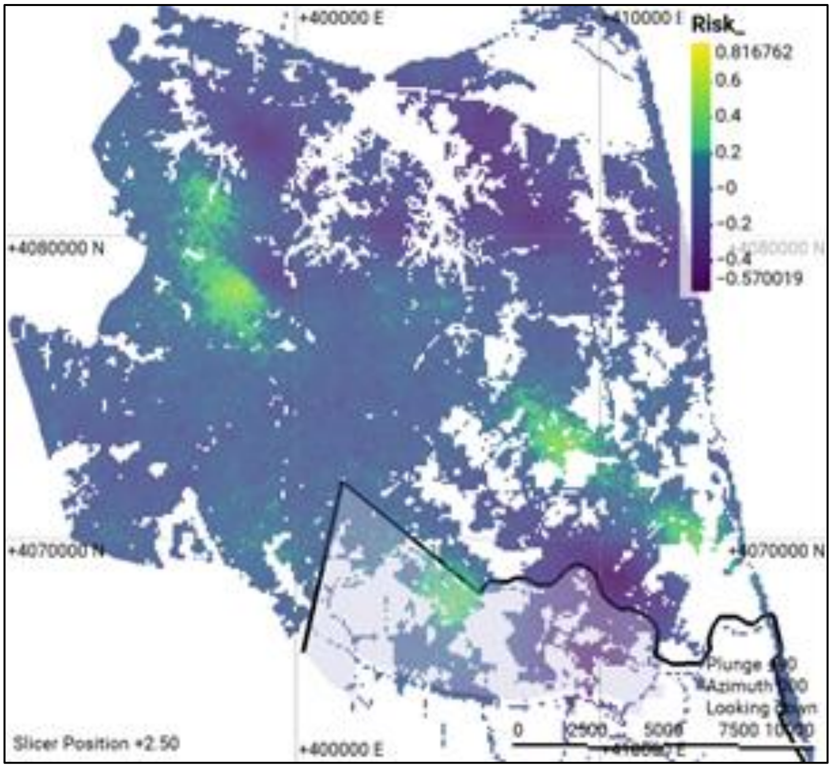

Figure 7. E-type map of the Composite Contamination Index (CCI), derived from 50 SGS realizations of Cl, Fe, and Mn.

4.5 Integrated risk-based groundwater zoning

Groundwater depth (sl_lev_va) and groundwater quality (CCI) were combined into a risk-based zoning designed to translate probabilistic geostatistical outputs into management-oriented categories. The zoning integrates depth classes (very shallow to very deep) with groundwater-quality conditions (very low to very high contamination), resulting in an operational classification that reflects both hydraulic vulnerability and water-quality stress.

The full zoning scheme distinguishes 10 combined classes (depth × quality), which are used to generate the final spatial map. However, for interpretation at the urban-domain scale, these combined classes were aggregated into final suitability categories based on groundwater usability for new abstraction. This aggregation avoids misinterpretation of individual depth-dependent subclasses and provides a clearer basis for reporting area percentages at the domain scale.

The spatial distribution of the 10-class zoning is shown in Figure 8, where extensive areas classified as unsuitable or highly constrained dominate the urban landscape, particularly south of the Green Line and within the Transition Zone.

Integrating groundwater depth and quality highlights extensive areas classified as unsuitable for use across the urban domain (Figure 8).

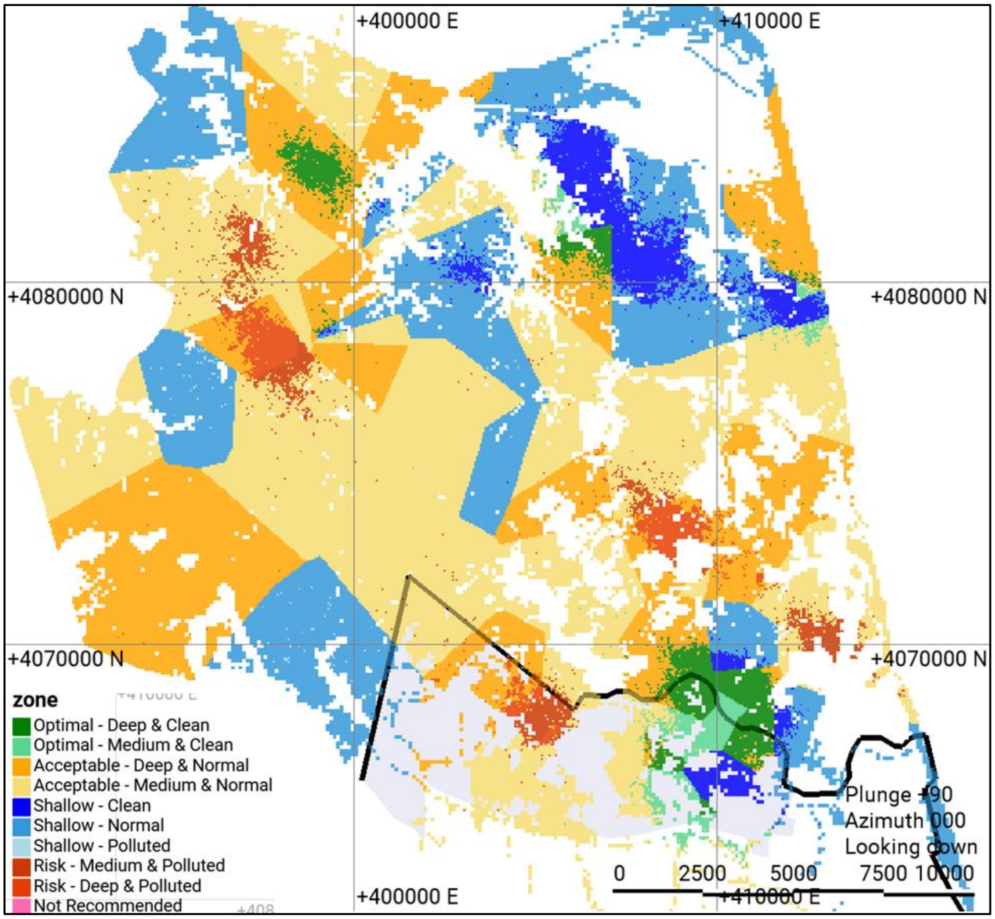

Figure 8. Spatial distribution of the 10-class groundwater risk zoning derived from combined groundwater depth (sl_lev_va) and groundwater quality (CCI) within the urban domain of Virginia Beach.

4.6 Zoning summary and quantitative distribution

For interpretation at the scale of the full urban domain, the depth-dependent zoning classes derived from the integrated map were summarized using two complementary perspectives. First, the detailed 10-class zoning is retained to describe the full spatial classification and to support the legend of the zoning map. Second, these classes are aggregated into final groundwater-suitability categories, independent of depth, to enable consistent reporting of area percentages and support domain-scale conclusions.

The detailed zoning classes, resulting from the combination of groundwater depth and groundwater-quality conditions, are summarized in Table 5. These classes correspond directly to the legend used in (Figure 8) and preserve the spatial complexity of the integrated zoning.

Table 5. Detailed groundwater zoning classes used in the legend of the integrated zoning map (Figure 8).

Zone	Area (m^2)	% Total
Shallow – Acceptable	17,500	0%
Shallow – Risk	1,287,500	0%
Shallow – Polluted	26,582,500	1%
Shallow – Not recommended	1,539,520,000	49%
Deep – Optimal	7,500	0%
Deep – Acceptable	227,500	0%
Deep – Risk	13,725,000	0%
Deep – Polluted	141,035,000	4%
Deep – Not recommended	1,412,417,500	45%
Total	3,134,820,000	100%

While Table 5 provides a complete description of the depth-dependent zoning, interpretation at the urban-domain scale requires aggregation of these classes into final groundwater-suitability categories. This aggregation avoids misinterpretation of individual subclasses and allows direct comparison across the entire study area.

The aggregated distribution of groundwater-suitability categories is summarized in Table 6.

Table 6. Aggregated groundwater-suitability categories across the urban domain.

Final suitability category	**% of total urban area**
Not recommended	**94.17%**
Risk	~5%
Acceptable	< 1%
Optimal	< 0.01%

The aggregated results indicate that groundwater conditions suitable for new abstraction are extremely limited. Areas classified as Not recommended account for more than 94 % of the urban domain, reflecting the combined influence of shallow groundwater levels, groundwater-quality constraints, and elevated uncertainty. Zones classified as Acceptable or Optimal occur only as small, spatially fragmented patches and represent less than 1 % of the total area.

4.7 Summary of key spatial patterns

Across the urban domain of Virginia Beach, shallow groundwater levels, elevated uncertainty, and groundwater-quality constraints frequently overlap, particularly south of the Green Line and within the Transition Zone. These areas coincide with zones of limited recharge capacity, proximity to wetlands and tidal water bodies, and reduced data support, all of which contribute to heightened hydrogeological vulnerability.

The spatial patterns identified through E-type estimates, uncertainty metrics, conservative percentile scenarios, and integrated zoning converge on a consistent interpretation: areas meeting both depth and quality criteria for new groundwater abstraction are rare and spatially discontinuous. In contrast, large portions of the urban domain are dominated by shallow and constrained conditions that limit the feasibility of additional groundwater development.

The combined use of probabilistic groundwater levels, groundwater-quality indicators, and risk-based zoning provides a coherent framework for understanding groundwater limitations under current conditions. These results support a management focus on monitoring prioritization and precautionary planning, rather than identification of specific locations for new abstraction, within the constraints of available public data.

5. DISCUSSION

South of the Green Line, shallow groundwater levels and elevated simulation uncertainty coincide across most of the Transition Zone. This spatial pattern extends previous USGS findings by indicating not only where groundwater conditions are sensitive to pumping (Smith, 2005), but also where limitations in data support magnify hydrogeological risk. In these areas, uncertainty is not a secondary modeling outcome; it directly constrains the reliability of any assessment based solely on expected groundwater levels.

The conservative percentile analysis reinforces this interpretation. While E-type estimates indicate shallow groundwater primarily in southern sectors, P90 scenarios reveal that shallow conditions may extend farther inland under unfavorable but realistic configurations. This behavior is particularly relevant in low-relief coastal settings, where small changes in hydraulic gradients can significantly alter groundwater conditions. Together, these results demonstrate that average conditions alone may underestimate potential groundwater risk.

Groundwater quality exhibits a distinct spatial behavior compared to groundwater levels. The strong nugget effect observed in the CCI variogram indicates weak spatial continuity and limited correlation beyond short distances. This response suggests that groundwater-quality patterns are dominated by local-scale factors such as land use, infrastructure, and site-specific geochemical conditions. As a result, areas with sufficient groundwater depth do not necessarily satisfy groundwater-quality criteria, underscoring the need to evaluate hydraulic and chemical constraints jointly.

The integrated risk-based zoning provides a useful synthesis of these interacting factors. The dominance of categories classified as Not recommended across the urban domain reflects the cumulative effect of shallow groundwater levels, groundwater-quality stress, and uncertainty. Suitable conditions for additional abstraction are restricted to small, spatially fragmented areas, primarily in deeper northern sectors. From a management perspective, these patterns indicate limited potential for expanding groundwater use without targeted mitigation or additional data acquisition.

Several limitations should be acknowledged. The analysis relies exclusively on publicly available datasets, which exhibit uneven spatial density and temporal coverage, particularly for groundwater quality. Multiyear averaging improves spatial representation but smooths short-term variability associated with seasonal pumping or extreme events. In addition, the geostatistical framework assumes local stationarity and approximate Gaussian behavior, simplifying complex hydrogeochemical processes. These constraints reinforce the interpretation of the results as screening-level guidance, rather than site-specific design input.

Overall, the results demonstrate that explicit consideration of uncertainty, combined with groundwater depth and quality, provides a more realistic basis for groundwater assessment than deterministic surfaces alone. In a coastal urban system such as Virginia Beach, this integrated approach helps avoid overconfident management decisions based on incomplete information.

6. CONCLUSIONS

This study evaluated shallow groundwater conditions in the urban domain of Virginia Beach by integrating groundwater levels, groundwater quality, and spatial uncertainty within a unified geostatistical framework. Using publicly available data, the analysis shows that groundwater suitability for new abstraction is highly constrained under current conditions.

The results indicate that areas classified as Not recommended account for more than 94 % of the urban domain, while zones meeting acceptable or optimal criteria represent less than 1 % of the total area. This distribution reflects the combined influence of shallow groundwater levels, groundwater-quality limitations, and elevated uncertainty, particularly south of the Green Line where groundwater remains the primary source of supply.

A central contribution of this work is the explicit characterization of spatial uncertainty. Simulation results demonstrate that uncertainty concentrates in hydrogeologically sensitive areas such as the Transition Zone, where monitoring density is limited and subsurface conditions are complex. In these sectors, reliance on expected groundwater levels alone would provide an incomplete assessment of risk.

The integrated risk-based zoning translates complex probabilistic outputs into an operational product that can support groundwater management discussions. Although not intended for regulatory or site-specific design, the zoning identifies areas where additional monitoring would most effectively reduce uncertainty and where precautionary management is warranted. For Virginia Beach, these findings suggest that management efforts should prioritize data acquisition and protection of sensitive areas rather than expansion of abstraction capacity.

The methodology applied here is transferable to other coastal cities facing similar challenges related to shallow aquifers, urban development, and heterogeneous public datasets. Future efforts would benefit from expanded groundwater-quality monitoring, inclusion of additional chemical indicators, and higher-frequency observations to better capture temporal dynamics. Targeted monitoring in areas identified as both shallow and uncertain offers a practical pathway toward more robust groundwater management decisions.

7. REFERENCES

Alley, W. M., Reilly, T. E., & Franke, O. L. (2002). *Sustainability of ground-water resources*. U.S. Geological Survey Circular 1186. https://pubs.usgs.gov/circ/circ1186/

Chiles, J. P., & Delfiner, P. (2012). *Geostatistics: Modeling spatial uncertainty* (2nd ed.). Wiley.

Deutsch, C. V., & Journel, A. G. (1998). *GSLIB: Geostatistical software library and user's guide* (2nd ed.). Oxford University Press.

Eggleston, J. R. (2010). *Outdoor water use and water conservation opportunities in Virginia Beach, Virginia*. U.S. Geological Survey Fact Sheet 2010–3007.

Goovaerts, P. (1997). *Geostatistics for natural resources evaluation*. Oxford University Press.

Homer, C. G., Dewitz, J. A., Yang, L., Jin, S., Danielson, P., Xian, G., et al. (2020). Completion of the 2016 National Land Cover Database for the conterminous United States—Representing a decade of land cover change information. *Photogrammetric Engineering & Remote Sensing, 86*(8), 737–747. https://doi.org/10.14358/PERS.86.8.737

Isaaks, E. H., & Srivastava, R. M. (1989). *An introduction to applied geostatistics*. Oxford University Press.

National Oceanic and Atmospheric Administration (NOAA). (2023). *VDatum: Vertical datum transformation tool (Version 4.7.1)*. https://vdatum.noaa.gov

Smith, B. S. (2003). *Ground water flow and saline water in the shallow aquifer system of the southern watersheds of Virginia Beach, Virginia*. U.S. Geological Survey Water-Resources Investigations Report 03-4258.

Smith, B. S. (2005). *Simulated changes in water levels caused by potential changes in pumping from shallow aquifers of Virginia Beach, Virginia*. U.S. Geological Survey Scientific Investigations Report 2005-5067.

U.S. Environmental Protection Agency (EPA). (2023). *Secondary drinking water standards: Guidance for nuisance chemicals*. https://www.epa.gov/sdwa

U.S. Geological Survey (USGS). (2024). *USGS water data for the nation*. https://waterdata.usgs.gov

Johnson, H. M., IV. (1999). The Virginia Beach shallow ground-water study. U.S. Geological Survey Fact Sheet 173–99.