State and trend analysis of groundwater levels in the Heretaunga and Ruataniwha Plains

Groundwater level state, trends and patterns 1984-2024

Report number: 5674

HAWKES BAY REGIONAL COUNCIL

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This report focuses on evaluating groundwater levels measured as part of the Regional Council's State of the Environment monitoring network. The main objectives of this report are to assess and report on changes in groundwater levels over time. The analysis is based on statistical methods, including the Seasonal Kendall and Mann-Kendall tests to detect trends and the Sen's slope method to quantify the rate of groundwater level change. Trends were assessed over 10, 20, 30, and 40-year periods to provide a comprehensive long-term perspective.

Observed groundwater level changes

In the Heretaunga Plains, groundwater levels have declined by approximately 0.4–2 metres over the last four decades. The most persistent declines are observed northwest of Hastings, particularly between Roy's Hill and Fernhill. Seasonal groundwater level variations have also increased but are typically smaller in the Heretaunga Plains due to its transmissive aquifers and strong hydraulic connection to surface water.

In contrast, the Ruataniwha Plains have experienced more substantial groundwater declines, averaging 2.8–6 metres since the 1980s. Seasonal fluctuations are more pronounced in this region, with significant drawdowns occurring during peak irrigation months from December to March. During this period, groundwater levels decline at an accelerated rate, increasing from 7 cm/year to 13 cm/year, highlighting the strong influence of seasonal water demand on aquifer depletion.

2021-2024 hydrological year

The most significant feature of the 2021-2024 period was the above-normal and record-high groundwater levels observed during the summer and autumn of the 2022-2023 hydrological year. During the 2022–2023 hydrological year, groundwater levels across the Heretaunga and Ruataniwha Plains were notably high due to increased rainfall and reduced abstraction. In the Heretaunga Plains, groundwater levels were among the highest on record, with a median percentile of 85.8 percent, and 75 percent of observations above the 73rd percentile, indicating widespread high levels. Some wells reached their highest-ever recorded levels. Similarly, in the Ruataniwha Plains, groundwater levels were also above average, with a median percentile of 82.5 percent and 75 percent of observations above the 65th percentile, reflecting generally elevated conditions.

Overall, the assessment indicated a transition from drier conditions in 2021 to significantly elevated groundwater levels in 2022-2023, highlighting the influence of climatic variability on regional groundwater systems. While 2023 remained largely above normal, some localised declines suggest that ongoing monitoring is necessary to determine whether this represents a temporary recharge event or a longer-term recovery trend in groundwater levels.

Key drivers of short and long-term changes

The changes in groundwater levels, can be explained by a combination of increasing groundwater abstraction, changes in river recharge processes, and climatic variability.

1. Groundwater pumping and increased water use

- For over a century, groundwater use has increased without comprehensive basin-wide limits. As both the number of groundwater takes and volumes have increased, water levels have progressively declined. The most pronounced changes have occurred during the summer months, which have seen the greatest increases in groundwater use over time. Groundwater models have successfully demonstrated a strong match between changing water use patterns and long-term groundwater

level trends; however, discrepancies remain in certain areas where additional data or refinements to the models may be needed.

2. Changes in river recharge and surface water interactions

- The Ngaruroro River is the primary recharge source for the Heretaunga aquifer system; however, historical gravel extraction, river engineering, and the narrowing of the braidplain near Roy's Hill have reduced the wetted area available for infiltration, thereby limiting recharge capacity. In this area, basin-scale models have struggled to accurately simulate groundwater levels, highlighting the complexity of surface water–groundwater interactions. More recent localised investigations suggest that observed groundwater level changes can largely be attributed to alterations in the riverbed, reinforcing the need for improved modelling approaches that account for these physical modifications.

3. Climatic variability

- Short-term fluctuations in groundwater levels are strongly influenced by climatic conditions, with drier-than-normal periods exacerbating seasonal declines. Seasonal variability in water availability plays a key role in driving groundwater level fluctuations, often masking long-term trends associated with persistent groundwater pumping and inter-decadal climate patterns. This seasonal influence can make it challenging to distinguish between short-term climate-driven changes and the cumulative effects of long-term groundwater abstraction.

Management issues

Two major management challenges arise from these changes: reductions in surface water flows and increasing risks to water supply security. Groundwater abstraction has significantly reduced streamflow in major rivers and spring-fed streams, particularly during summer. Modelling indicates that the most affected surface water body is the Ngaruroro River, which has experienced a loss of nearly 50 percent of its flow during the driest periods, amounting to approximately 1,000 L/s of depletion. Other major rivers, including the Tukituki and Tūtaekurī Rivers, have also been impacted, though to a lesser extent. The depletion effect is particularly severe in spring-fed streams such as the Karamū, Irongate, Kārewarewa, Mangateretere, and Raupare Streams, where groundwater pumping has reduced flows by up to 60–90 percent of their natural discharge.

Beyond flow reductions, these declines in groundwater levels threaten water supply security, particularly for shallow wells in areas such as Bridge Pā, Tikokino, and Ongaonga, where some domestic and stock water supplies have been affected during periods of extreme low groundwater levels. Additionally, declining groundwater levels impact recharge processes, leading to slower recovery after dry periods and a longer duration of low flows in rivers.

Management solutions

To address these challenges, the Hawke's Bay Regional Council (HBRC) has implemented groundwater allocation limits, developed through stakeholder-led processes to balance the benefits of water use with the impacts of groundwater pumping. However, to enhance environmental outcomes and meet future water demands, additional measures may be necessary, including:

- Refining and enforcing groundwater abstraction limits in the Heretaunga and Ruataniwha Plains to prevent further declines.

- Expanding groundwater monitoring to fill data gaps and improve understanding of groundwater-surface water interactions.
- Investigating Managed Aquifer Recharge (MAR) feasibility in targeted locations to enhance groundwater storage.
- Encouraging irrigation efficiency improvements and evaluating alternative water storage solutions to reduce reliance on groundwater.

Without effective intervention, ongoing declines could lead to further ecological degradation, reduced water availability, and increased competition for limited resources, particularly during drought conditions.

1 Introduction | Whakatakinga

Groundwater is among Hawke's Bay's most important natural resources. It provides water for drinking, irrigation, and industry, in addition to sustaining the flow of streams and rivers and maintaining riparian and wetland ecosystems. Approximately 85 percent of all water consented[1] in Hawke's Bay is for groundwater (IRIS database, November 2024). The main groundwater use is for irrigation, which accounts for approximately 85 percent of the groundwater consents issued, and approximately 65 percent of the annual volume of groundwater allocated (IRIS database, November 2024)[2].

The main groundwater resources in Hawke's Bay are located within the Heretaunga and Ruataniwha Basins. Here, unconsolidated alluvium form highly productive aquifers that account for more than 80 percent of the region's consented annual groundwater allocation (IRIS database, November 2024) and 84 percent of the wells drilled (WellStor database, November 2024). The remaining groundwater takes are sourced from smaller valley aquifer systems and, to a lesser extent, from hard-rock aquifers.

Groundwater use in Hawke's Bay has been occurring for over a century (Dravid and Brown, 1997). Consequently, the region's major aquifer systems are highly modified from their natural state (Harper, 2015; Rakowski and Knowling, 2018). Human activities, such as groundwater pumping, change the natural groundwater flow system. These changes not only affect the volume of groundwater in storage but the exchange of water between surface water and groundwater resources. An important role of groundwater management is understanding how resource use such as groundwater abstraction effect the environment and balancing these with the benefits of water use. Long-term monitoring provides crucial information on where changes are occurring, the timing of impacts, and helps to inform the processes driving them.

To evaluate changes in the groundwater resource, develop models, forecast trends, and design and monitor the effectiveness of Resource Management Plans, the Hawke's Bay Regional Council (HBRC) measures groundwater levels at dedicated State of the Environment monitoring wells. These wells provide direct access to the subsurface and make it possible to measure groundwater levels, obtain water samples, conduct aquifer tests, and estimate the physical and geochemical properties of the earth's material.

Every three years the HBRC reviews and analyses data collected from the State of the Environment programmes and makes publicly available comprehensive State of the Environment reports. This report focuses on evaluating groundwater levels measured as part of the Regional Council's State of the Environment monitoring network. The main objectives of this report are to assess and report on changes in groundwater levels over time.

1.1 Purpose and scope

Under the Resource Management Act (RMA) 1991, Regional Council's across New Zealand are responsible for the integrated management of the region's natural and physical resources. Section 35(2)(a) of the RMA mandates that Regional Councils monitor the state of the environment to the extent necessary to effectively carry out its functions under the Act. The primary purpose of state of the environment monitoring is to gather sufficient data to provide information on the overall health of the environment and to understand how the region's natural and physical resources are impacted by resource development.

Part II of the Resource Management Act mandates that Regional Councils promote the sustainable management of natural and physical resources. State of the environment monitoring and reporting are critical for assessing compliance with these requirements, offering early warnings of environmental issues. Additionally, these processes enable Regional Councils and communities to obtain crucial information on the

[1] Excluding water consented for hydro-electricity
[2] Irrigation use is seasonal with most groundwater used over summer.

state of the environment, identify significant environmental pressures, and evaluate potential and actual responses.

Although there is no explicit requirement under the RMA to report on the state of the environment, the Regional Council is required under Section 35(2)(b) to report on the effectiveness and efficiency of its plans and policies at intervals of not more than five years. State of the Environment monitoring provides information about groundwater resources that can assist planners in meeting this requirement.

1.2 Previous reports

Technical reports for the State of the Environment reporting cycles exist for the periods 2003-2008, 2008-2013, and 2013-2018 (Brooks et al., 2003; Harper, 2015, 2010). In 2003, the effects of changes on the groundwater resource were reported in terms of both water quantity and water quality (Brooks et al., 2003). By 2008, these two aspects of groundwater were reported separately (Harper, 2010). The 2003 and 2008 reports used linear regression to calculate the rate and direction of groundwater trends, with changes reported in metres per 10 years (Brooks et al., 2003; Harper, 2010). Both reports also assessed changes in seasonal variation over time; the first report focused on the current state of seasonal variation, while the second evaluated changes over time.

In 2015 and 2020, trends were assessed using non-parametric tests (Harper, 2020, 2015). The Mann-Kendall method (Kendall, 1975; Mann, 1945) was employed to test for statistically significant monotonic changes, and a non-parametric decomposition method was used to characterise trend and seasonal behaviour over time (Cleveland, 1979). In 2021, HBRC changed the reporting frequency from every five years to every three years. During this reporting cycle, the emphasis was on developing a comprehensive summary report, making technical reports non-mandatory for the reporting period.

2 Background | Papamuri

2.1 Groundwater resource areas

Groundwater can be found in many parts of Hawke's Bay, but the most productive groundwater resources are formed within unconsolidated sediments such as the open-framework gravels and sands that make up the aquifers of the Heretaunga and Ruataniwha Plains (Figure 2-1). These aquifer systems are renowned for their high-quality water, substantial storage capacity, and excellent transmissive properties, making them highly valuable for productive uses such as irrigation, drinking water and industrial uses. Many wells are also located outside of these areas, highlighting the importance of groundwater for the wider regional community, not just well owners on the Heretaunga and Ruataniwha Plains (Figure 2-2).

2.1.1 Heretaunga aquifer system

The Heretaunga Plains encompasses a significant aquifer system that serves as a critical water resource for the area. The plains span approximately 300 km^2 bounded by the Ngaruroro River to the north, the Tukituki River to the south, and the Pacific Ocean to the east. The area includes the urban centres of Hastings, Havelock North, and Napier, along with extensive agricultural and horticultural lands.

The Heretaunga Plains were formed by the sedimentation processes of the Ngaruroro, Tukituki, and Tūtaekurī rivers. The geology of the plains is characterised by layers of alluvial deposits, including gravels, sands, silts, and clays, which have accumulated over thousands of years. These sediments create a highly heterogeneous aquifer system with varying permeability and storage capacities (Begg, 2017).

The Heretaunga Plains aquifer system is a multi-layered aquifer system recharged by river infiltration, rainfall, and irrigation return flows. The Ngaruroro River is the major source of recharge, contributing to both the surface water and groundwater systems. The hydraulic connectivity between the rivers and the aquifers plays a crucial role in maintaining the water balance and quality (Wilding, 2017).

The land use on the Heretaunga Plains is diverse, with a mix of urban, industrial, agricultural, and horticultural activities. The region is renowned for its fertile soils and favourable climate, making it a prime area for fruit and vegetable production. The aquifer system underpins these economic activities by providing a reliable supply of high-quality water for irrigation, domestic, and industrial use.

2.1.2 Ruataniwha aquifer system

The Ruataniwha Plains, located in the central part of Hawke's Bay, features an aquifer system used mainly for agricultural water supply. These plains cover an extensive area, bordered by the Ruahine Ranges to the west and flowing into the broader Hawke's Bay catchment to the east (Baalousha, 2009). The area is characterised by a mix of rural towns and expansive agricultural lands, including significant pastoral and crop farming.

Formed through the sedimentary deposits of local rivers, the Ruataniwha Plains are underlain by a complex geology of gravels, sands, silts, and clays. This diverse sediment composition forms a heterogeneous aquifer system, which varies greatly in permeability and storage capacity compared with the Heretaunga Plains.

Land use in the Ruataniwha Plains is predominantly agricultural, with a strong emphasis on sheep and cattle farming, alongside cropping and dairy farming. The aquifers play a fundamental role in supporting these activities, providing consistent and high-quality water necessary for irrigation and other agricultural needs.

2.1.3 Minor aquifer systems

Outside of the Heretaunga and Ruataniwha Plains, the predominant geology is dominated by fine-grained marine deposits, which are generally poor conduits for groundwater flow. Wells screened into these types of deposits typically supply groundwater for low-rate purposes such as stock or domestic water supply. Smaller alluvial groundwater resources are located along existing and buried river valleys throughout the region. Some examples of river-valley-aquifer systems are along the Tūtaekurī, Esk and Ngaruroro Rivers.

In limestone and sandstone-dominated catchments, consolidated aquifer systems are present. An example of groundwater use in such aquifer systems can be found on the northern outskirts of the peripheral hill country adjacent to the Heretaunga Plains. The high density of wells in this area predominantly serves domestic water needs, reflecting the large number of lifestyle properties there.

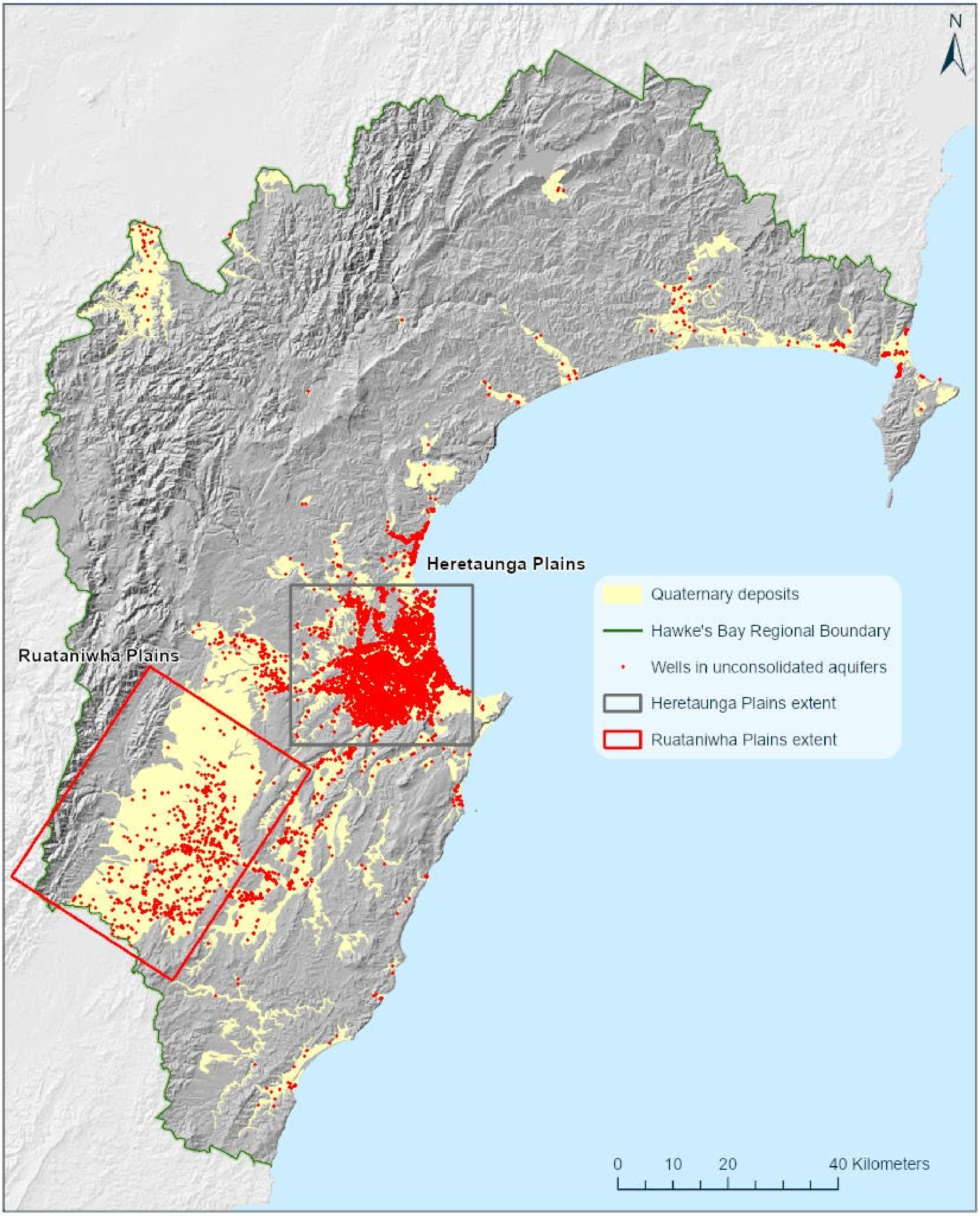

Figure 2-1: Location of wells in unconsolidated aquifers within Hawke's Bay.

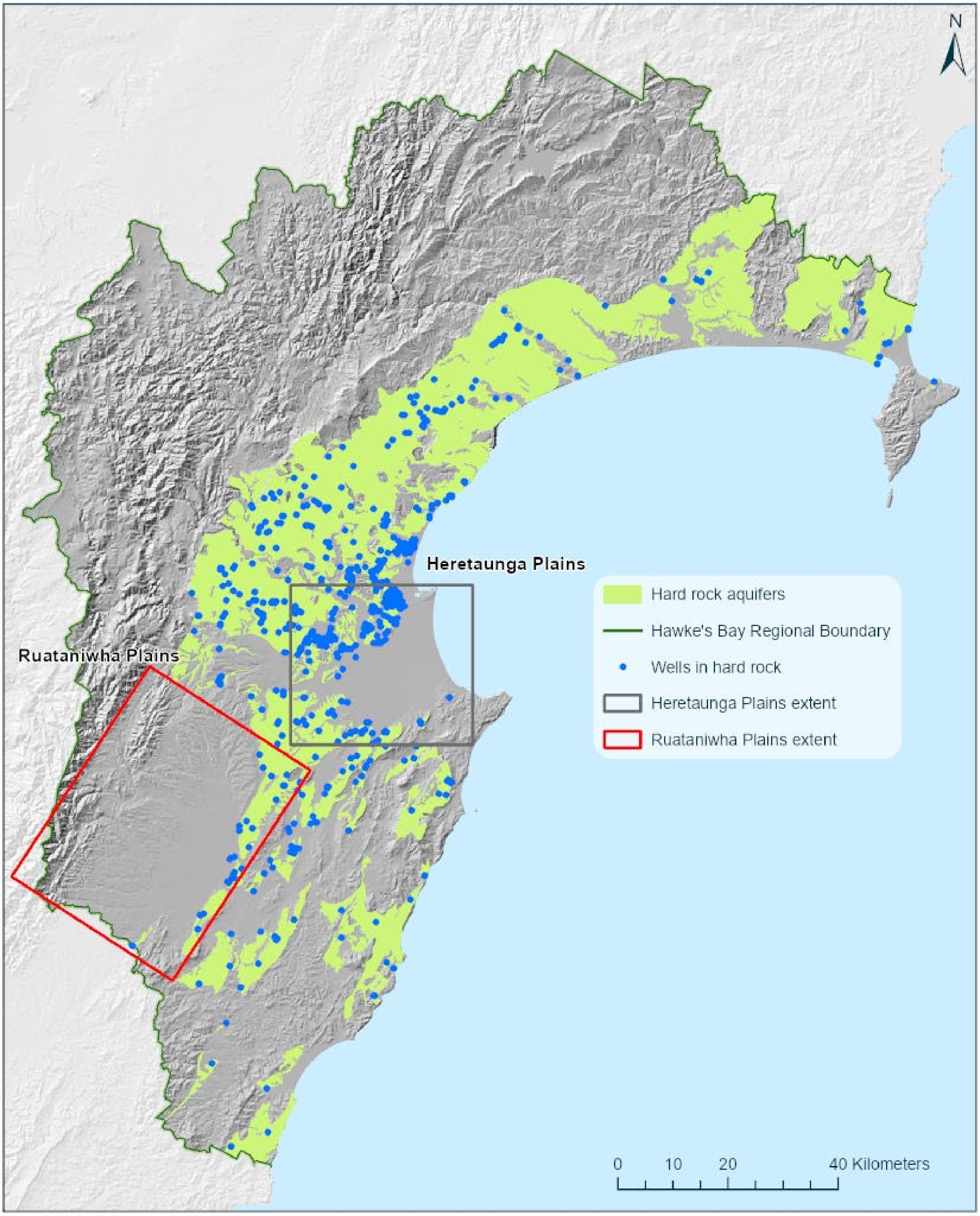

Figure 2-2: Location of wells screened within hard rock aquifers in Hawke's Bay

2.2 Climatic conditions

The Hawke's Bay region is characterised by significant spatial variations in rainfall, shaped by its complex topography and geographic features. Coastal areas tend to receive lower levels of precipitation, with annual rainfall ranging from 600 to 800 millimetres. In contrast, the inland ranges and foothills often experience considerably higher rainfall, with totals sometimes surpassing 1,200 millimetres per year (Chappel, 2014).

In northern Hawke's Bay, rainfall patterns are distinct, with these areas often experiencing greater precipitation compared to their southern counterparts. This is due to the northern region's closer proximity to prevailing moist, northeasterly winds, which contribute to higher annual rainfall totals that can surpass 1,000 millimetres (Chappel, 2014).

Eastern parts of Hawke's Bay, such as the Heretaunga and Ruataniwha Plains, endure a drier climate due to the rain shadow effect caused by the western ranges. This results in lower moisture levels and increased reliance on irrigation for agricultural activities. In contrast, the western foothills benefit from orographic rainfall leading to higher precipitation levels.

2.2.1 Heretaunga and Rutaniwha Plains

The Heretaunga Plains experiences a temperate climate with moderate rainfall distributed throughout the year. The annual rainfall averages around 800 to 1,000 millimetres, with significant variation between seasons. Most rainfall occurs during the winter months (June to August), contributing to the recharge of the plains' aquifer system. Summer months are typically drier, which increases the reliance on groundwater and irrigation for agricultural and horticultural activities.

The Ruataniwha Plains is also characterised by a temperate climate that sees moderately distributed rainfall throughout the year. Annual rainfall on the plains averages between 900-1000 millimetres (NIWA database, December 2019), with distinct seasonal variations. Most of this precipitation falls also during the winter months. Conversely, the summer months tend to be drier, increasing dependence on both groundwater and irrigation to support the area's agricultural and horticultural sectors.

2.3 Groundwater use

The total volume of groundwater used by resource consent holders indicates how much pumping pressure exists in each of the groundwater systems. The most productive and heavily used groundwater systems are the Heretaunga and Ruataniwha Plains. Groundwater use in these areas reflects distinct seasonal and regional variations.

Heretunga Plains

Between July 2014 and June 2024, the volume of groundwater used in the Heretaunga Plains ranged from 40.3 to 67.7 GL (Figure 2-3). This is roughly triple the amount of water used in Ruataniwha and more than 5 times the combined use from all other groundwater resources in Hawke’s Bay (Harper and Wilson, T, 2024). Approximately half of this water supports industrial and municipal needs year-round, while the remainder is predominantly used for irrigation during summer and early autumn, leading to heightened groundwater pressure during these periods (Figure 2-4).

Ruataniwha Plains

On the Ruataniwha Plains, groundwater use is primarily concentrated in the irrigation season, with comparatively minor volumes used for domestic and livestock needs during other months (Figure 2-5). Although the total volume of water used in the Ruataniwha Plains is lower than that of the Heretaunga Plains, the average monthly usage per consent is higher. This is due to the larger areas irrigated under each consent in the Ruataniwha Plains compared to those in the Heretaunga Plains.

Other areas

In the remaining minor aquifer systems of Hawke's Bay, the volume of groundwater used in Hawke's Bay is significantly lower compared to the Heretaugna and Ruataiwha Plains.

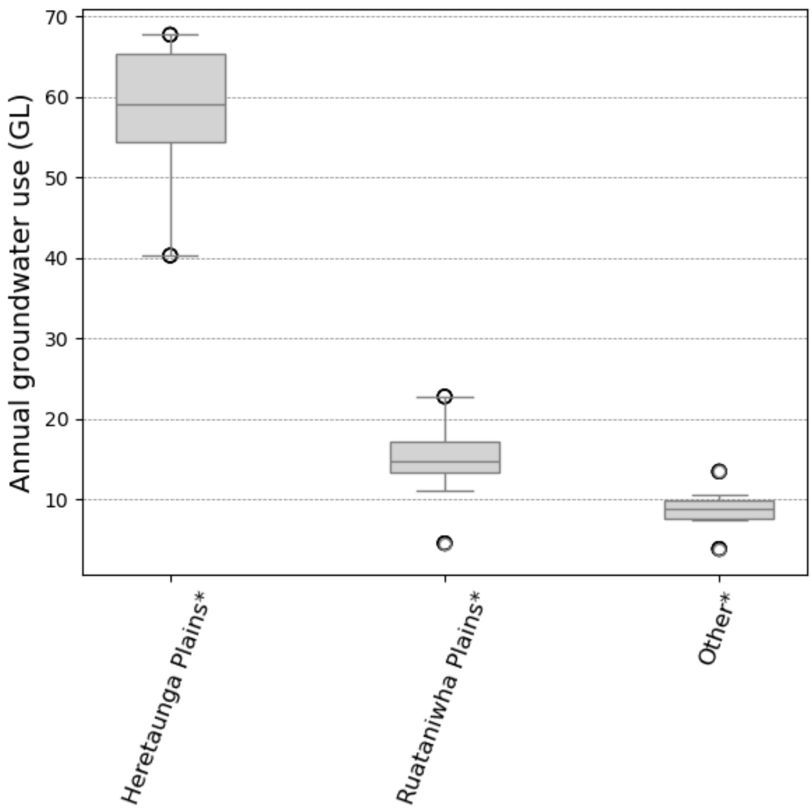

Figure 2-3: Box and whisker plot for groundwater use across Hawke's Bay between 2014-2024 *(Adapted from Harper and Wilson, T, 2024*).

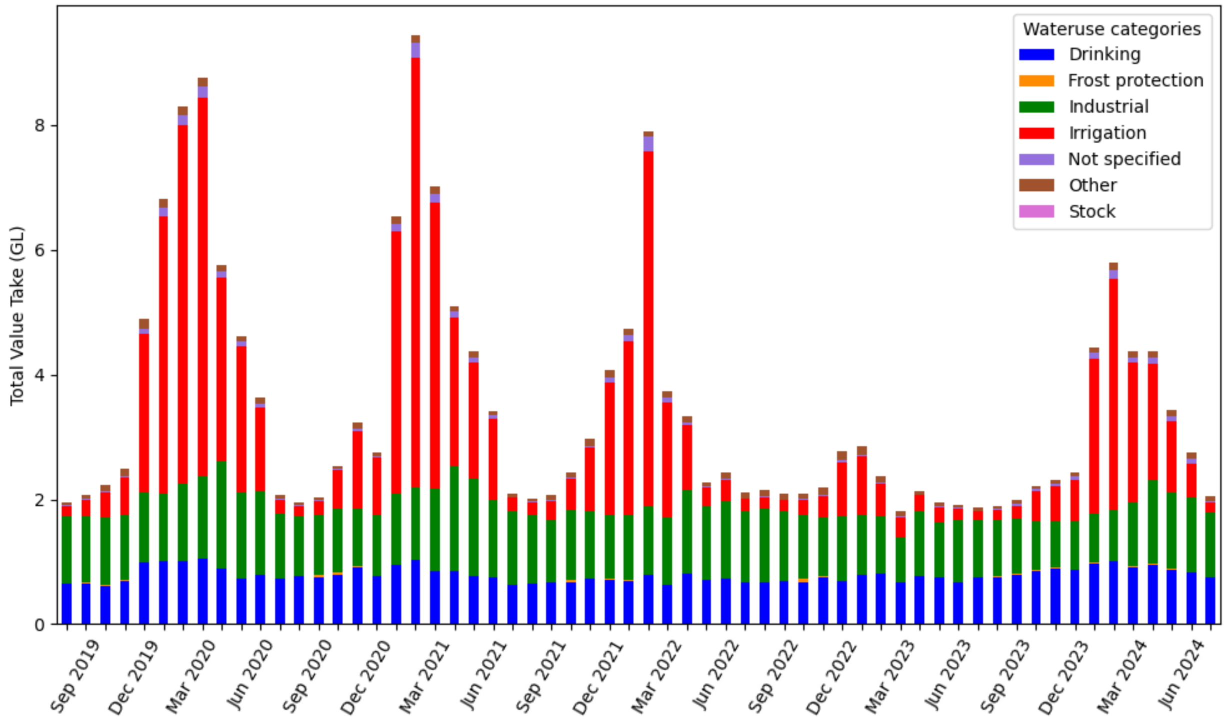

Figure 2-4: Metered monthly groundwater use on the Heretaunga Plains between July 2019 and June 2024.

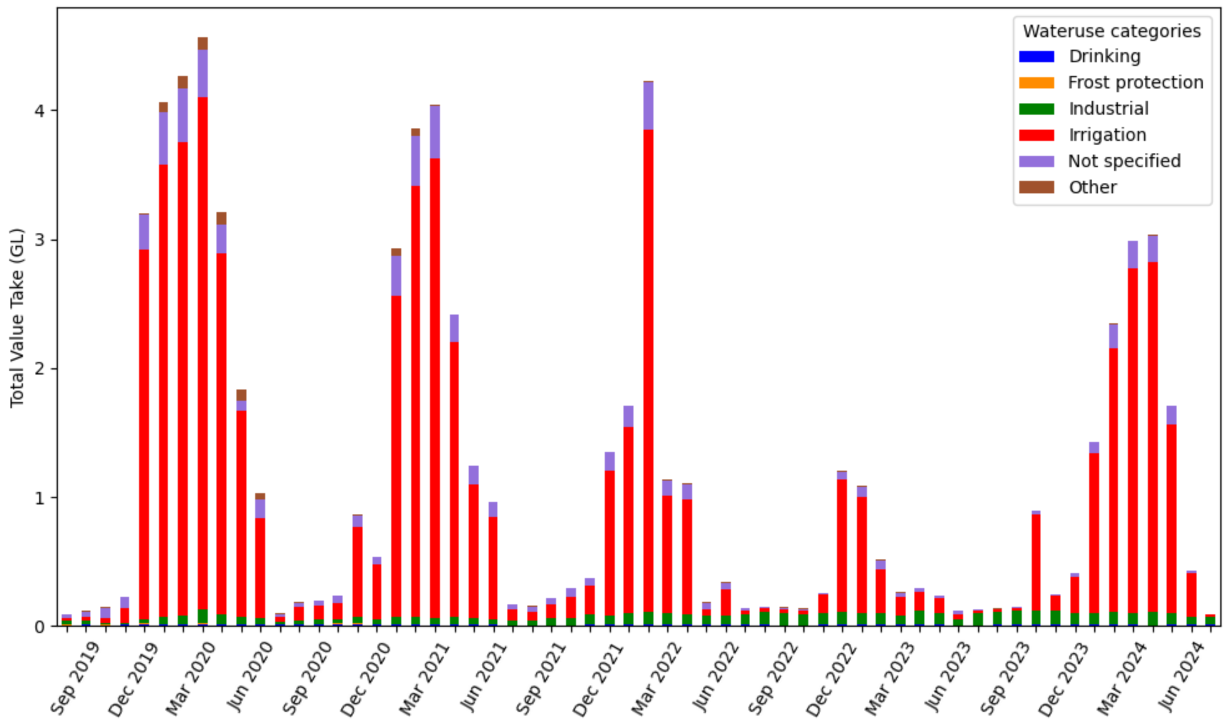

Figure 2-5: Metered monthly groundwater use on the Ruataniwha Plains between July 2019 and June 2024.

2.4 Groundwater monitoring

Long-term systematic monitoring of the groundwater resources in Hawke's Bay has been occurring since the late 1960s. However, many of the older monitoring wells were initially drilled for purposes other than monitoring the State of the Environment. A dedicated State of the Environment programme was not established until the early 1990s. Consequently, evidence of the long-term response to groundwater pumping is primarily limited to the last 30-40 years.

The largest number of monitor wells are in the Heretaunga and Ruataniwha Plains (Figure 2-6). Pressure from groundwater pumping is greatest in these areas and therefore more monitoring is needed to understand these impacts. HBRC collects information about the groundwater resources in the Heretaunga and Ruataniwha Plains using a network of monitor wells, as shown in Figure 2-6. This provides a better spatial understanding of how the system responds to stressors and the factors that control these changes. Outside of the Heretaunga and Ruataniwha Plains, where groundwater pressure is significantly lower, groundwater conditions are typically assessed using a smaller number of monitor wells.

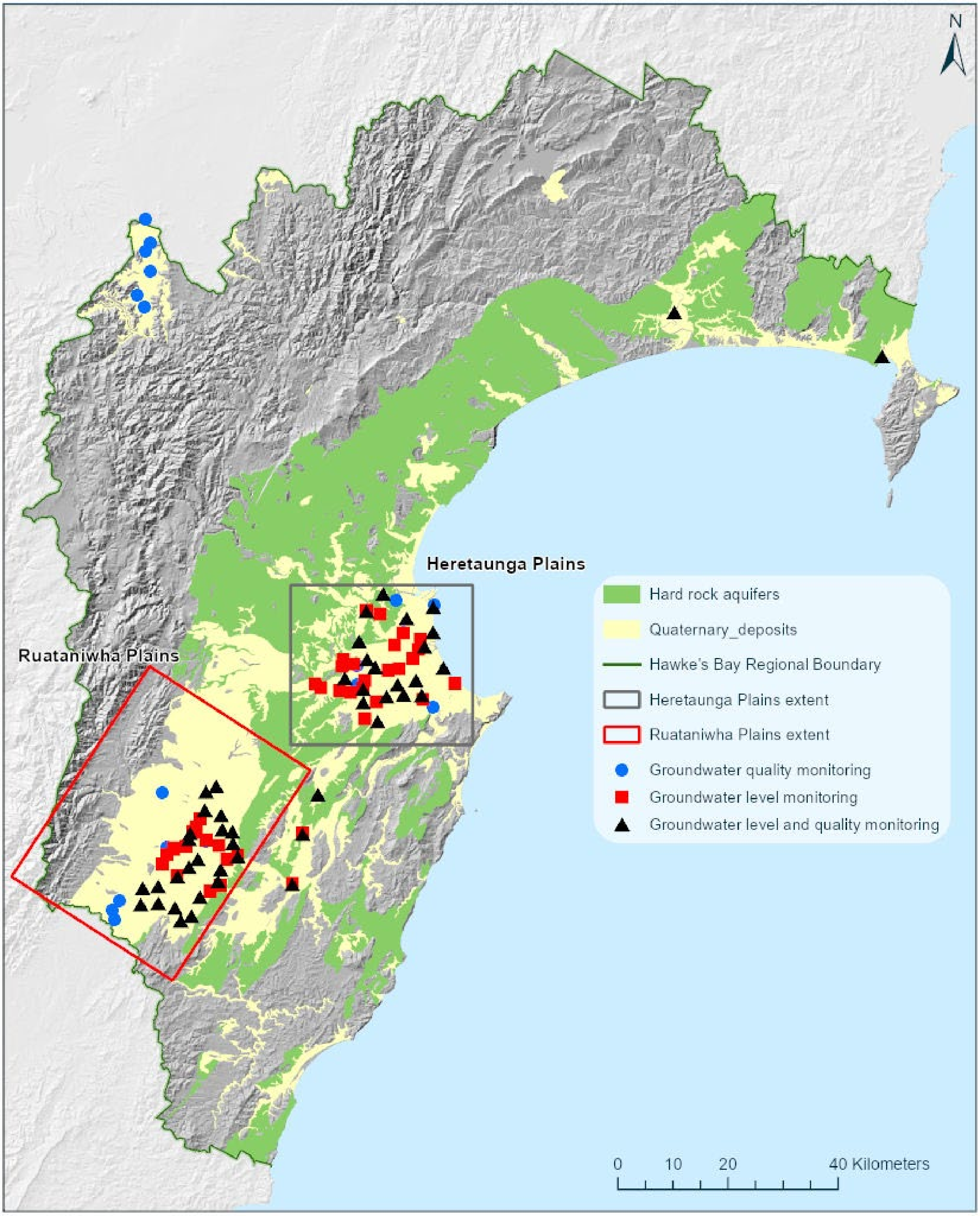

Figure 2-6: Distribution of groundwater monitor wells within Hawke's Bay 2024.

3 Methodology and Rationale | Huarahi

3.1 Data compilation

Groundwater levels were compiled from HBRC's database (Hilltop) using the HillR package (Cooke, J, 2023) and prepared as R data frames for statistical analysis. Data sources included groundwater level measurements used for compliance monitoring, groundwater investigations, and State of the Environment monitoring. At most sites, groundwater level data is collected monthly. These measurements are not equally spaced, occurring between 1 to 4 weeks apart. In some cases, measurements have been taken twice in one month or missed during the preceding month.

Data gaps occur for various reasons, including access issues, staff resourcing, and other monitoring commitments. At some sites, groundwater levels are recorded at 15-minute intervals using level loggers. Where available, this high-frequency data is combined with discrete monthly data to calculate a single monthly measurement and to fill data gaps. Figure 3-1 provides the hierarchy of steps taken to retrieve groundwater level data for analysis.

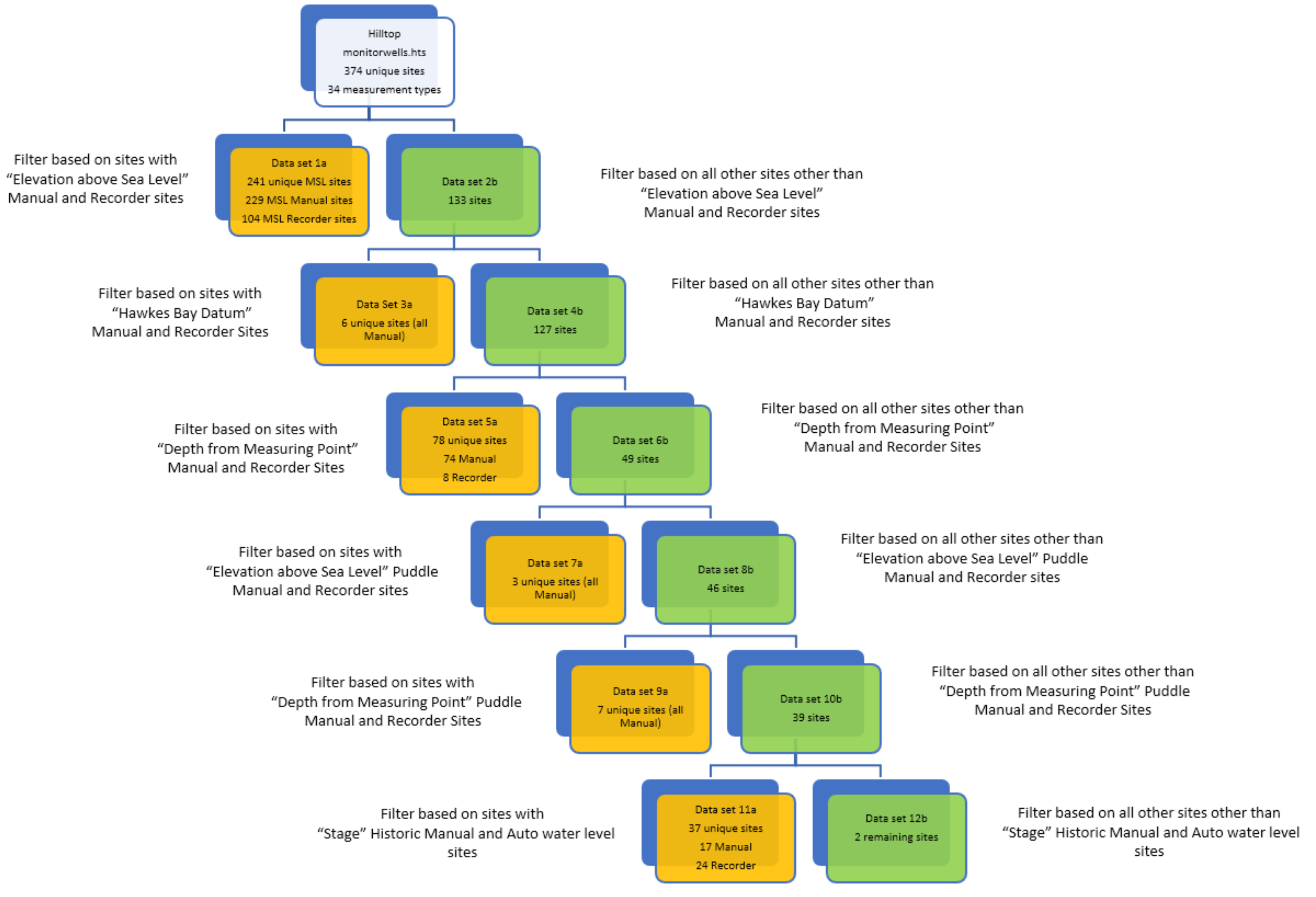

Figure 3-1: Data retrieval process.

3.2 State analysis

Groundwater level conditions for the last three hydrological years (2021–2024) were assessed using percentile rankings to provide a standardised comparison across monitoring wells. This period was chosen to align with the three-year State of the Environment reporting cycle.

Percentile rankings were calculated for each groundwater level measurement within the historical dataset of each well. This was done by ranking each observation as a percentage of the full record for that well. This transformation expresses groundwater levels in terms of their relative standing within the full historical dataset rather than as absolute values. For example, a groundwater level at the 90th percentile indicates that the measured level was higher than 90 percent of all previous observations for that well.

This standardisation approach accounts for variations in measurement datums (e.g., metres relative to mean sea level vs metres below land surface) and ensures that groundwater levels are comparable across different wells and aquifers. By expressing groundwater levels as percentiles, we can identify periods of anomalously high or low groundwater conditions relative to historical records.

3.3 Trend analysis

Groundwater level time series were tested for monotonic change using the Seasonal Kendall and Mann-Kendall methods (Kendall, 1975; Mann, 1945). These methods are non-parametric or distribution-free technique used to test whether there is statistical evidence of monotonic trends within time series data: i.e., consistently increasing or decreasing trends. The rate of change was computed using the Sen slope method which is computed as the median of all possible pairwise (linear) slopes in a temporal dataset (Helsel and Hirsch, 2002). Both methods were implemented in R (R Core Team, 2017) using the R package “EnvStats version 2.3.0” (Millard, 2013).

3.3.1 Seasonal Kendall and Mann Kendall methods

The Seasonal Kendall and Mann-Kendall test analyses the difference in signs between measurements. The idea is that if a trend is present, the sign value will tend to increase constantly or decrease constantly over time (i.e., monotonic). Every value is compared to every preceding value. A highly positive test statistic indicates an increasing trend, and a highly negative value indicates a decreasing trend. To quantify the statistical significance of the trend, it is necessary to compute the probability associated with the test statistic and sample size. The significance of the test statistic is tested by determining whether more increases or decreases occur than would be expected by chance alone. In our tests, we choose a probability value (p-value) of less than 0.05 as the criterion for rejecting the null hypothesis, meaning that there is a 5 percent chance we might observe evidence of a change (trend) due to random sampling error.

The Seasonal Kendall test is similar to the Mann-Kendall method and computes the Mann-Kendall test on each of the seasons separately, and then combines the results to formulate an overall test Statistic. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February, etc. In this way, variations in water levels throughout the year do not add to the uncertainty of the data. Computing the Mann-Kendall test separately on each season also reduces the effects of serial correlation, which can bias trend predictions. Combining results adds statistical power by allowing all measurements to be included. For example, each month viewed by itself might show a positive test statistic, none of which is statistically significant, but when combined, the overall Seasonal Kendall test could be highly significant. A limitation of the Seasonal Kendall test is that it provides a single pattern of trend across all seasons, which can fail to reveal differences in behaviour between seasons. As such, it is also useful to perform and present the full analysis of the Mann-Kendall analysis on each season (Helsel and Hirsch, 2002).

Because our monitor wells contain groundwater levels with multiple starting dates, ending dates, and gaps, we choose to examine trends over different periods. However, to allow a comparison of trends between sites, tests were also undertaken using common periods. For this, we tested trends over 10, 20, 30, and 40-year periods, beginning in 1984. Before performing trend tests, the data sets were screened for missing data to minimise significant gaps from biasing the trend analysis. For a time-series to be considered as having sufficient data, a tolerance of at least 80 percent data coverage was used to select appropriate sites over the evaluated period. For example, if a well has been monitored for 10 years and monthly measurements were expected (i.e., 120 total readings), it must have at least 96 recorded measurements (80 percent of 120) to meet the coverage threshold.

The Mann-Kendall and Seasonal Kendal test results are available for download – see sections 9.1 and 9.2 respectively for instructions on how to access and download these files.

3.3.2 Van Belle and Hughes method

An assumption of the Seasonal Kendall test is that trends within seasons must follow the same direction: i.e. are homogenous. When trend directions differ between seasons, the Seasonal Kendall test can be misleading. For example, spring and summer could have strong upward trends, while autumn and winter have strong downward trends; thus cancelling each other out and resulting in an overall Seasonal Kendall test statistic stating no trend. Van Belle and Hughes (1984) developed a method to test for trend homogeneity. This method was performed on each well to determine whether the Seasonal Kendall test could be applied appropriately.

3.3.3 Sen’s slope estimator

Sen’s slope (Sen, 1968) was used to estimate the direction and magnitude of the trend. Sen’s slope, also referred to as the Kendall-Theil robust line (Helsel et al., 2020), is a nonparametric estimator of trend magnitude per time interval (slope) for a univariate time series when the time interval is constant (equally spaced). This method is particularly effective because it is resistant to the effects of outliers, making it reliable for datasets that may contain extreme values or anomalies. Furthermore, Sen's slope is advantageous for environmental data analysis as it provides a straightforward, interpretable measure of changes over time, facilitating the identification of significant environmental trends without assuming a specific distribution for the data.

4 Results | Putanga

4.1 Number of sites assessed

The original dataset consisted of groundwater level time series from 377 monitor wells. After screening for data completeness and ensuring at least 80 percent coverage, this number was refined to 149 sites. This was further reduced to 143 sites for the Seasonal Kendall test after evaluating for seasonal homogeneity, as outlined by Van Belle and Hughes (1984).

The number of monitor wells available for analysis varied significantly across the periods assessed, reflecting changes in the monitoring network over time. In Hawke’s Bay, the monitoring network has generally expanded; however, reductions have occurred, driven by factors such as access issues, budget constraints, and well damage. Due to the differences in the number of wells available care must be taken when interpreting results between different periods and areas.

4.2 Number of trends detected

Groundwater level trends were assessed for the 10, 20, 30, and 40-year periods starting in 1984 using the Mann Kendall test. The results of this analysis are summarised in Table 4-1 and Table 4-2 while trends identified using the Seasonal Kendall test are presented in Table 4-3. These tables provide an overview of the number of statistically significant trends detected over different timeframes and regions.

Our analysis shows that longer and more recent monitoring periods reveal the most substantial evidence of groundwater level change. Notably, the Heretaunga and Ruataniwha Plains exhibit the most persistent declines, consistent with previously identified trends (Harper, 2020, 2015, 2010). This aligns with historical analyses but now benefit from expanded monitoring coverage, which strengthens confidence in statistical significance and allows trends to be identified in previously unmonitored areas.

Mann Kendall vs Seasonal Kendall

The Mann-Kendall and Seasonal Kendall tests produced comparable results in terms of the number of sites where trends were detected. However, the Seasonal Kendall method identified fewer trends overall, as certain sites were excluded following the Van Belle and Hughes (1984) test for homogeneity between seasons. This exclusion occurs when groundwater level fluctuations across different seasons are inconsistent, limiting the ability to apply a seasonal trend analysis.

Seasonal variation and rates of change

Although there were clear differences in the rates of change between annual maximum and minimum groundwater levels, evidence of trends in seasonal variation was more limited and observed at fewer sites. Similar to trends derived from monthly time-series data, the likelihood of detecting trends increased with longer and more recent monitoring records. Most identified trends pointed to greater variation over time, likely driven by increasingly lower annual minimum levels rather than rising maximum groundwater levels. This suggests that low groundwater levels are becoming more extreme, which has implications for water availability and aquifer resilience.

Data variability and trend dection

Trend detection is inherently influenced by data variability. In Hawke's Bay, gradual changes in groundwater levels can be masked by seasonal fluctuations, making it challenging to distinguish long-term trends from short-term variations.

To address this, long-term monitoring is essential for reliably identifying persistent changes. Trends in groundwater levels become more apparent over extended timeframes, with the strongest evidence of change emerging from longer and more recent monitoring records. This highlights the importance of continuous data collection to improve confidence in trend assessments and better understand the evolving state of groundwater resources.

Table 4-1: Mann-Kendall test results for the trend periods assessed.

Note: The unbracketed numbers represent the total number of wells assessed for trends, while the bracketed numbers indicate the number of months where statistically significant trends were detected. For example, during the period from 1984 to 1994, trends were assessed at 5 wells in the Heretaunga Plains, with decreasing trends identified at 1 of these well locations. However, these trends were not consistent throughout the year with only 3 out of the 12 months exhibiting a statistically significant decreasing trend.

Years of record	1984-1994	1994-2004	2004-2014	2014-2024	1984-2004	1994-2014	2004-2024	1984-2014	1994-2024	1984-2024
	Ten-year periods				20-year periods			30-year period		40-year period
Heretaunga										
Wells tested	5	28	30	38	5	28	24	4	23	26
Increasing Trends	2(18)	3(3)	1(1)	21(24)	2(16)	4(9)	1(1)	2(20)	2(4)	3(23)
Decreasing Trends	1(3)	16(34)	5(11)	3(10)	0(0)	13(51)	17(73)	2(12)	20(132)	22(141)
Insignificant	4(39)	28(299)	30(348)	38(422)	4(44)	27(276)	23(214)	3(16)	19(140)	21(148)
Ruataniwha										
Wells tested	0	14	21	25	0	10	21	1	10	11
Increasing Trends	0	2(5)	4(7)	9(21)	0	3(12)	5(20)	0	2(6)	3(9)
Decreasing Trends	0	6(19)	5(1)	1(3)	0	7(50)	14(55)	1(12)	8(69)	8(81)
Insignificant	0	14(144)	21(234)	25(276)	0	10(58)	20(177)	0	8(45)	7(42)
Other areas										
Wells tested	0	0	8	2	0	0	9	0	0	0
Increasing Trends	0	0	1(7	1(1)	0	0	2(4)	0	0	0
Decreasing Trends	0	0	1(1	1(2)	0	0	3(3)	0	0	0
Insignificant	0	0	8(88	2(21)	0	0	9(101)	0	0	0

Table 4-2: Mann-Kendall test results for changes in seasonal variation between the maximum and minimum groundwater levels.

Years of record	1984-1994	1994-2004	2004-2014	2014-2024	1984-2004	1994-2014	2004-2024	1984-2014	1994-2024	1984-2024
	Ten-year periods				20-year periods			30-year period		40-year period
Heretaunga										
Wells tested	5	28	30	38	5	28	24	4	23	26
Increasing Trends	2	1	3	0	2	5	0	3	2	5
Decreasing Trends	0	0	0	0	0	0	1	0	1	1
Insignificant	3	27	27	38	3	23	23	1	20	20
Ruataniwha										
Wells tested	0	14	21	25	0	10	21	1	10	11
Increasing Trends	0	0	6	0	0	5	5	1	5	7
Decreasing Trends	0	0	0	3	0	0	3	0	0	0
Insignificant	0	14	15	22	0	5	18	0	5	4
Other areas										
Wells tested	0	0	8	2	0	0	9	0	0	0
Increasing Trends	0	0	1	0	0	0	0	0	0	0
Decreasing Trends	0	0	0	0	0	0	0	0	0	0
Insignificant	0	0	7	2	0	0	9	0	0	0

Table 4-3: Seasonal-Kendall test results for the trend periods assessed.

Years of record	1984-1994	1994-2004	2004-2014	2014-2024	1984-2004	1994-2014	2004-2024	1984-2014	1994-2024	1984-2024
	Ten-year periods				20-year periods			30-year period		40-year period
Heretaunga										
Wells tested	5	28	30	38	5	27	24	3	22	24
Increasing Trends	2	0	3	19	2	4	0	2	1	2
Decreasing Trends	1	15	6	3	1	12	18	1	19	19
Insignificant	2	13	21	16	2	11	6	0	2	3
Ruataniwha										
Wells tested	0	13	21	25	0	10	18	1	8	10
Increasing Trends	0	1	2	11	0	3	3	1	1	3
Decreasing Trends	0	7	7	1	0	7	14	0	6	7
Insignificant	0	5	12	13	0	0	1	0	1	0
Other areas										
Wells tested	0	0	8	2	0	0	9	0	0	0
Increasing Trends	0	0	5	1	0	0	3	0	0	0
Decreasing Trends	0	0	1	1	0	0	3	0	0	0
Insignificant	0	0	2	0	0	0	3	0	0	0

4.2.1 Mann-Kendall results

The highest number of trends are observed during late autumn and winter months, particularly in May, June, and July (Figure 4-1). This pattern is attributed to the smaller seasonal variations in groundwater levels observed during winter, compared to other times of the year. Since groundwater levels tend to be more stable in winter, trend analysis is more likely to identify a consistent direction of change, increasing the likelihood of detecting statistically significant trends during these months.

Trend vs rate of change

While the late autumn and winter months show the highest number of trends, this does not directly correspond to how fast groundwater levels are changing (slope). The reduced variability during winter improves trend detection but does not necessarily indicate signficant changes in groundwater recharge or abstraction patterns. This is because hypothesis tests like the Mann-Kendall method evaluate the probability of a trend's direction rather than its magnitude (slope). For example, a trend with a consistent direction regardless of the trend magnitude is more likely to be detected than a larger trend with greater variability.

Groundwater recovery in winter

The results also suggest that, in some wells, groundwater levels are not recovering to normal levels during winter. A common assumption is that groundwater levels are sustainable if they return to typical winter levels. However, trend analysis indicates that at some sites, groundwater levels are continuing to decline despite seasonal recovery. This suggests that the system is not in equilibrium, or other factors may be influencing long-term groundwater depletion.

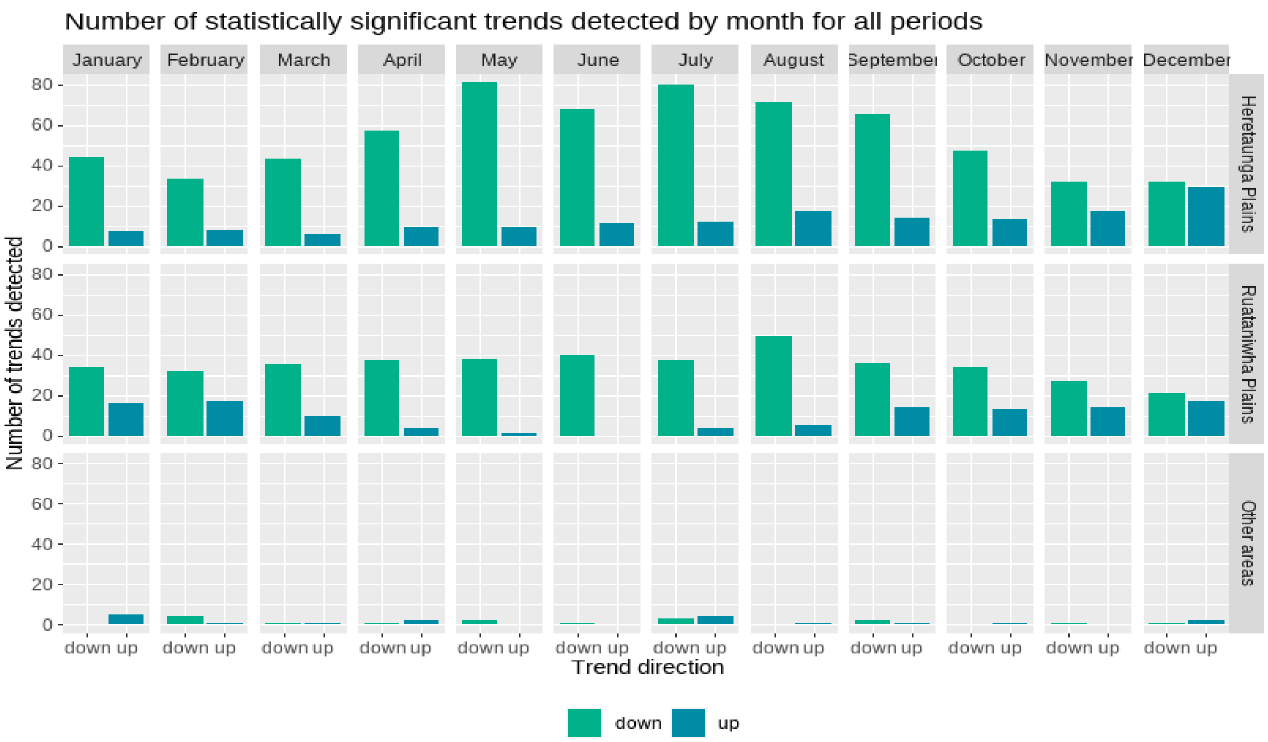

Figure 4-1: Number of statistically significant trends identified for each month using the Mann Kendall method for all periods assessed.

4.3 Rates of change in groundwater levels

While Section 4.2 identified the presence of groundwater level trends, this section examines the rate of change—that is, how quickly groundwater levels and seasonal variations are rising or declining over time. Understanding the magnitude of change is useful for assessing the severity of groundwater depletion and determining whether observed trends are gradual or accelerating.

4.3.1 Changes in groundwater level

In Hawke's Bay, the greatest rates of change occur in the Ruataniwha Plains. Here, less transmissive aquifers, with lower storage properties, are pumped at greater rates resulting in deeper drawdown impacts and slower recovery. In contrast, despite an overall greater volume of groundwater pumped, the declines have been smaller on the Heretaunga Plains. In the Heretaunga Plains, highly transmissive aquifers with strong surface water connections result in shallow and widespread drawdown impacts with rapid recovery.

Seasonal shifts in rates of groundwater level decline

In both the Heretaunga and Ruataniwha Plains, the onset of the irrigation period and increase in groundwater use is marked by a subtle shift in the rates of groundwater level declines. On the Heretaunga Plains, groundwater level trends show a modest increase in the rate of decline at the start of the irrigation period, shifting from an average decrease of approximately 2 centimetres per year to 3 centimetres per year. In contrast, on the Ruataniwha Plains, this shift is more pronounced, particularly between December and January, where the average rate of decline increases significantly from 7 centimetres per year to 13 centimetres per year.

The end of the irrigation period and the decrease in groundwater use also mark a shift in the rate of change. On the Heretaunga Plains, the rates of decline show a small but marked reduction in the April groundwater level trends, gradually reducing through the autumn and winter months, before reaching their lowest rates of declines around October. In the Ruataniwha Plains, a similar pattern is observed, albeit with a noticeable delay.

Overall summary

Overall, the rates of change indicate that, on average, groundwater levels have dropped by 0.4 to 2 metres in the Heretaunga Plains and by 2.8 to 6 metres in the Ruataniwha Plains over the past 40 years (1984-2024). To illustrate the differences in trend patterns, summary statistics for Sen's slope from statistically significant trends are shown in Figure 4-2 and presented in Table 4-4. In Table 4-4 the cells are colour-coded to highlight variations in trends across the hydrological year (July–June).

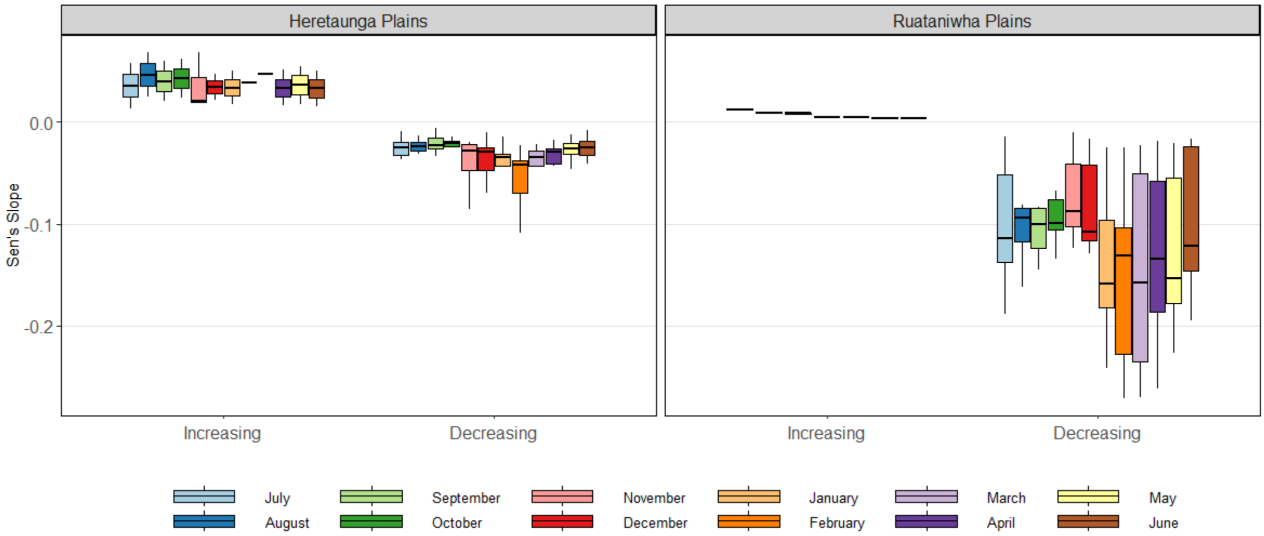

Figure 4-2: Magnitude of statistically significant groundwater level trends in the Heretaunga and Ruataniwha Plains (1984–2024) by Season. The box and whisker plots are ordered from July-June to reflect the hydrological year.

Table 4-4: Summary of Sen's slope estimates for statistically significant trends on the Heretaunga and Ruataniwha Plains between 1984-2024.

Stat	No. wells	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June
Heretaunga Plains													
min	25	-0.08	-0.07	-0.08	-0.07	-0.09	-0.09	-0.1	-0.12	-0.12	-0.09	-0.09	-0.08
mean	25	-0.02	-0.02	-0.02	-0.01	-0.01	-0.02	-0.03	-0.05	-0.04	-0.03	-0.03	-0.02
median	25	-0.02	-0.02	-0.02	-0.02	-0.02	-0.03	-0.03	-0.04	-0.03	-0.03	-0.03	-0.02
max	25	0.06	0.07	0.06	0.06	0.07	0.05	0.05	0.04	0.05	0.05	0.05	0.05
Ruataniwha Plains													
min	11	-0.19	-0.16	-0.14	-0.13	-0.12	-0.13	-0.24	-0.27	-0.27	-0.26	-0.23	-0.19
mean	11	-0.1	-0.08	-0.07	-0.07	-0.06	-0.07	-0.13	-0.15	-0.13	-0.13	-0.13	-0.1
median	11	-0.11	-0.09	-0.09	-0.08	-0.08	-0.1	-0.15	-0.13	-0.14	-0.13	-0.15	-0.12
max	11	-0.01	0.01	0.01	0.01	0	0	0	-0.02	0	-0.02	-0.02	-0.02
Other areas (2004_2024)													
min	5	-0.02	NA	-0.03	NA	NA	0.03	0.03	-0.07	NA	NA	NA	NA
mean	5	0.01	NA	-0.03	NA	NA	0.03	0.03	-0.07	NA	NA	NA	NA
median	5	0.01	NA	-0.03	NA	NA	0.03	0.03	-0.07	NA	NA	NA	NA
max	5	0.04	NA	-0.03	NA	NA	0.03	0.03	-0.07	NA	NA	NA	NA

4.3.2 Changes in seasonal variation

In Section 4.3.2, "Changes in Seasonal Variation," we analyse the increasing fluctuations in groundwater levels over the past four decades. This analysis focuses on the difference between annual maximum and minimum water levels to detect significant changes. Only statistically significant trends are reported, as illustrated by the box plot in Figure 4-3.

Figure 4-3 provides a visual summary of data distribution, highlighting the median, quartiles, and potential outliers. In the context of our study, Figure 4-3 illustrates the range and variability of these changes, offering a clear depiction of the rate of change in seasonal fluctuations observed and how they compare between groundwater areas.

Ruataniwha Plains

The Ruataniwha Plains has experienced significant changes in seasonal groundwater level fluctuations, with the difference between annual maximum and minimum levels increasing at an average rate of approximately 12 cm per year over the last 40 years, totaling about 5 meters from 1984 to 2014. This trend indicates growing seasonal variability, which can increase the frequency and duration of extreme events

Heretaunga Plains

In the Heretaunga Plains, groundwater level changes have been less pronounced than in the Ruataniwha Plains. Over the past four decades, the average rate of change has been approximately 3 centimeters per year, totaling about 1.2 meters between 1984 and 2014. This indicates that while both regions are experiencing shifts in groundwater levels, the Ruataniwha Plains are undergoing more significant long-term changes compared to the Heretaunga Plains.

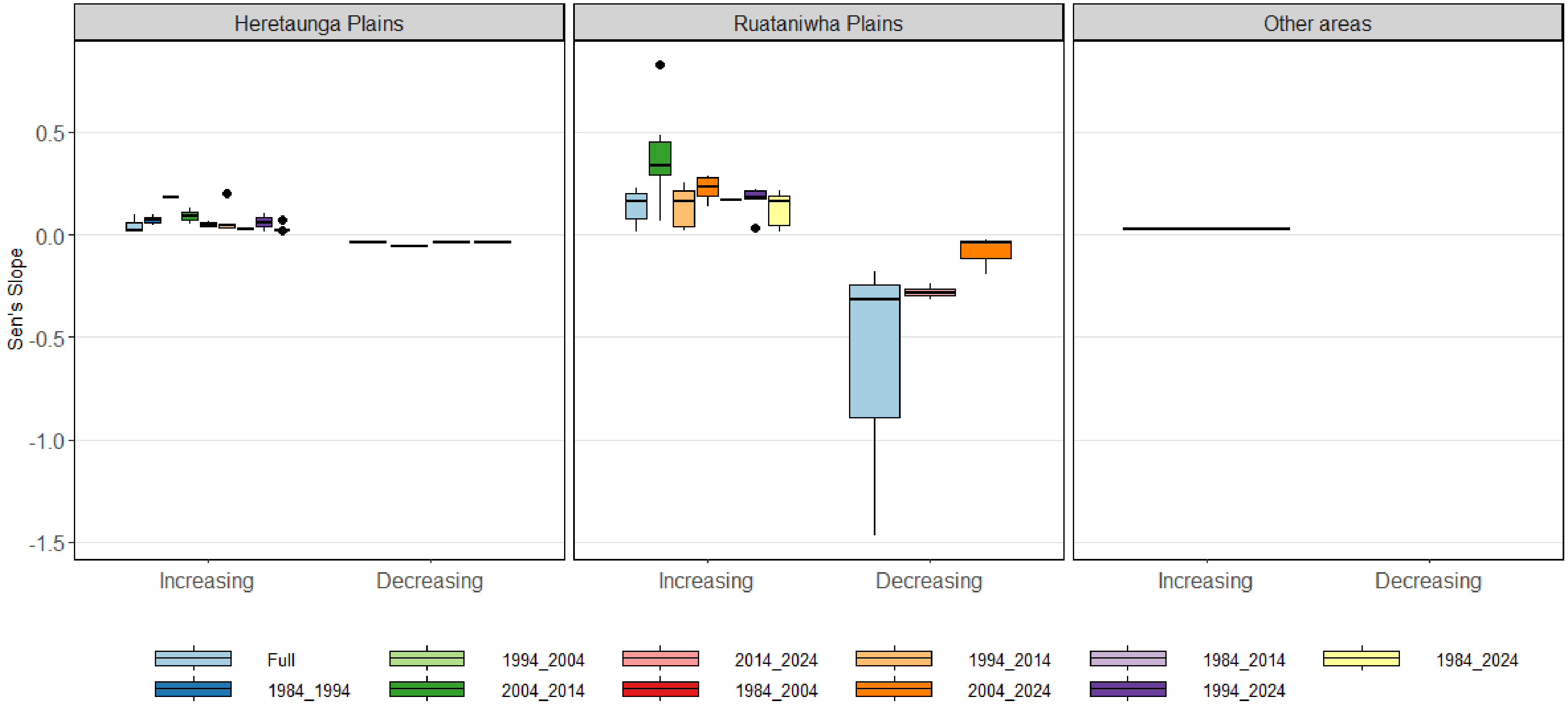

Figure 4-3: Magnitude of statistically significant trends for the difference between annual maximum and minimum groundwater levels between 1984-2024.

4.4 Location of groundwater level trends

In Section 4.4, "Location of Groundwater Level Trends," provides a detailed analysis of the spatial distribution of statistically significant changes in groundwater levels within Hawke's Bay's major aquifer systems. This analysis is supported by Figures 4-4, 4-5, and 4-6, which offer visual representations of these trends across the Heretaunga and Ruataniwha Plains.

Visual Representation of Trends

- Figure 4-4 and Figure 4-5: These maps illustrate groundwater level trends from 1984 to 2024 across the Heretaunga and Ruataniwha Plains, respectively. Each monitoring site is marked with arrows, where the direction and color denote the nature and significance of the observed changes in groundwater levels.

- Figure 4-6: This figure presents trends in the seasonal variation of groundwater levels, highlighting areas with notable fluctuations between annual maximum and minimum levels.

Heretaunga and Ruataniwha Plains

In the Heretaunga Plains, statistically significant groundwater level declines are predominantly observed northwest of Hastings in the unconfined area. A persistent decline is notable between Roy’s Hill and Fernhill across nearly all periods assessed, becoming particularly evident with longer monitoring records.

The Ruataniwha Plains exhibit greater variability in groundwater level trends. Declines are frequently located in the western and northwestern regions, with several sites showing significant reductions, as indicated by blue arrows in the figures.

Rising groundwater levels

In some areas, groundwater level monitoring indicates increasing trends. The reason for these patterns is unclear. While it is expected that groundwater pumping will generally result in an overall loss of storage, there are some areas, which may experience rises due to factors such as increased recharge through returned irrigation or be more strongly influenced by climatic conditions rather than changes caused by pumping. For example, a period of wetter years may have a greater impact on water levels than a reduction caused by pumping, resulting in an increasing trend. Rising groundwater level trends are limited to a small number of wells located in the eastern parts of both the Heretaunga and Ruataniwha Plains.

Changes in seasonal variation

In the Heretaunga Plains, changes in seasonal variation are primarily concentrated in the western part of Hastings, near Roy’s Hill, with one exception at a well located near Haumoana along the coastline. Most sites in this area show increasing seasonal variation over time, although less than half of these changes are statistically significant. Notably, only one site indicates a significant decrease in groundwater levels. Overall, the magnitude of changes in the Heretaunga Plains tends to be small, with most sites exhibiting minimal shifts in seasonal variation.

In the Ruataniwha Plains, changes in seasonal variation are mainly observed in the western region and at wells where long-term declines are occurring. Most sites in the Ruataniwha Plains also show increasing trends, but there are significant differences in the rates of change. Several sites exhibit noticeable increases in groundwater levels, reflecting more substantial shifts compared to the Heretaunga Plains.

Limitations

The limited number of long-term groundwater level sites across both the Heretaunga and Ruataniwha Plains hinder a complete spatial comparison of trends. On the Heretaunga Plains, spatial gaps in long-term monitoring wells (i.e. greater than 10 years of data) are apparent north of the Ngaruroro River towards Napier and east of Hastings. On the Ruataniwha Plains, spatial gaps are apparent toward the southwest and centre of the basin.

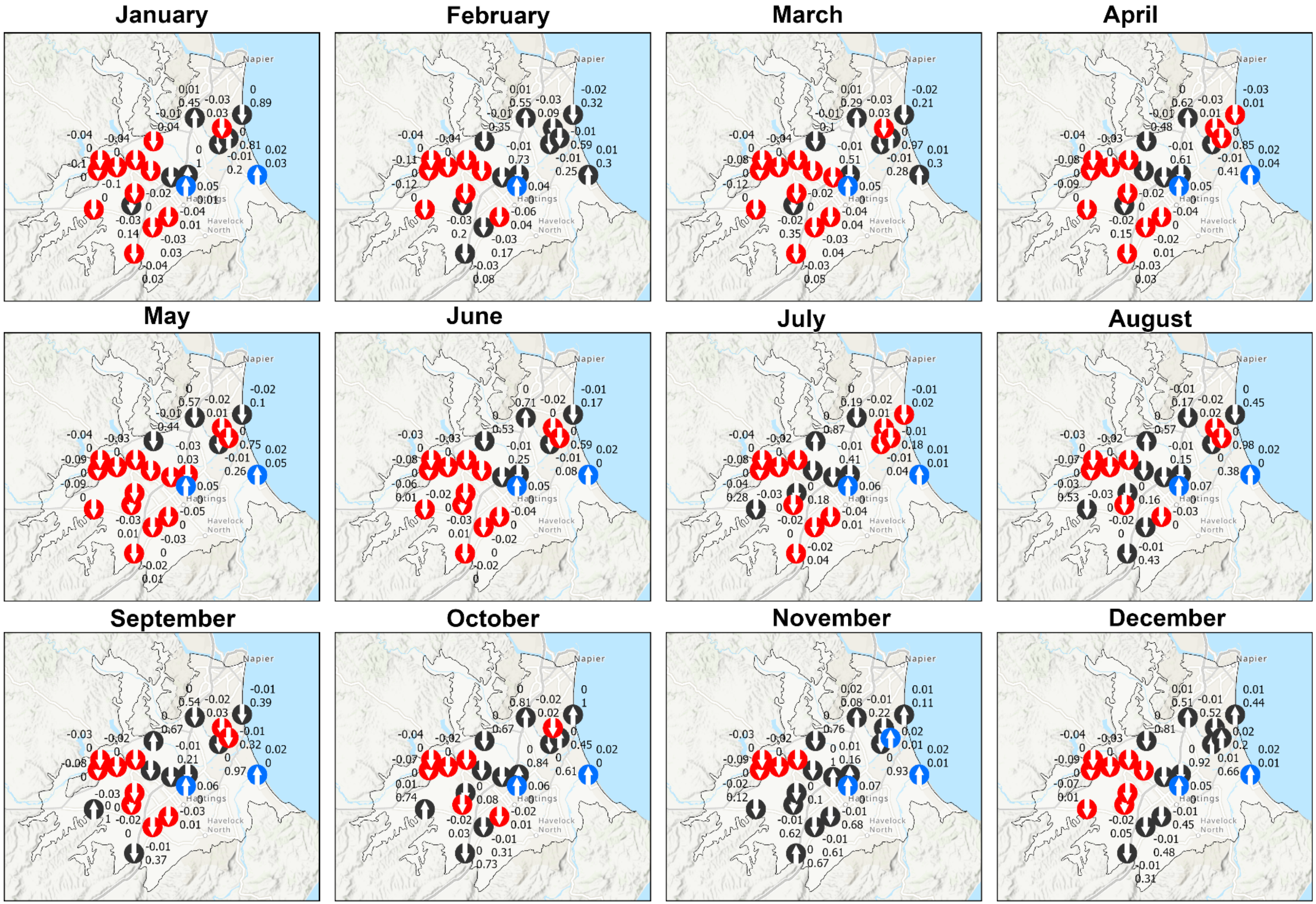

Figure 4-4: Map of groundwater level trends on the Heretaunga Plains for the period 1984–2024, analysed using the Mann–Kendall method.

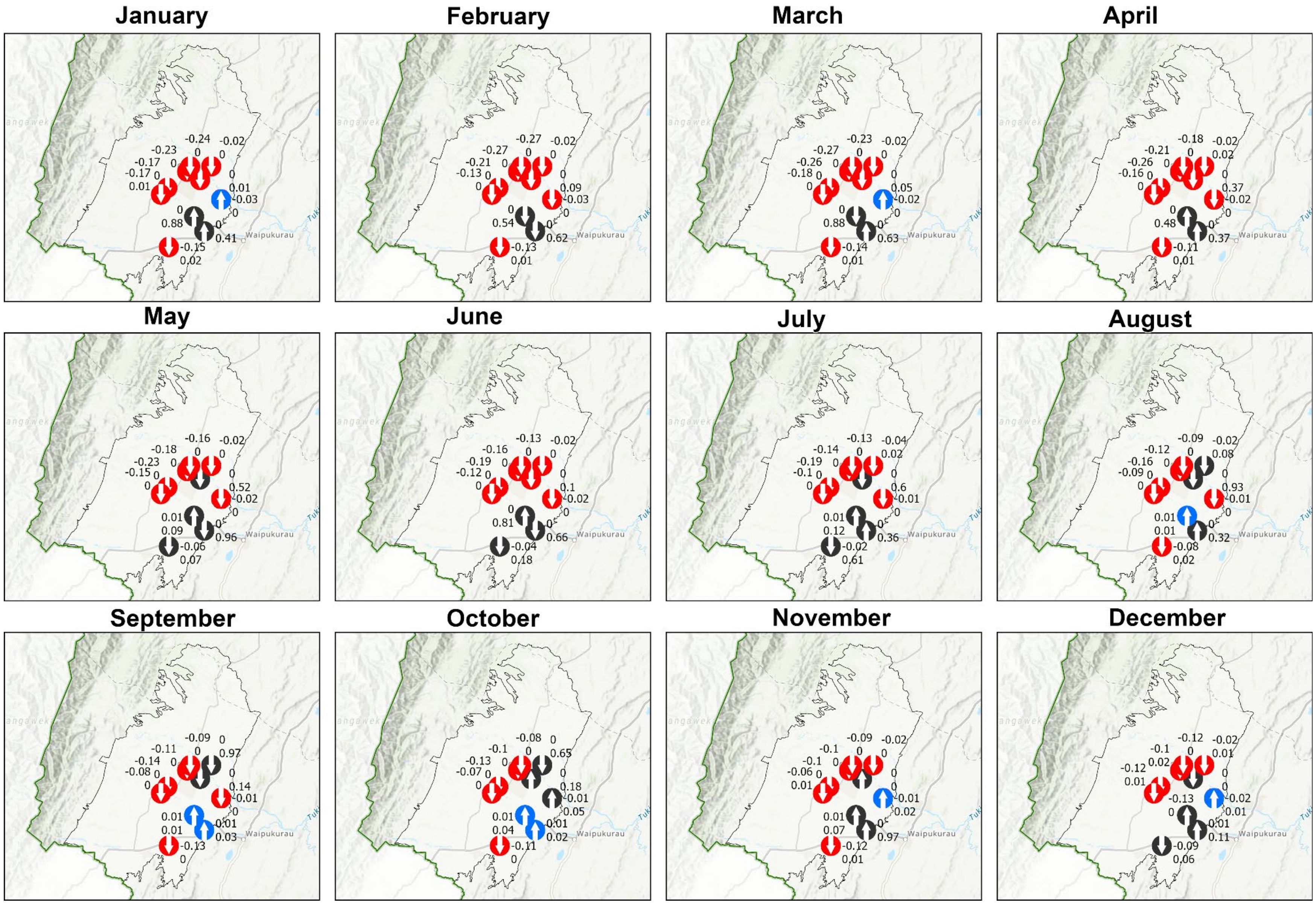

Figure 4-5: Map of groundwater level trends on the Ruataniwha Plains for the period 1984-2024, analysed usng the Mann-Kendall method.

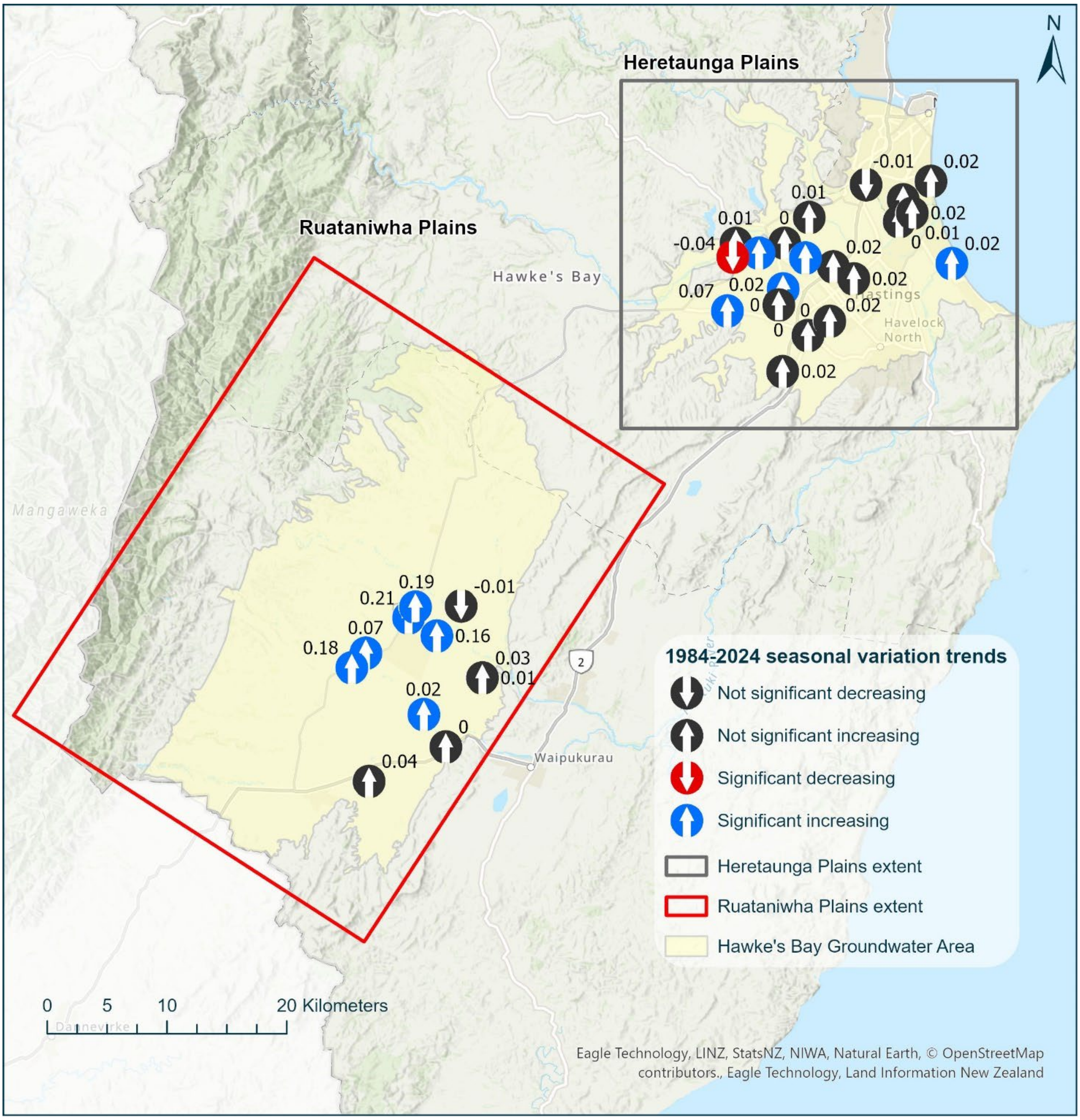

Figure 4-6: Map of trends in seasonal variation on the Heretaunga and Ruataniwha Plains for the period 1984-2024 using the Mann-Kendall method.

4.5 Groundwater level conditions (2021-2024)

Figure 4-7 shows the resulting percentile rankings using boxplots to compare groundwater conditions across different years. The 2022-2023 hydrological year stands out as a period of above-average groundwater levels across all monitored aquifers.

In the Heretaunga Plains, groundwater levels were notably high during the 2022-2023 hydrological year. The median percentile was 85.8 percent, meaning that for most wells, groundwater levels were higher than in most historical records. Furthermore, 75 percent of observations were above the 73rd percentile, indicating sustained high groundwater conditions across the region. Some wells experienced their highest-ever recorded levels, as reflected in the maximum percentile of 100 percent.

Similarly, in the Ruataniwha Plains, groundwater levels were also above average, with a median percentile of 82.5 percent. While the overall distribution was slightly lower than in Heretaunga, levels were still high, with 75 percent of observations above the 65th percentile. As in Heretaunga, some wells recorded percentiles of 100 percent, indicating extreme highs in certain locations.

Groundwater levels outside the Heretaunga and Ruataniwha Plains, which encompass various smaller groundwater systems, exhibited greater variability. The median percentile was 80.5 percent, indicating generally elevated levels. However, conditions varied widely, with some wells recording groundwater levels as low as the 38.8th percentile.

Despite this variability, certain locations experienced exceptionally high levels, with maximum percentiles reaching 98.3 percent. These results suggest that 2022-2023 was one of the wetter years, with groundwater levels generally well above normal across most monitoring sites. These conditions are maintly attributed to both a higher-than-usual rainfall pattern over the summer months culminating in reduced abstraction.

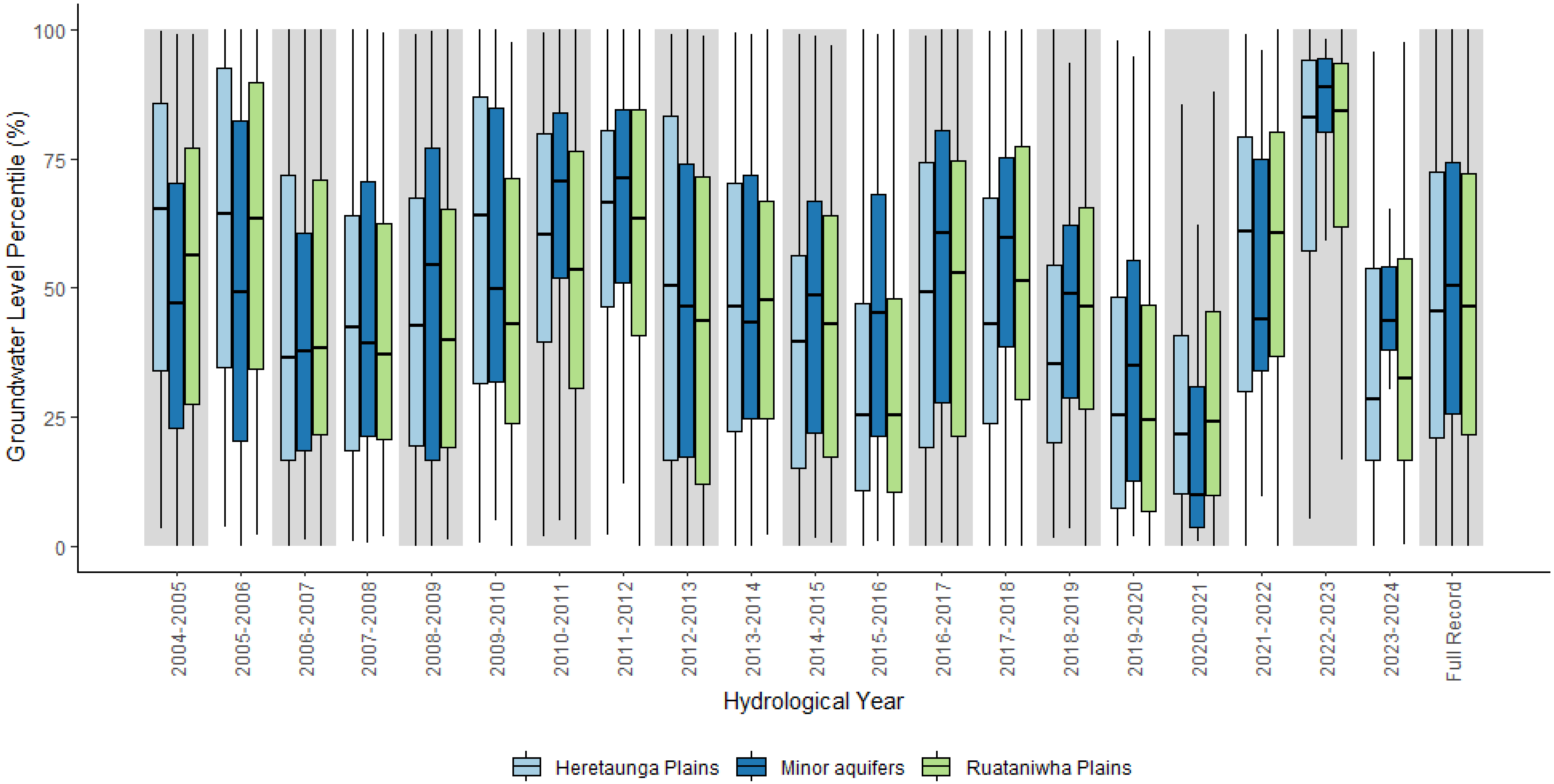

Figure 4-7: Groundwater level conditions as percentile between 2004-2024

4.5.1 Heretaunga and Ruataniwha Plains

Figure 4-8 and Figure 4-9 presents a seasonal comparison of groundwater level conditions across the Heretaunga and Ruataniwha Plains from 2021 to 2024, categorised using percentile rankings. To ensure robust long-term comparisons, wells with fewer than ten years of data were excluded. HBRC assesses groundwater conditions by comparing current measurements with historical records, categorising levels as below or above normal relative to their monitoring history. This analysis groups groundwater levels into five percentile-based categories: Lowest-ever, Below-normal (0-25th percentile), Normal (25-75th percentile), Above-normal (75-100th percentile), and Highest-ever.

Key highlights

The most significant feature of the 2021-2024 period was the above-normal and record-high groundwater levels observed during the summer and autumn of the 2022-2023 hydrological year. The extreme weather patterns over this period had widespread hydrological impacts, with record groundwater conditions mirrored across multiple State of the Environment datasets, including water use data, river flows, rainfall, and water quality monitoring.

During spring, summer, and autumn of 2022-2023, less than 4 percent of sites recorded below-normal conditions, while 82 percent of monitored wells in the Heretaunga Plains reached their highest-ever levels. This suggests a period of exceptional recharge, likely driven by prolonged rainfall and reduced groundwater abstraction.

Overall summary

Overall, the data indicates a transition from drier conditions in 2021 to significantly elevated groundwater levels in 2022-2023, highlighting the influence of climatic variability on regional groundwater systems. While 2023 remained largely above normal, some localised declines suggest that ongoing monitoring is necessary to determine whether this represents a temporary recharge event or a longer-term recovery trend in groundwater levels.

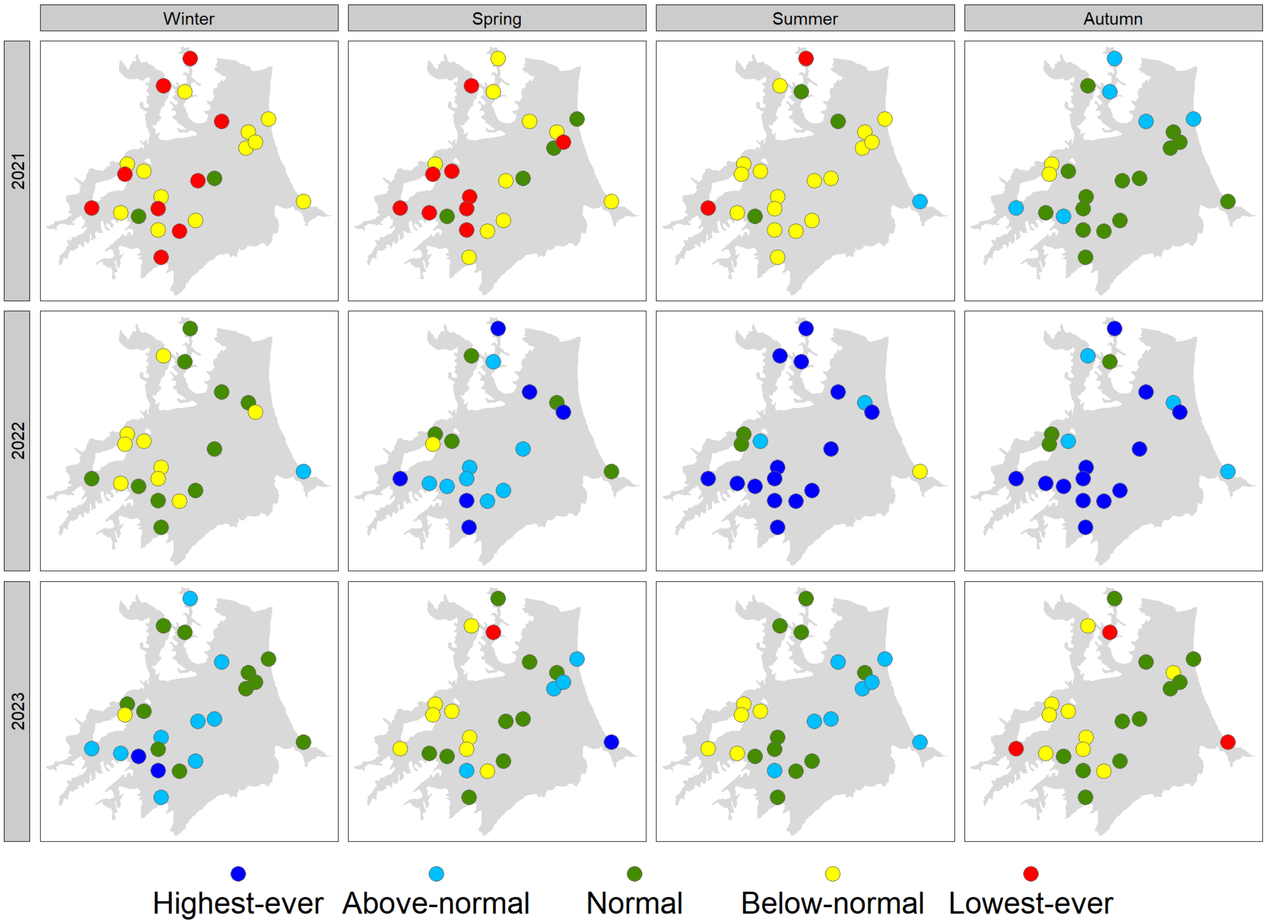

Figure 4-8: Seasonal groundwater levels in the Heretaunga Plains between and 2021 and 2024. Categories are: Below-normal (0-25th percentile), Normal (25-75th percentile), Above-normal (75th-100th percentile). Wells with fewer than 10 years of record are excluded from the analysis.

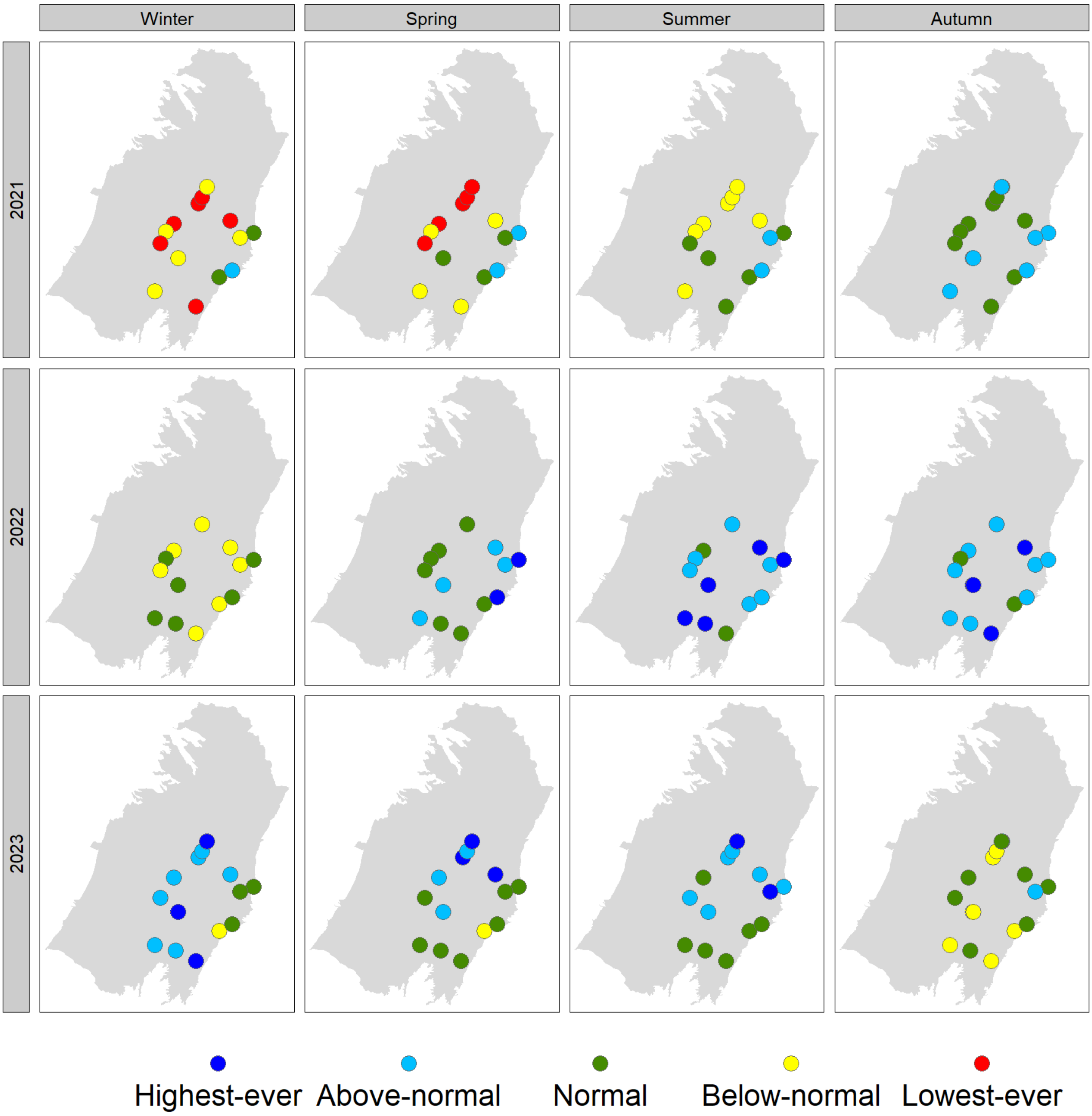

Figure 4-9: Seasonal groundwater levels in the Ruataniwha Plains between and 2021 and 2024. Categories are: Below-normal (0-25th percentile), Normal (25-75th percentile), Above-normal (75th-100th percentile). Wells with fewer than 10 years of record are excluded from the analysis.

5 Discussion and conclusions | Te matapaki me te whakatau

A comprehensive analysis of groundwater levels across Hawke's Bay offers critical insights into long-term changes in groundwater availability, seasonal variations, and the influence of human activities on the region's aquifer systems. The findings of this study reveal notable spatial and temporal variations in groundwater levels, including differences between aquifers and local-scale variations within each aquifer over time.

5.1 Long-term trends and groundwater level conditions

The trend analysis identified statistically significant groundwater level declines, particularly in the Heretaunga and Ruataniwha Plains. The highest number of trends were observed in areas with intensive groundwater abstraction, with the Ruataniwha Plains showing the most pronounced declines.

- **Heretaunga Plains:** The most persistent groundwater level declines were observed northwest of Hastings in the unconfined aquifer area, with a particularly strong downward trends between Roy's Hill and Fernhill. Over the past 40 years, groundwater levels have declined by 0.4 to 2.0 meters, with lower summer levels being the primary driver. i.e. winter water level have remained relatively unchanged over time compared to summer levels.

- **Ruataniwha Plains:** Declines were more pronounced in the Ruataniwha basin, where aquifers have lower storage properties and are more susceptible to pumping stress. The average groundwater level decline was between 2.8 to 6.0 meters over the last 40 years, with the highest rates of decline occurring between December and January.

- **Minor aquifer systems:** In minor aquifer systems, statistically significant groundwater level declines were detected, but their magnitude was lower than in the main aquifers. Some areas showed increasing trends.

Groundwater levels showed a temporary increase in 2022-2023, with many wells recording their highest-ever levels due to prolonged rainfall and reduced abstraction. However, by 2024, levels in some areas had begun to decline again, reaffirming the long-term downward trend, particularly in the Ruataniwha Plains.

5.2 Seasonal variability and increasing amplitude of fluctuations

Groundwater levels exhibit strong seasonal variation, with maximum levels typically occurring in winter and minimum levels in late summer or early autumn. The analysis found evidence of an increase in seasonal amplitude in some wells, but overall, the number of detections were small:

- Groundwater levels in the Heretaunga Plains exhibit smaller seasonal fluctuations compared to the Ruataniwha Plains, likely due to higher transmissivity and stronger hydraulic connections with surface water.

- In the Ruataniwha Plains, seasonal variability has intensified, with groundwater levels declining more rapidly in summer and exhibiting slower recovery in winter.

The increased seasonal fluctuations, driven by lower summer levels may lead to a greater risk of water supply issues in already susceptible locations like Bridge Pā and Ongaonga. This is unsurprising given the number and volume of groundwater takes has been increasing for decades, and aquifer pumping limits have only just been set.

5.3 Influence of groundwater abstraction

The onset of the irrigation season is marked by an increase in the rate of groundwater decline. The analysis identified the following key patterns:

- On the Heretaunga Plains, groundwater level declines increase slightly from an average of 2 cm/year to 3 cm/year at the start of the irrigation period.
- On the Ruataniwha Plains, the impact was more pronounced, with groundwater level declines increasing from 7 cm/year to 13 cm/year between December and January.
- At the end of the irrigation period, the rate of decline reduced, but groundwater levels did not recover fully in some areas, indicating long-term depletion of both summer and winter levels.
- In the Heretaunga Plains, most of the long-term declines in groundwater levels and increases in seasonal variation can be explained by increased pumping over time (Rakowski and Knowling, 2018).

5.4 Influence of gravel extraction

The Ngaruroro River recharge area, which is a major source of groundwater replenishment for the Heretaunga Aquifer, has experienced long-term declines in groundwater levels due to changes in river management (Durney and Wilson, 2024):

- Lowering of the riverbed elevation through gravel extraction and river engineering has reportedly reduced groundwater recharge. The modelled relationship between riverbed elevation and groundwater levels suggests that most of the observed declines in this area can be explained by this factor.
- The narrowing of the braidplain in the vicinity of Roy's Hill in the 1980s reduced the wetted area available for infiltration, further limiting recharge, and ultimately contributing to the observed groundwater level declines.

5.5 Uncertainty and Data Gaps

While the trend analysis provides a robust assessment of groundwater level changes, several uncertainties and limitations exist:

- Spatial Gaps in Monitoring: There are significant gaps in long-term monitoring data, particularly north of the Ngaruroro River towards Napier and east of Hastings. In the Ruataniwha Plains, data gaps exist in the southwest and central basin.
- Short-Term Monitoring: Several new wells have been drilled, but their records are too short to detect statistically significant trends. Variations in climate and pumping conditions mean groundwater levels also vary significantly. This variation means longer-term monitoring is required to observe changes masked by seasonal variability.
- Gaps in surface water monitoring: There is no dedicated programme to monitor changes in surface water and groundwater interactions. Most recharge to the groundwater systems is derived from river losses yet a concurrent flow program has not been established to monitor these inputs.
- No spring monitoring: No springs are monitored within the region, despite their high cultural significance and important role in sustaining stream flows. Spring discharge is especially critical during low-flow periods for maintaining healthy aquatic ecosystems.

6 Recommendations | Nga Tohutohu

Based on the findings of this study, the following recommendations are proposed to assist with managing groundwater resources in the Heretaunga and Ruataniwha Plains:

1. **Implement groundwater abstraction limits**
   - Establish and implement pumping limits in the Heretaunga Plains to prevent further declines.
   - Review groundwater allocation in the Ruataniwha Plains, where ongoing declines indicate potential long-term issues and wider implications for water security and surface water flows.

2. **Enhance groundwater recharge in key areas**
   - Continue investigating the pros and cons of widening the Ngaruroro River braidplain in key recharge areas (e.g., Roy's Hill) to improve infiltration and counteract the impacts of riverbed lowering.
   - Investigate Managed Aquifer Recharge (MAR) feasibility in targeted locations where artificial recharge could enhance groundwater storage, with a focus on improving recharge efficiency compared to past trials at Roy's Hill.
   - Assess the potential for flow augmentation schemes in spring-fed streams that are highly dependent on groundwater contributions.

3. **Monitoring and Data Collection**
   - Expand the groundwater monitoring network to fill data gaps, particularly in underrepresented areas of the Heretaunga and Ruataniwha Plains.
   - Dataworth analysis: Use existing numerical models to evaluate the value of different monitoring data types. This approach will allow for a systematic assessment of monitoring priorities and provide a framework for optimising future data collection efforts.
   - Review the groundwater monitoring program to ensure monitor wells are providing value, particularly in areas outside the Heretaunga and Ruataniwha Plains where pumping pressure is light and almost non-existent in some cases.
   - Monitor surface water and groundwater interactions
     - Develop a systematic and long-term concurrent flow programme to monitor major gain and loss sections in the Heretaunga and Ruataniwha basins.
     - Develop a monitoring programme to measure heads and flows at major spring locations that significantly contribute to baseflow of streams or have high cultural value.

4. **Adapt to Climate Variability**
   - Encourage water users to adopt more efficient irrigation techniques, such as precision irrigation and soil moisture monitoring, to optimise water use during dry periods.
   - Investigate the feasibility of water storage solutions, including off-stream reservoirs, to reduce reliance on groundwater during high-demand periods.

7 References | Tohutoro

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8 Appendix A – Groundwater level trend maps

8.1 Mann-Kendall trend results – changes in long-term groundwater levels

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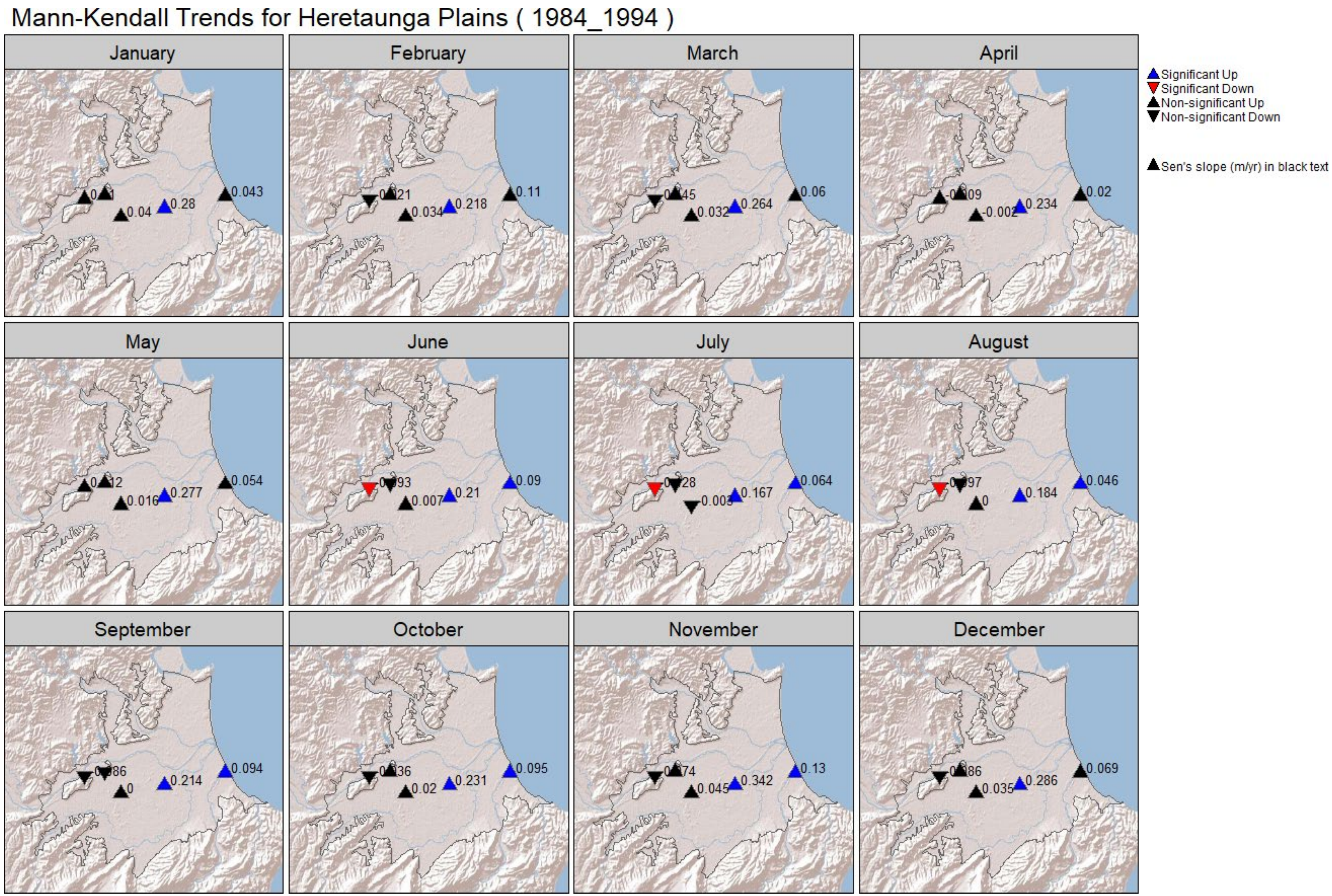


Figure 8-1: Groundwater level trends on the Heretaunga Plains for the 10-year period beween 1984-1994. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly "seasons", January groundwater levels are compared only with January, February only with February.

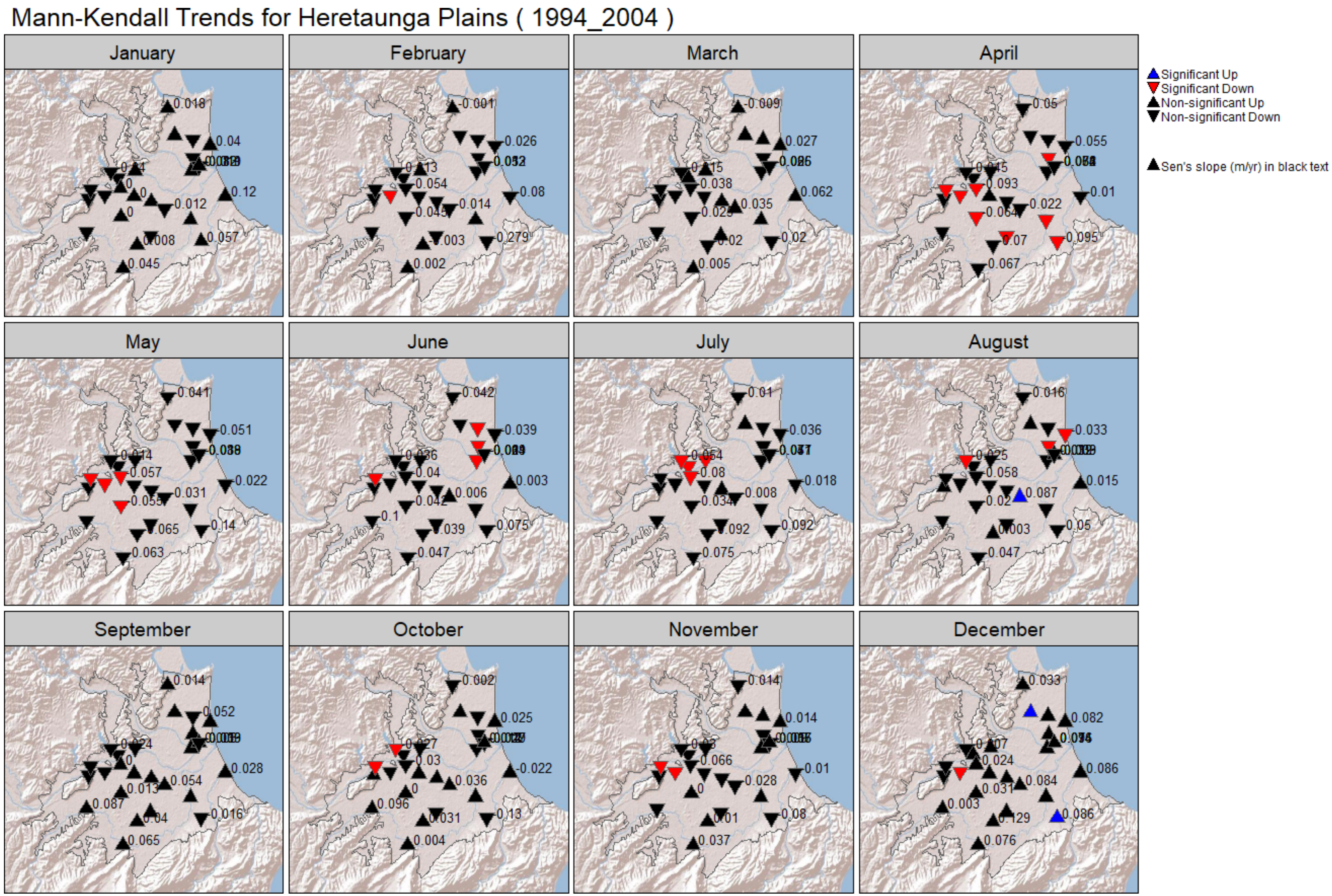


Figure 8-2: Groundwater level trends on the Heretaunga Plains for the 10-year period beween 1994-2004. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February.

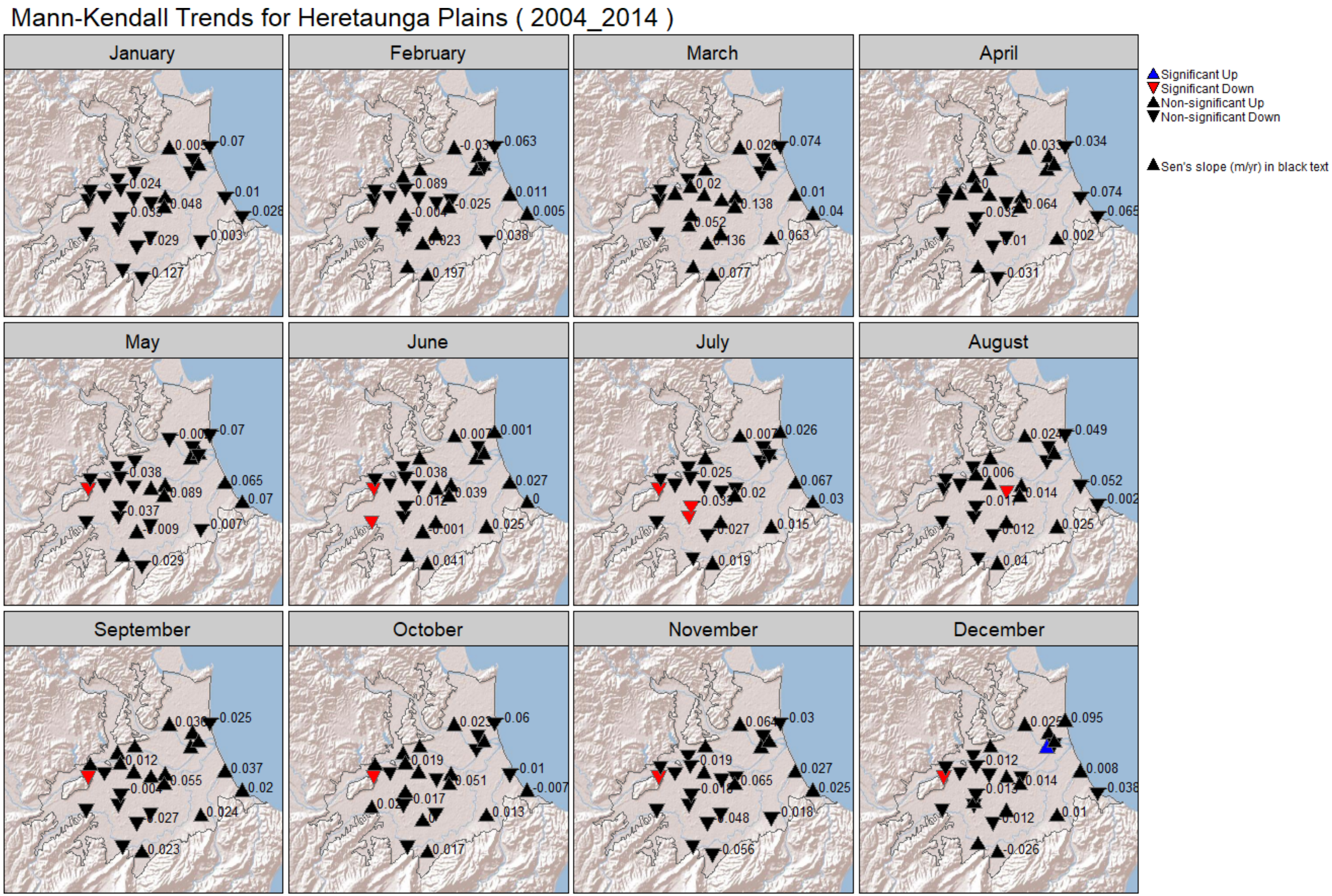


Figure 8-3: Groundwater level trends on the Heretaunga Plains for the 10-year period beween 2004-2014. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February.

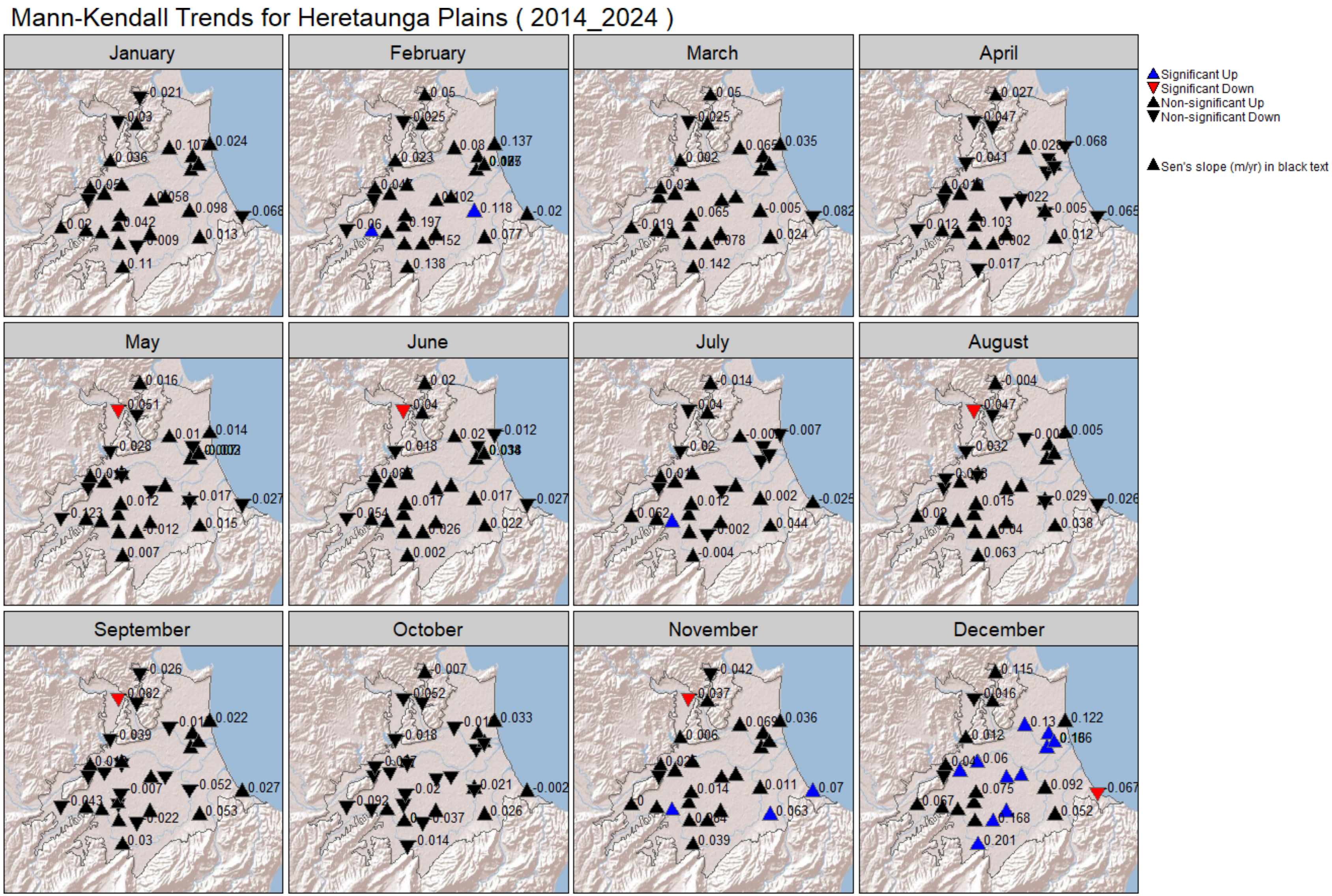


Figure 8-4: Groundwater level trends on the Heretaunga Plains for the 10-year period beween 2014-2024. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly "seasons", January groundwater levels are compared only with January, February only with February.

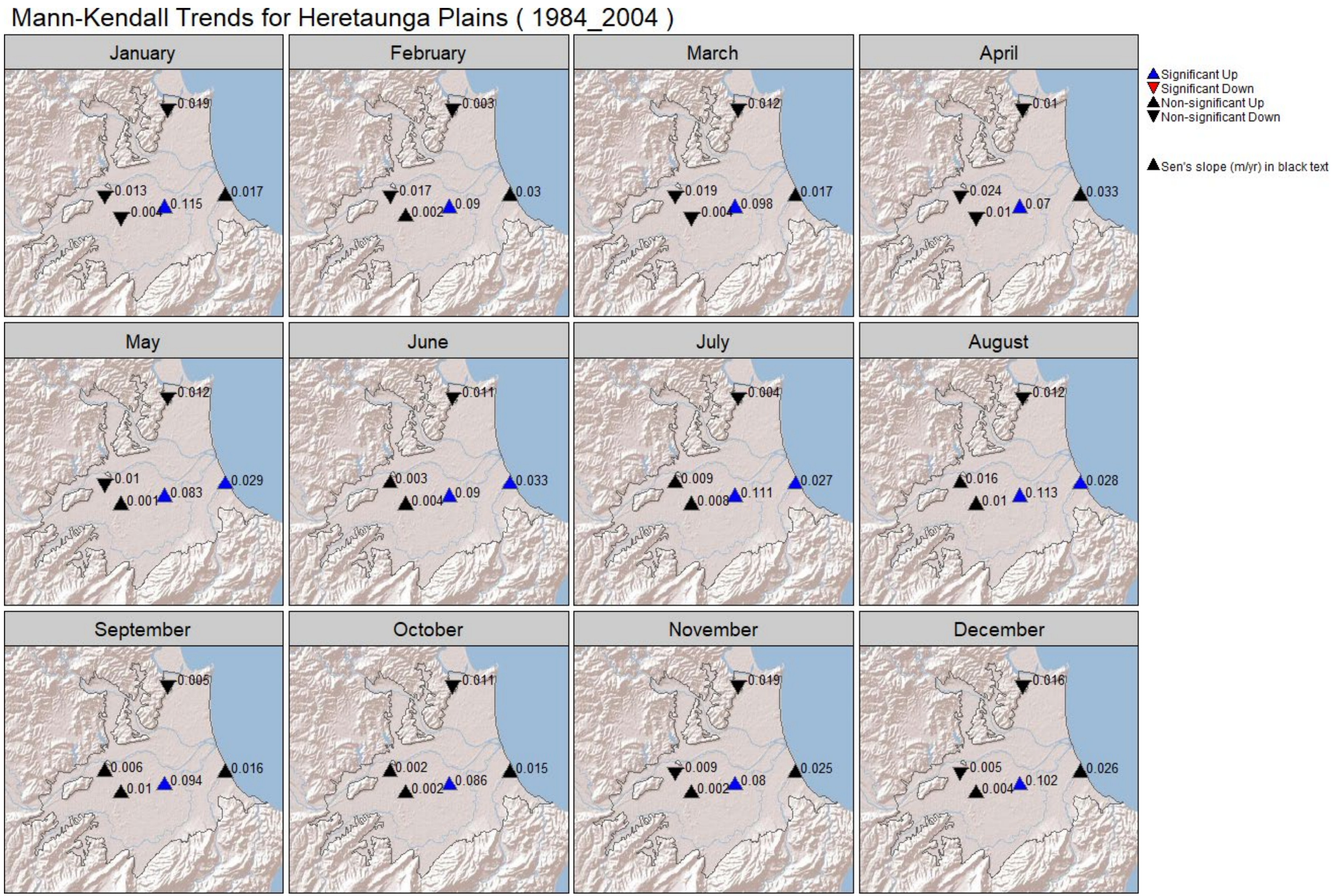


Figure 8-5: Groundwater level trends on the Heretaunga Plains for the 20-year period beween 1984-2004. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly "seasons", January groundwater levels are compared only with January, February only with February.

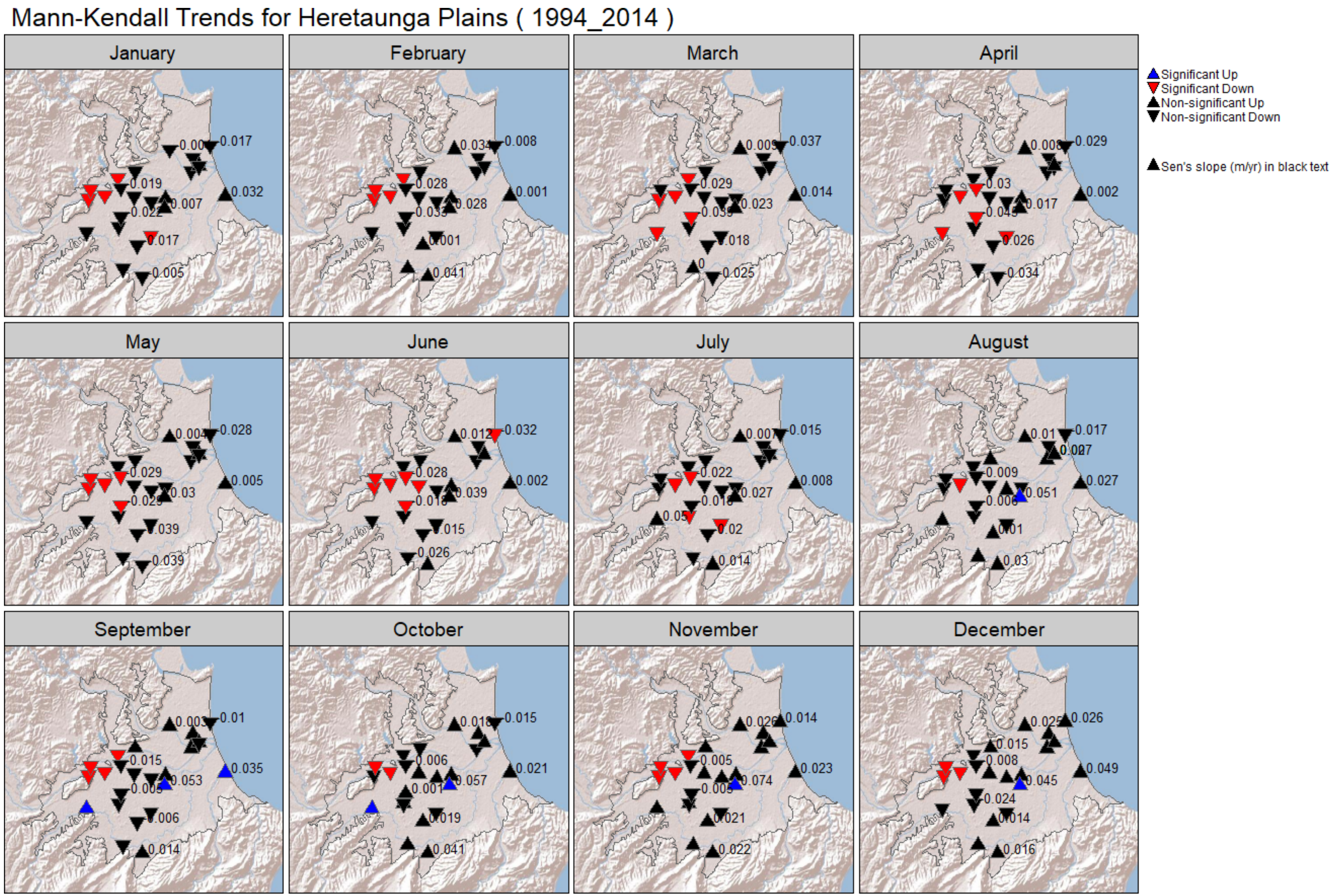


Figure 8-6: Groundwater level trends on the Heretaunga Plains for the 20-year period beween 1994-2014. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly "seasons", January groundwater levels are compared only with January, February only with February.

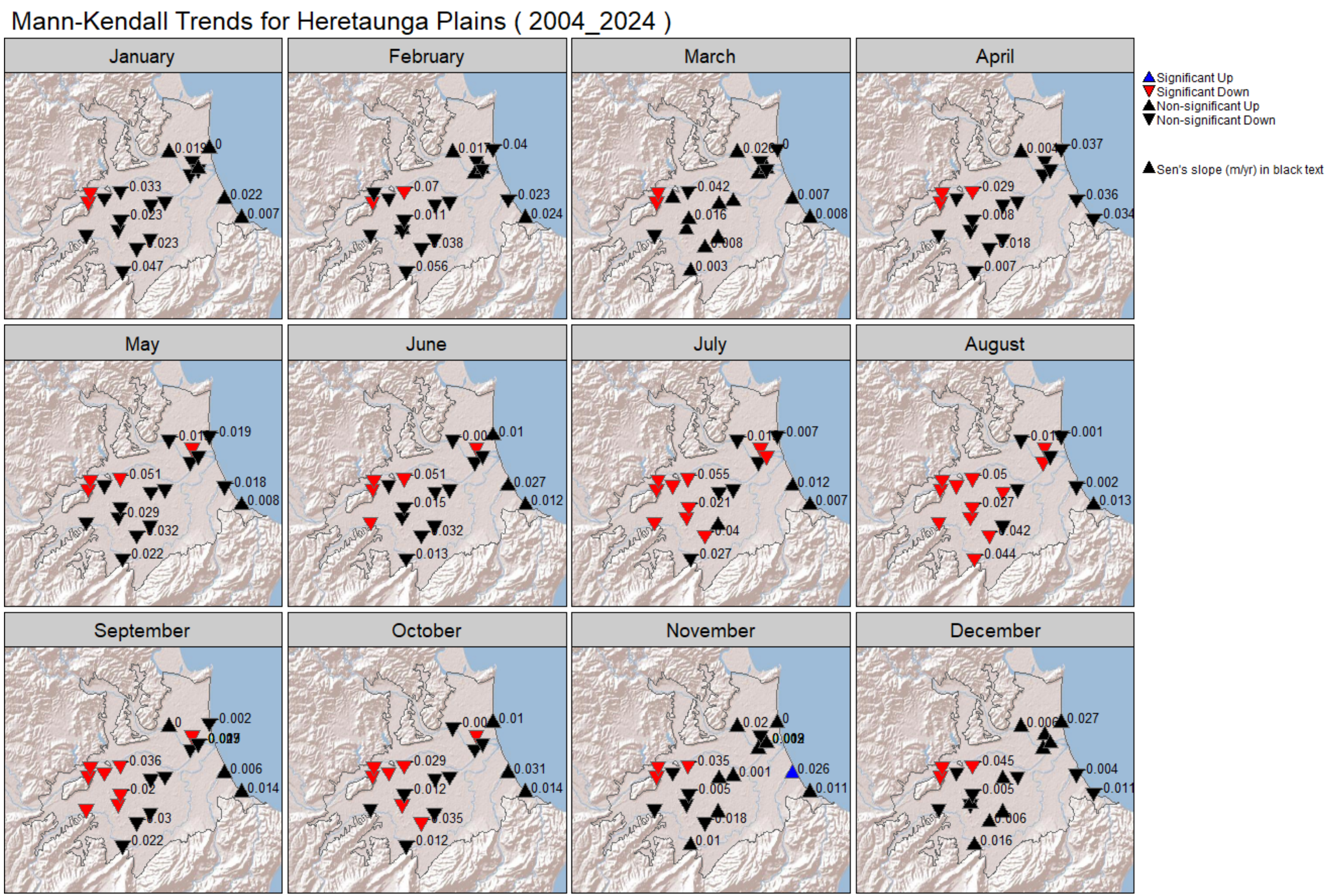


Figure 8-7: Groundwater level trends on the Heretaunga Plains for the 20-year period beween 2004-2024. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February.

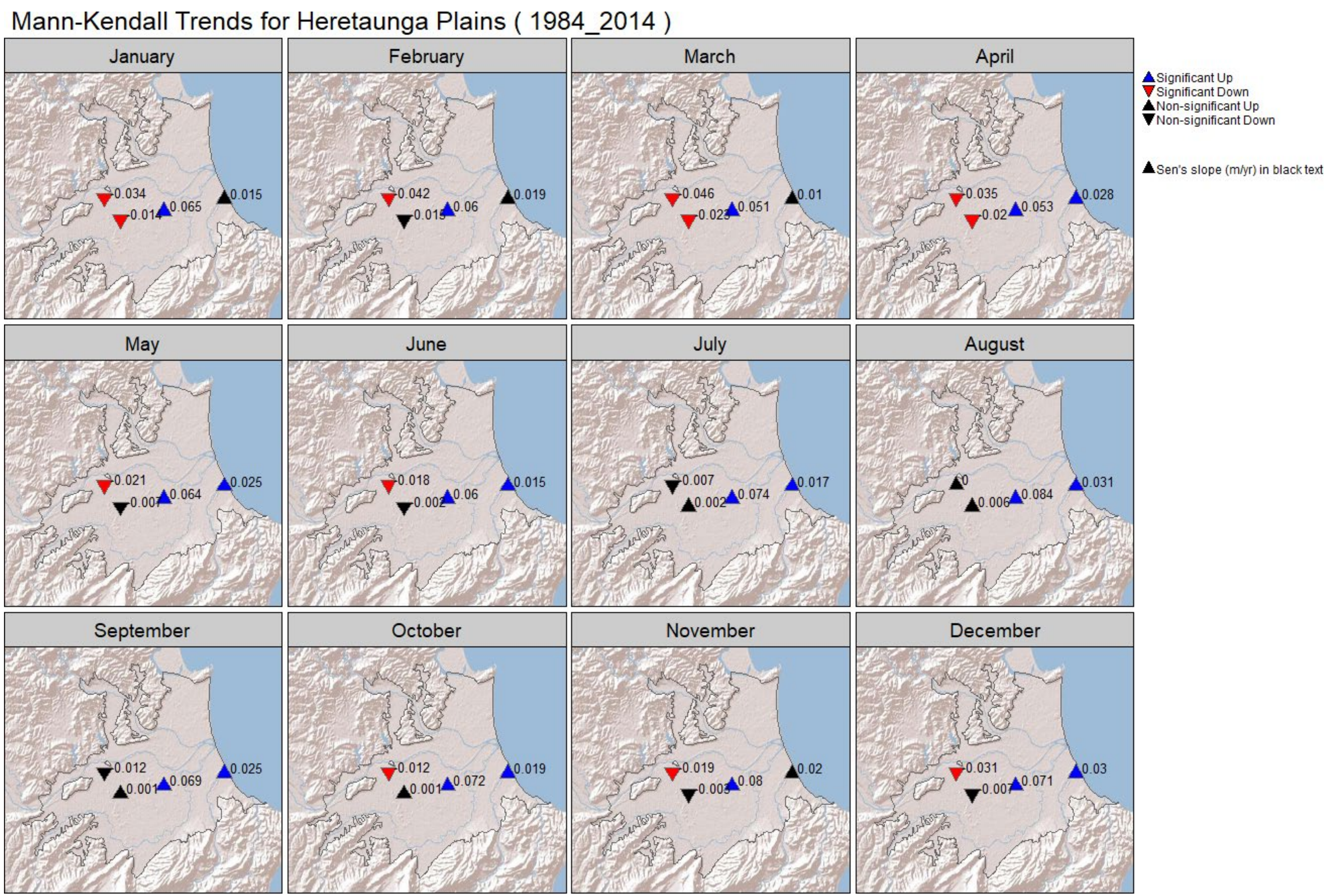


Figure 8-8: Groundwater level trends on the Heretaunga Plains for the 30-year period beween 1984-2014. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February

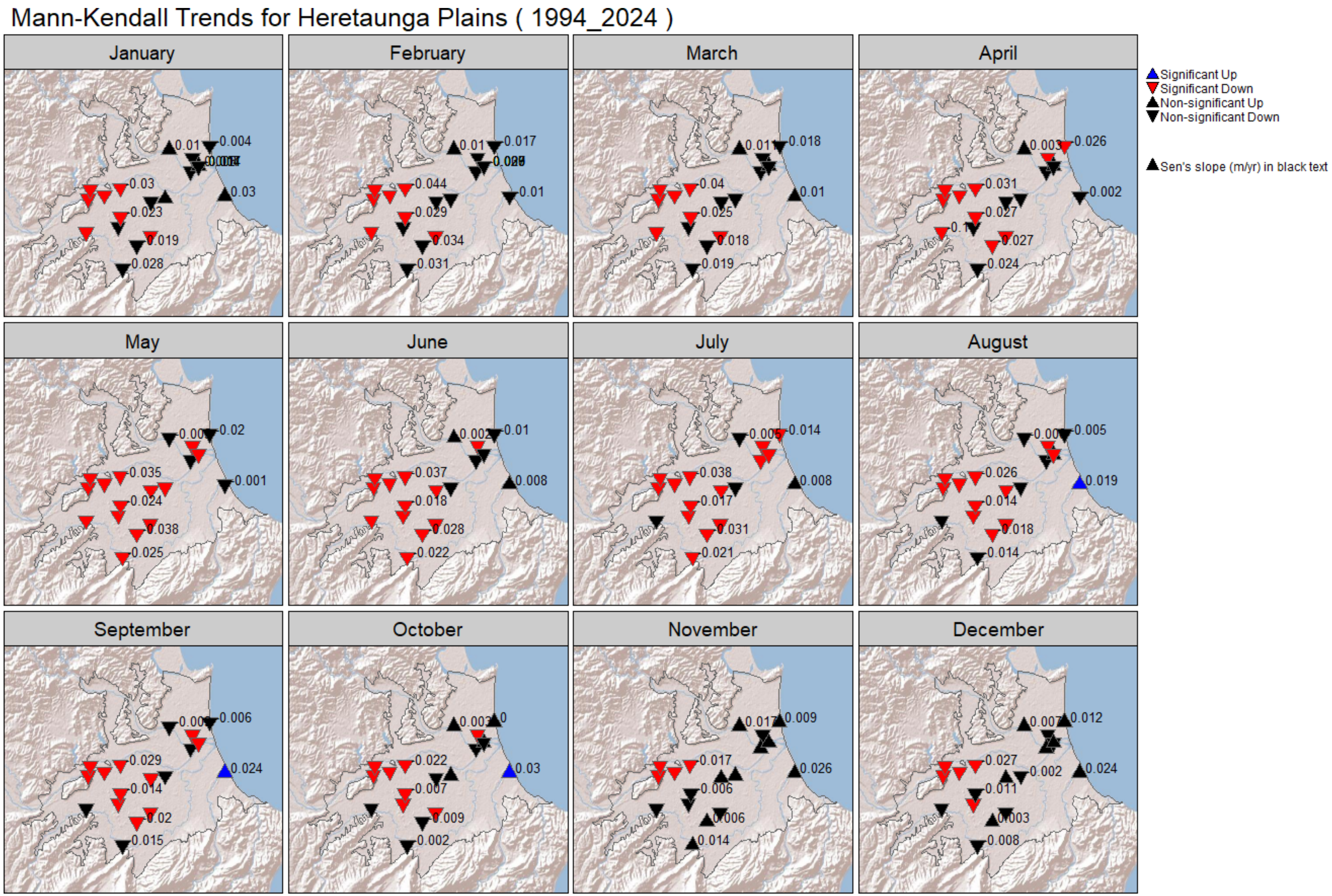


Figure 8-9: Groundwater level trends on the Heretaunga Plains for the 30-year period beween 1994-2024. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly "seasons", January groundwater levels are compared only with January, February only with February

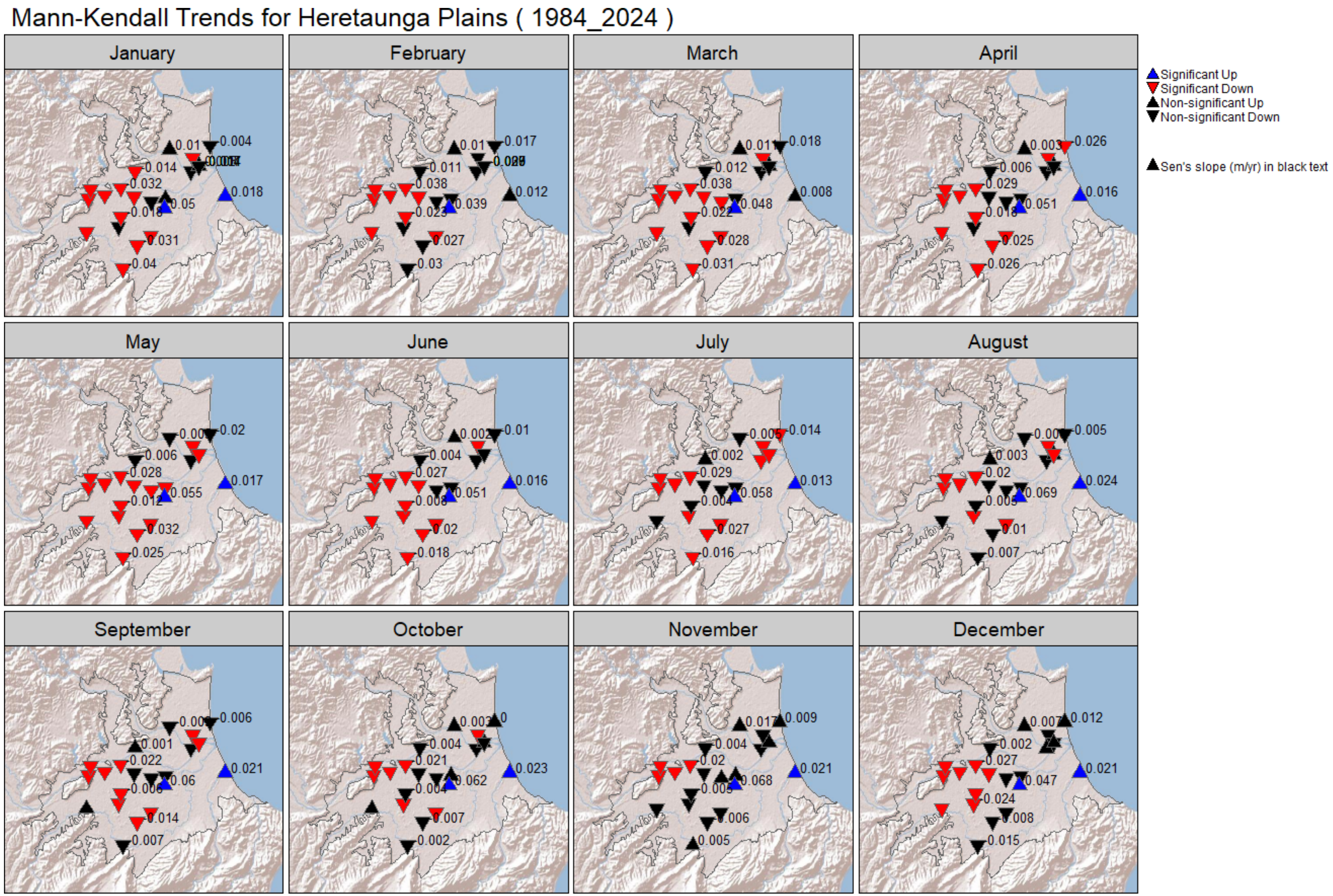


Figure 8-10: Groundwater level trends on the Heretaunga Plains for the 40-year period beween 1984-2024. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly "seasons", January groundwater levels are compared only with January, February only with February.

NO DATA

Figure 8-11: Groundwater level trends on the Ruataniwha Plains for the 10-year period beween 1984-1994. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February.

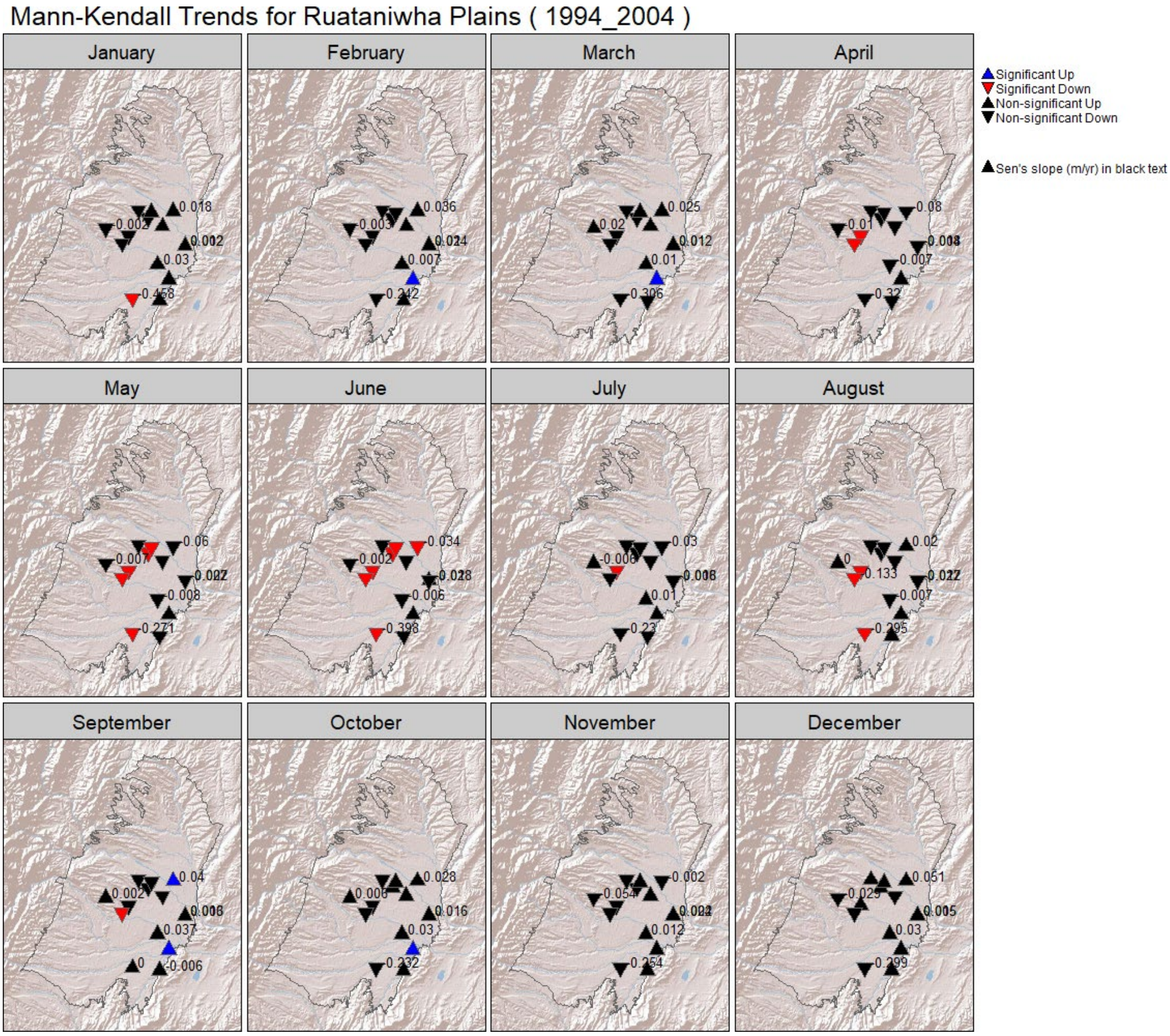


Figure 8-12: Groundwater level trends on the Ruataniwha Plains for the 10-year period beween 1994-2004. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February.

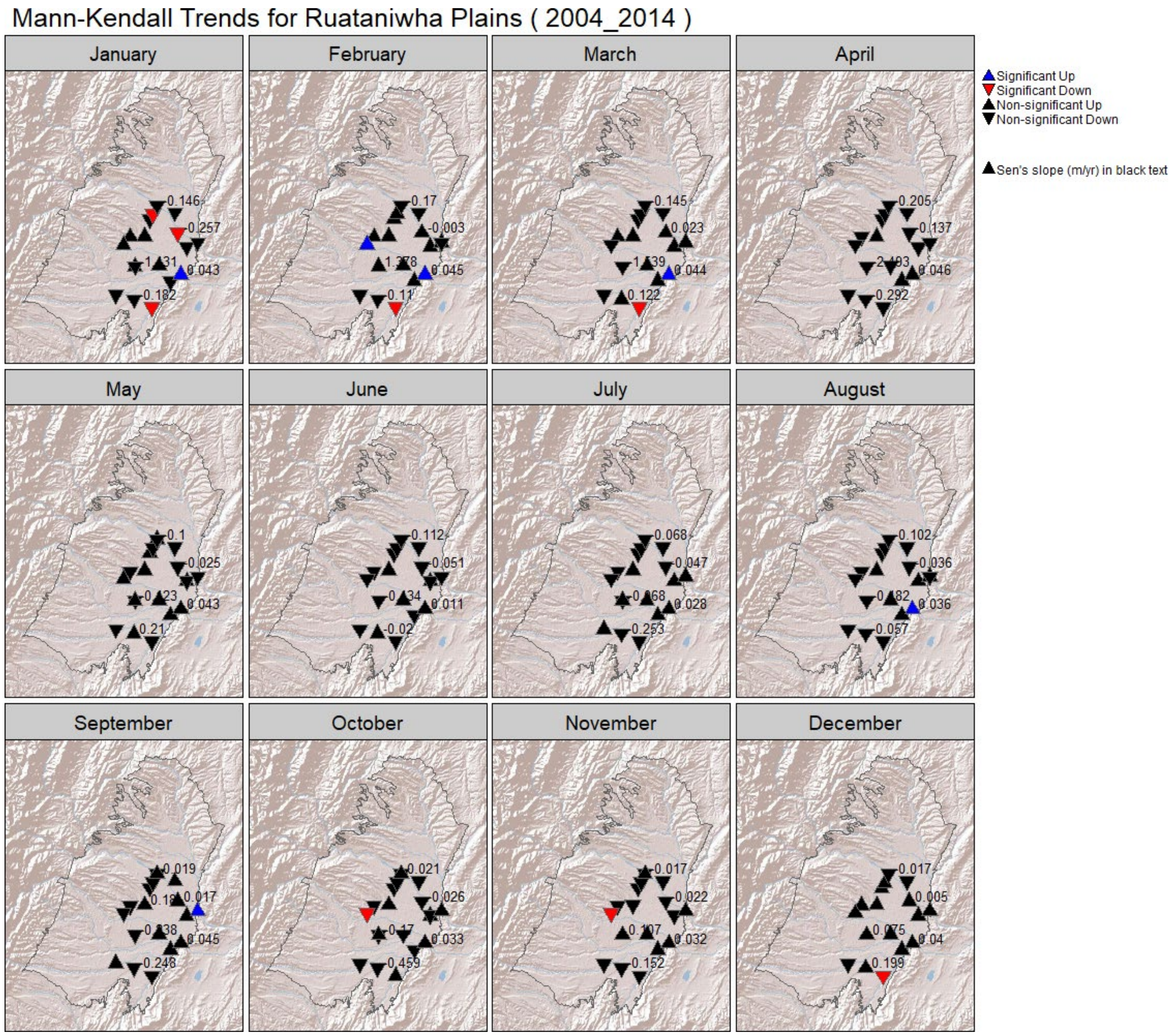


Figure 8-13: Groundwater level trends on the Ruataniwha Plains for the 10-year period beween 2004-2014. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly "seasons", January groundwater levels are compared only with January, February only with February.

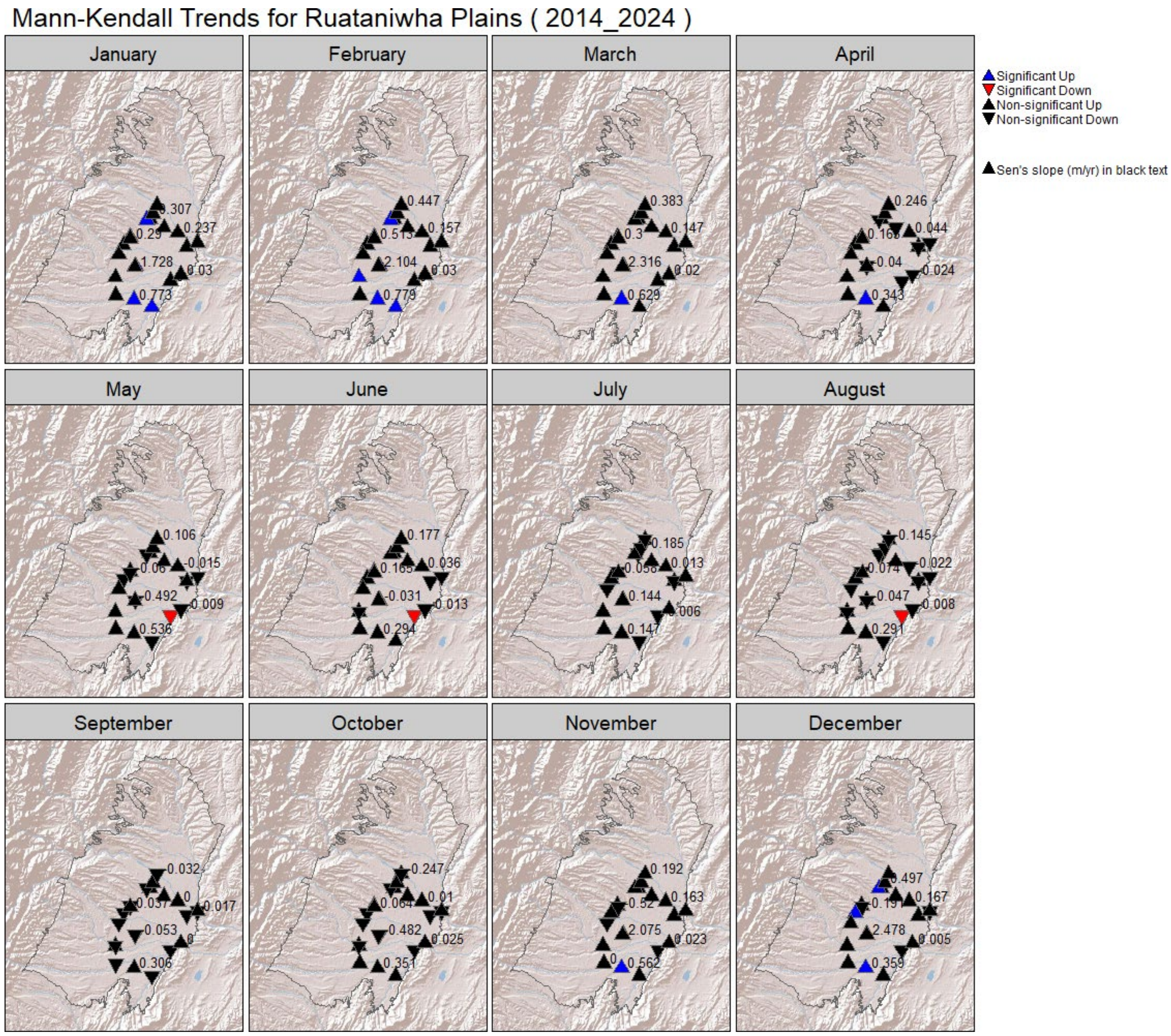


Figure 8-14: Groundwater level trends on the Ruataniwha Plains for the 10-year period beween 2014-2024. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February.

NO DATA

Figure 8-15: Groundwater level trends on the Ruataniwha Plains for the 20-year period beween 1984-2004. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February.

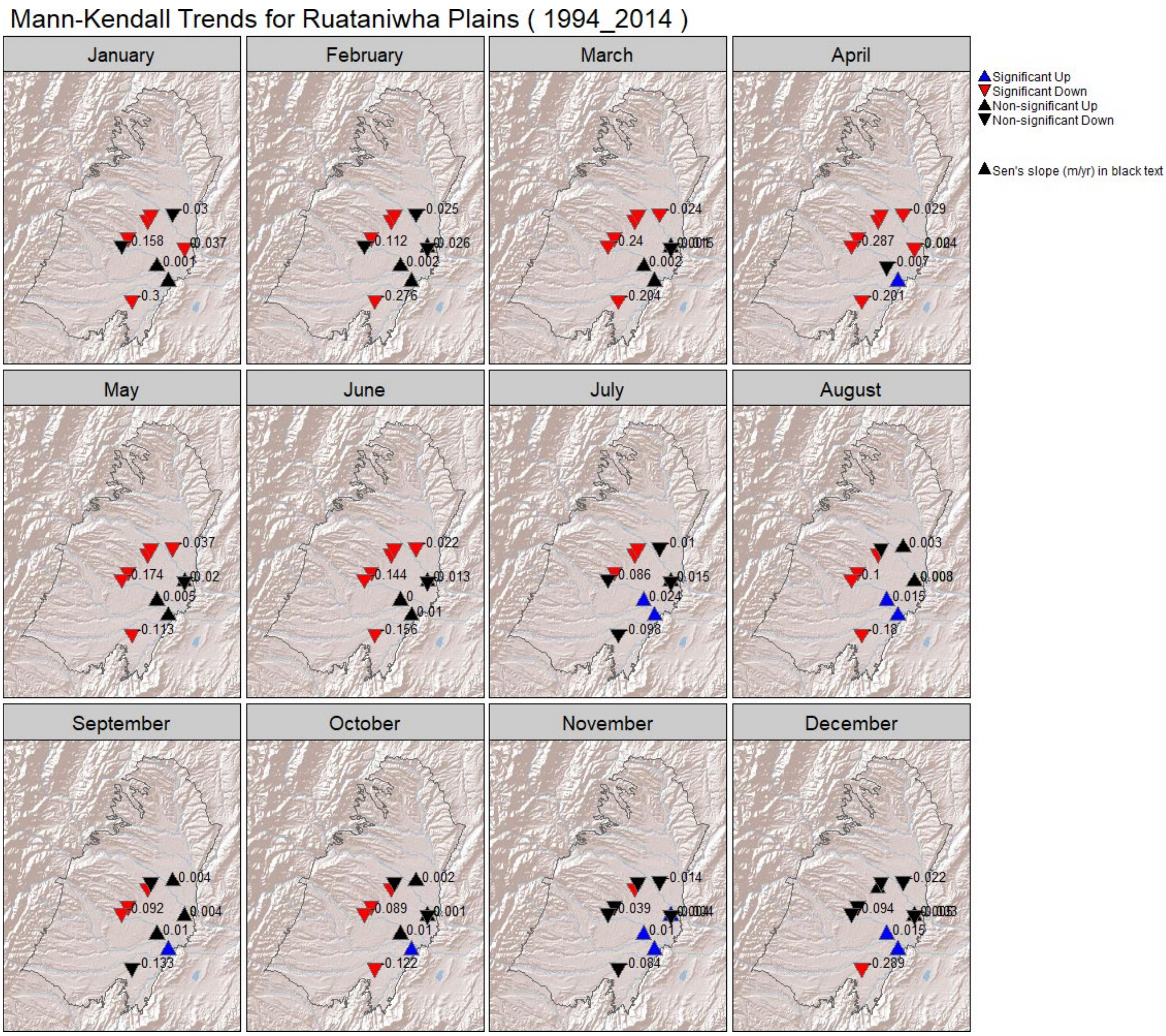


Figure 8-16: Groundwater level trends on the Ruataniwha Plains for the 20-year period beween 1994-2014. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February.

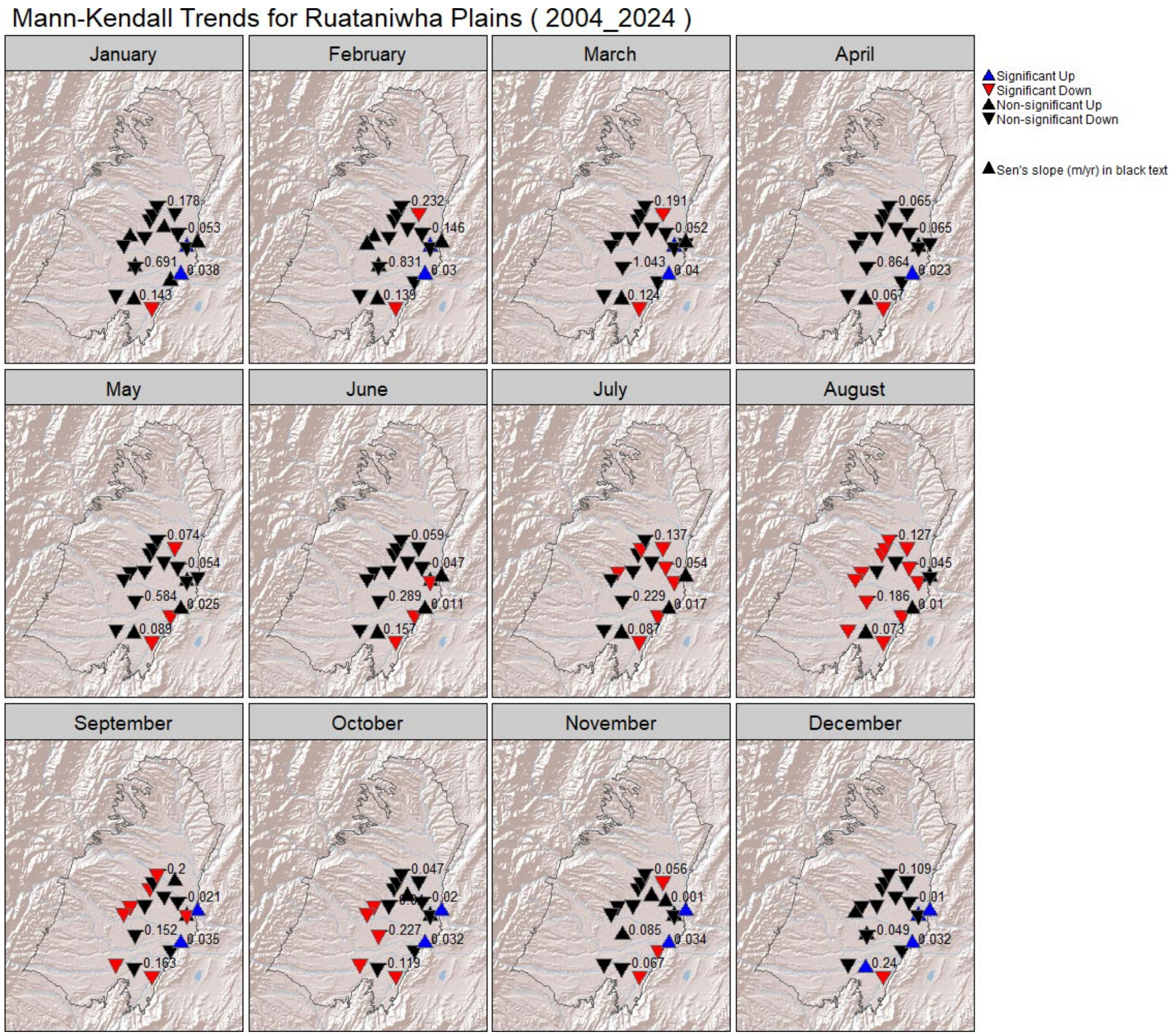


Figure 8-17: Groundwater level trends on the Ruataniwha Plains for the 20-year period beween 2004-2024. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February.

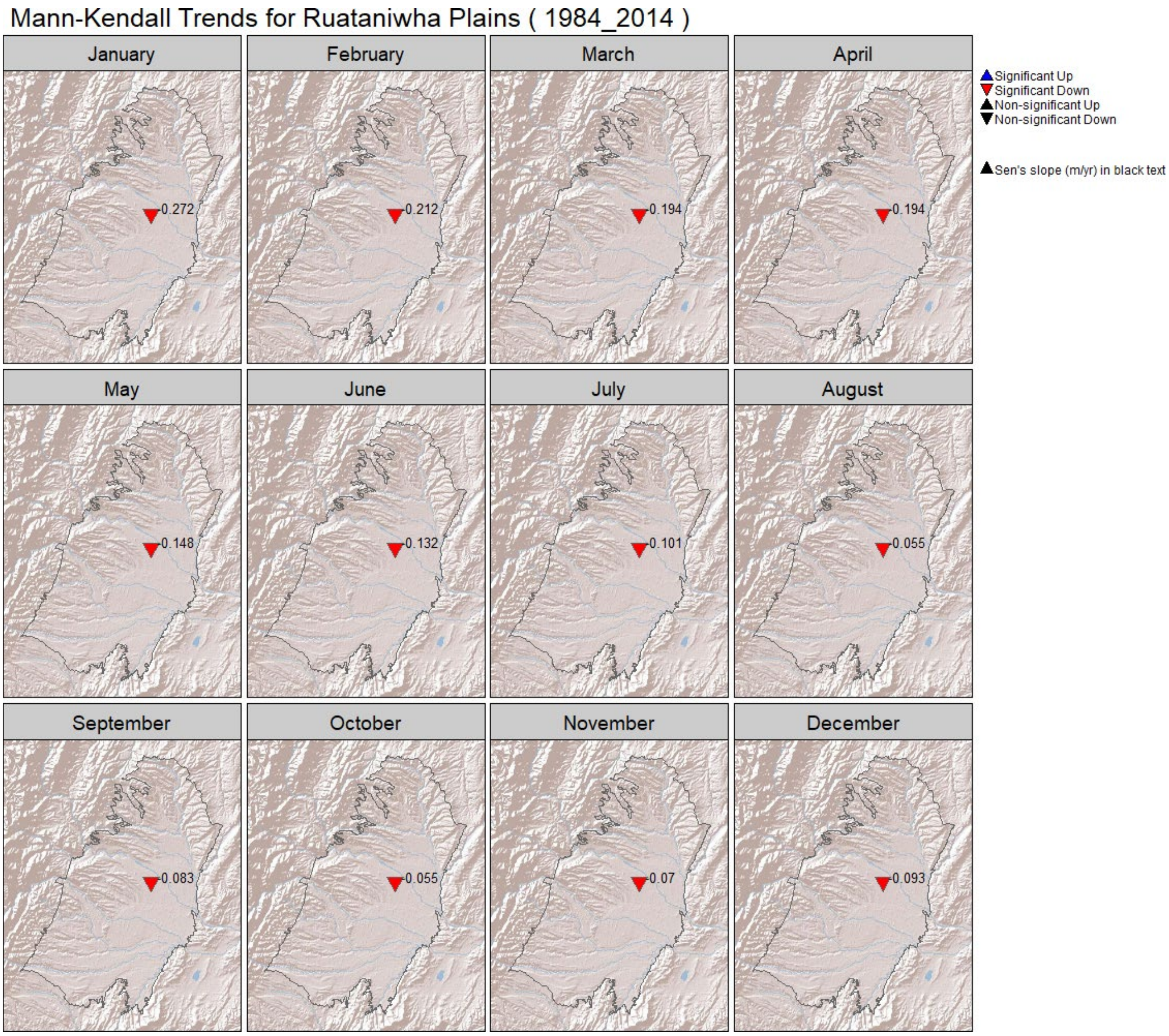


Figure 8-18: Groundwater level trends on the Ruataniwha Plains for the 30-year period beween 1984-2014. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly "seasons", January groundwater levels are compared only with January, February only with February

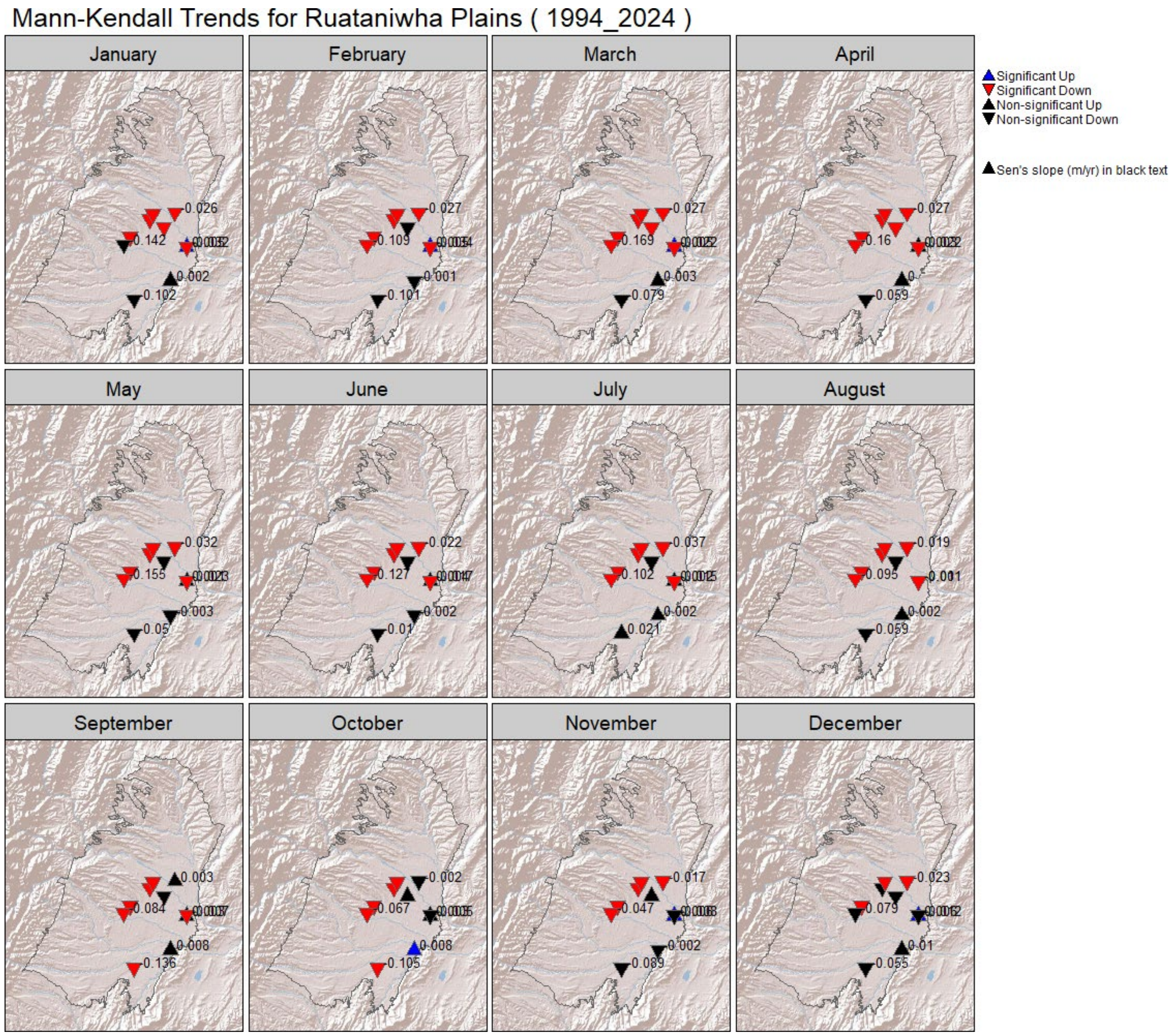


Figure 8-19: Groundwater level trends on the Ruataniwha Plains for the 30-year period beween 1994-2024. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February

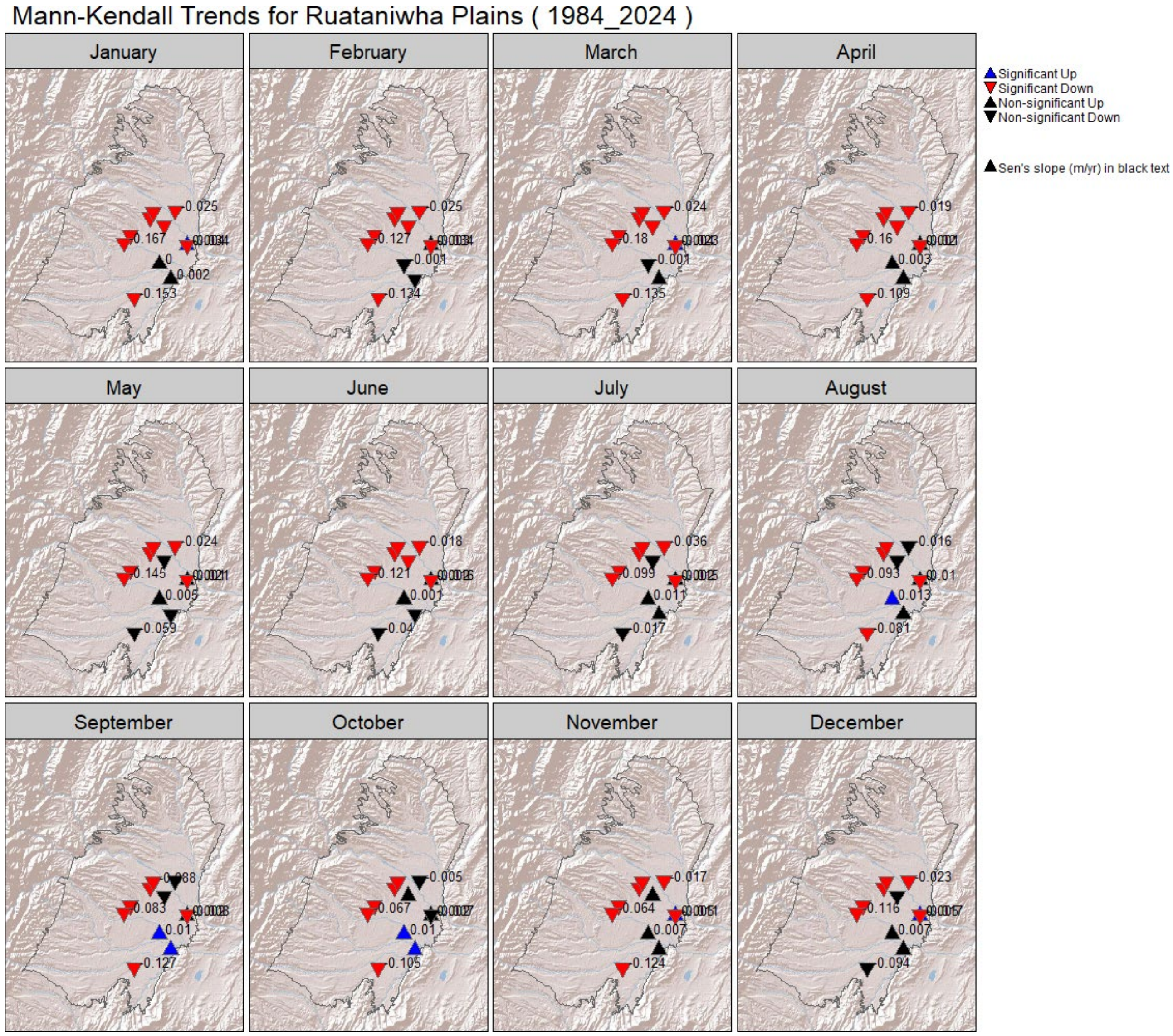


Figure 8-20: Groundwater level trends on the Ruataniwha Plains for the 40-year period beween 1984-2024. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February

NO DATA

Figure 8-21: Groundwater level trends on the minor aquifers for the 10-year period beween 1984-1994. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February.

NO DATA

Figure 8-22: Groundwater level trends on the minor aquifers for the 10-year period beween 1994-2004. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February.

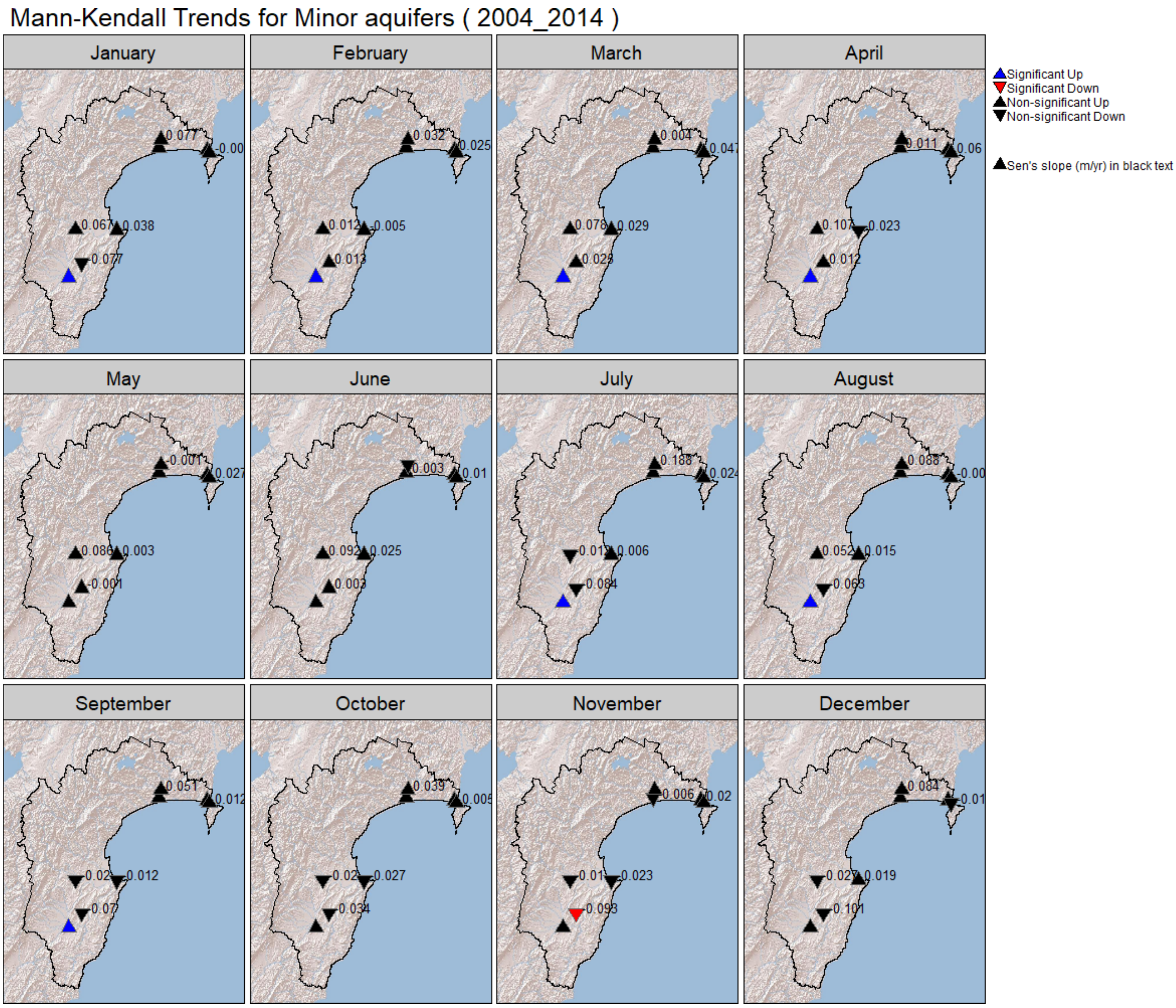


Figure 8-23: Groundwater level trends on the minor aquifers for the 10-year period beween 2004-2014. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly "seasons", January groundwater levels are compared only with January, February only with February.

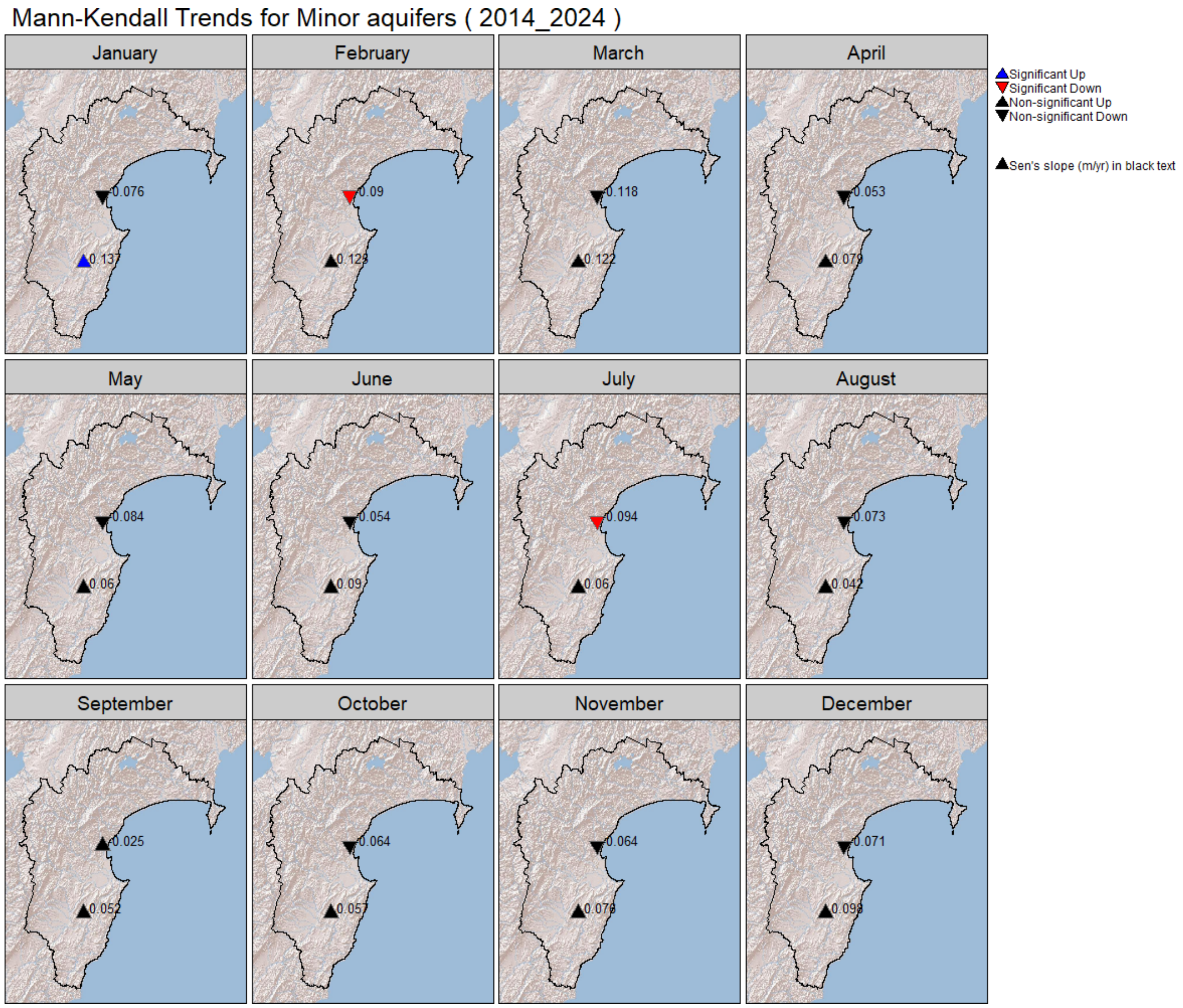


Figure 8-24: Groundwater level trends on the minor aquifers for the 10-year period beween 2014-2024. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly "seasons", January groundwater levels are compared only with January, February only with February.

NO DATA

Figure 8-25: Groundwater level trends on the minor aquifers for the 20-year period beween 1984-2004. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly "seasons", January groundwater levels are compared only with January, February only with February.

NO DATA

Figure 8-26: Groundwater level trends on the minor aquifers for the 20-year period beween 1994-2014. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly "seasons", January groundwater levels are compared only with January, February only with February.

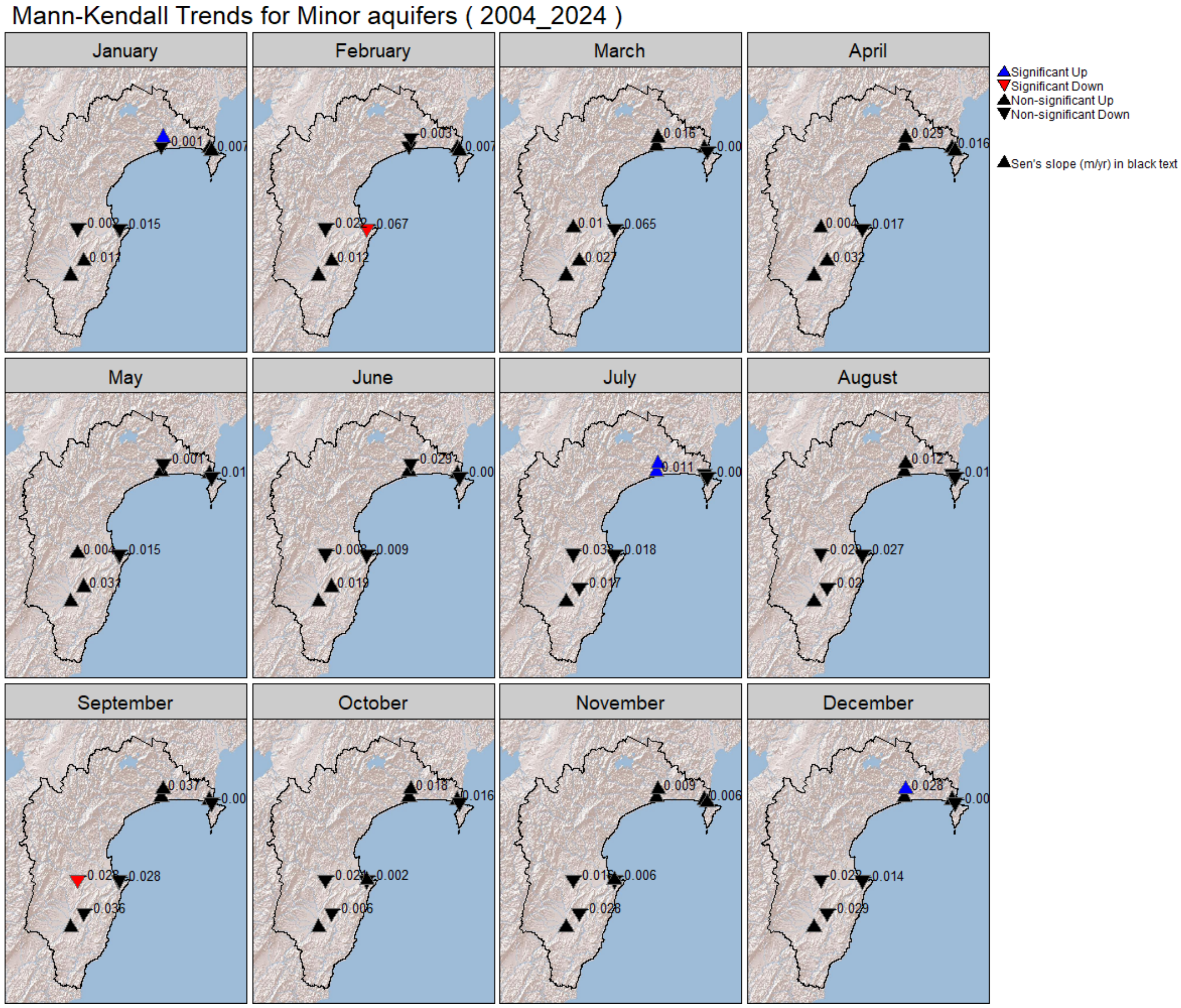


Figure 8-27: Groundwater level trends on the minor aquifers for the 20-year period beween 2004-2024. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly "seasons", January groundwater levels are compared only with January, February only with February.

NO DATA

Figure 8-28: Groundwater level trends on the minor aquifers for the 30-year period beween 1984-2014. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February

NO DATA

Figure 8-29: Groundwater level trends on the minor aquifers for the 30-year period beween 1994-2024. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February

NO DATA

Figure 8-30: Groundwater level trends on the minor aquifers for the 40-year period beween 1984-2024. Note: this test assesses trends on each season (month) seperately. Therefore, for monthly “seasons”, January groundwater levels are compared only with January, February only with February

8.2 Mann-Kendall trend results – changes in seasonal variation

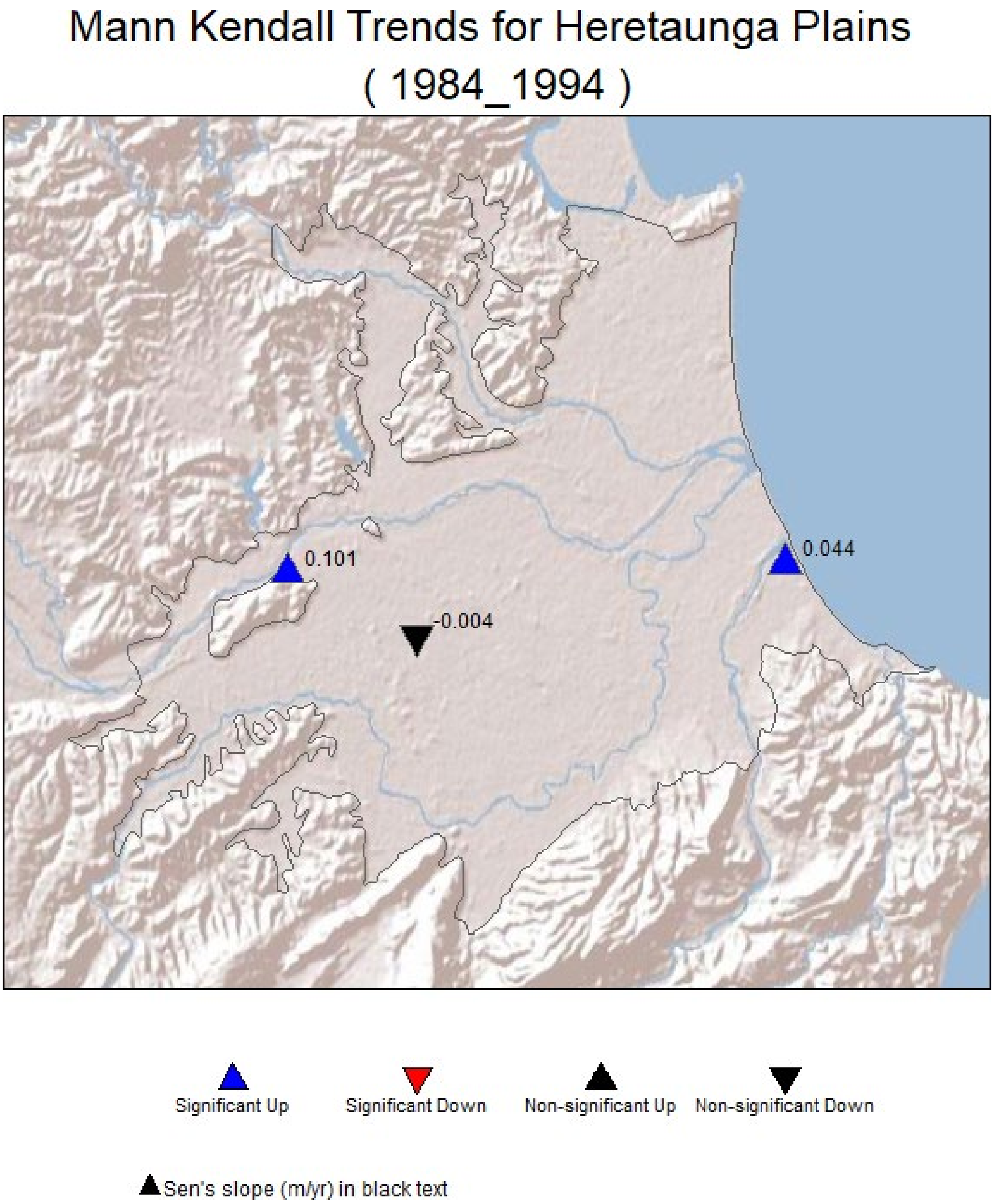


Figure 8-31: Groundwater level trends on the Heretaunga Plains for the 10-year period beween 1984-1994.

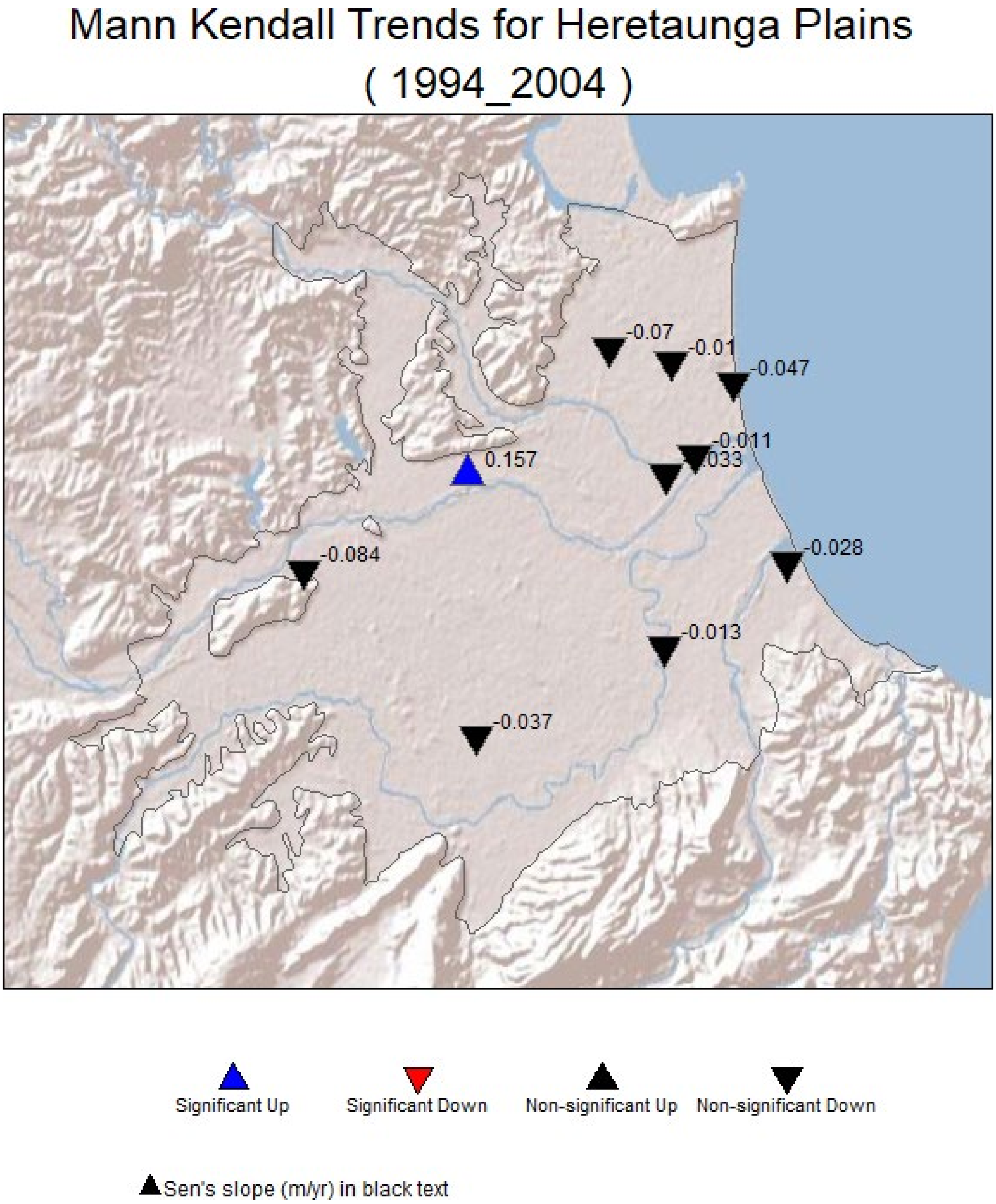


Figure 8-32: Groundwater level trends on the Heretaunga Plains for the 10-year period beween 1994-2004.

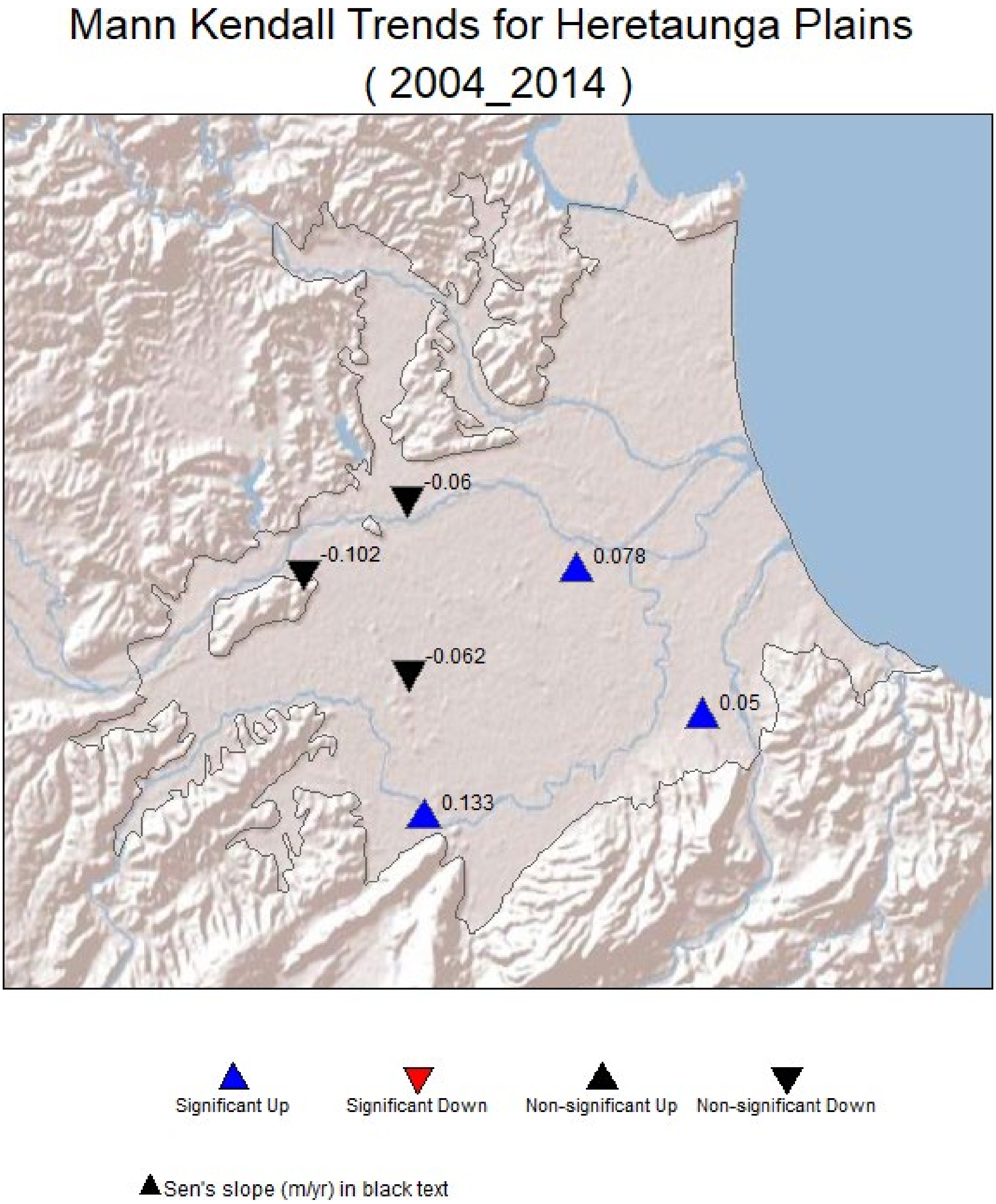


Figure 8-33: Groundwater level trends on the Heretaunga Plains for the 10-year period beween 2004-2014.

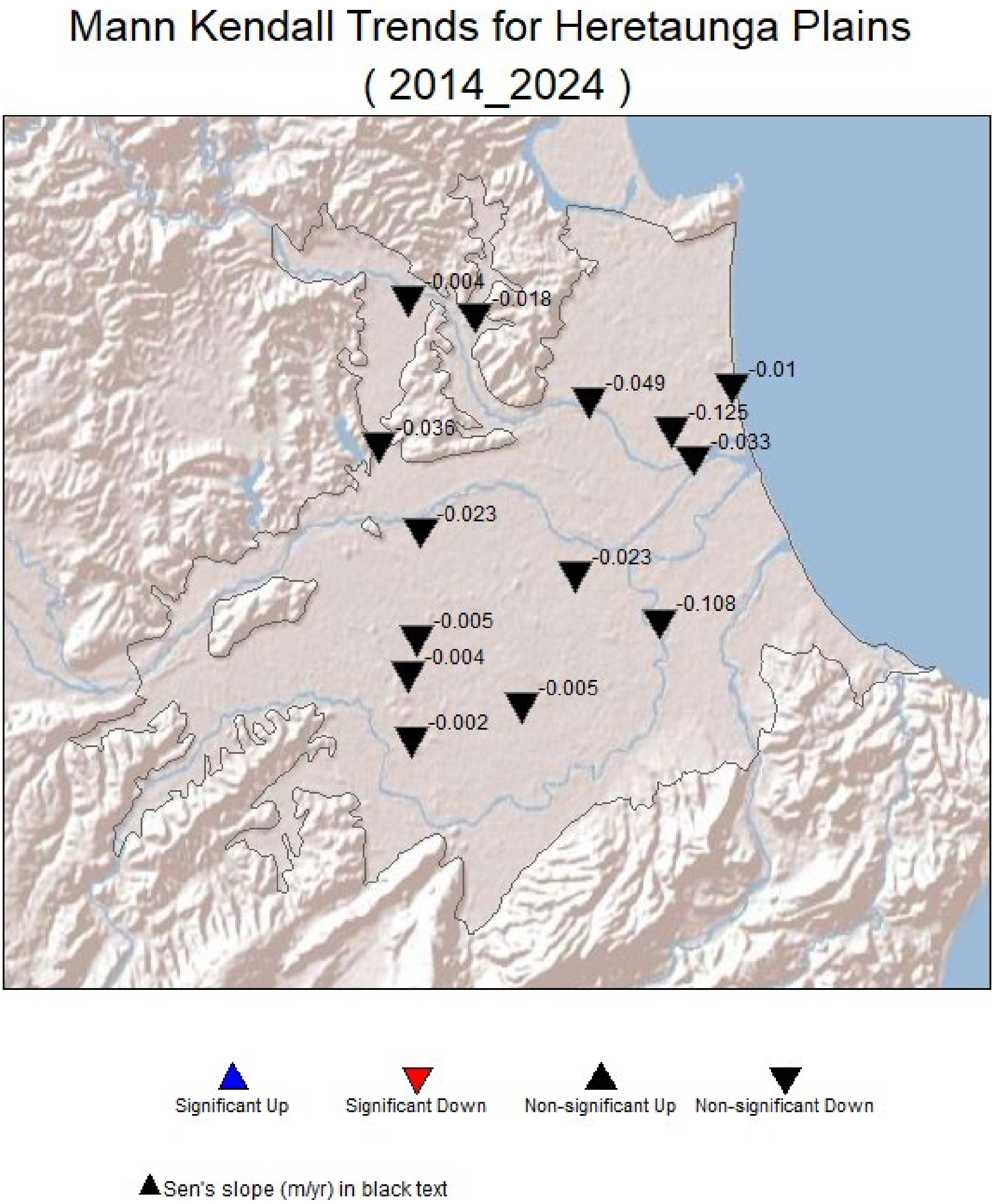


Figure 8-34: Groundwater level trends on the Heretaunga Plains for the 10-year period beween 2014-2024.

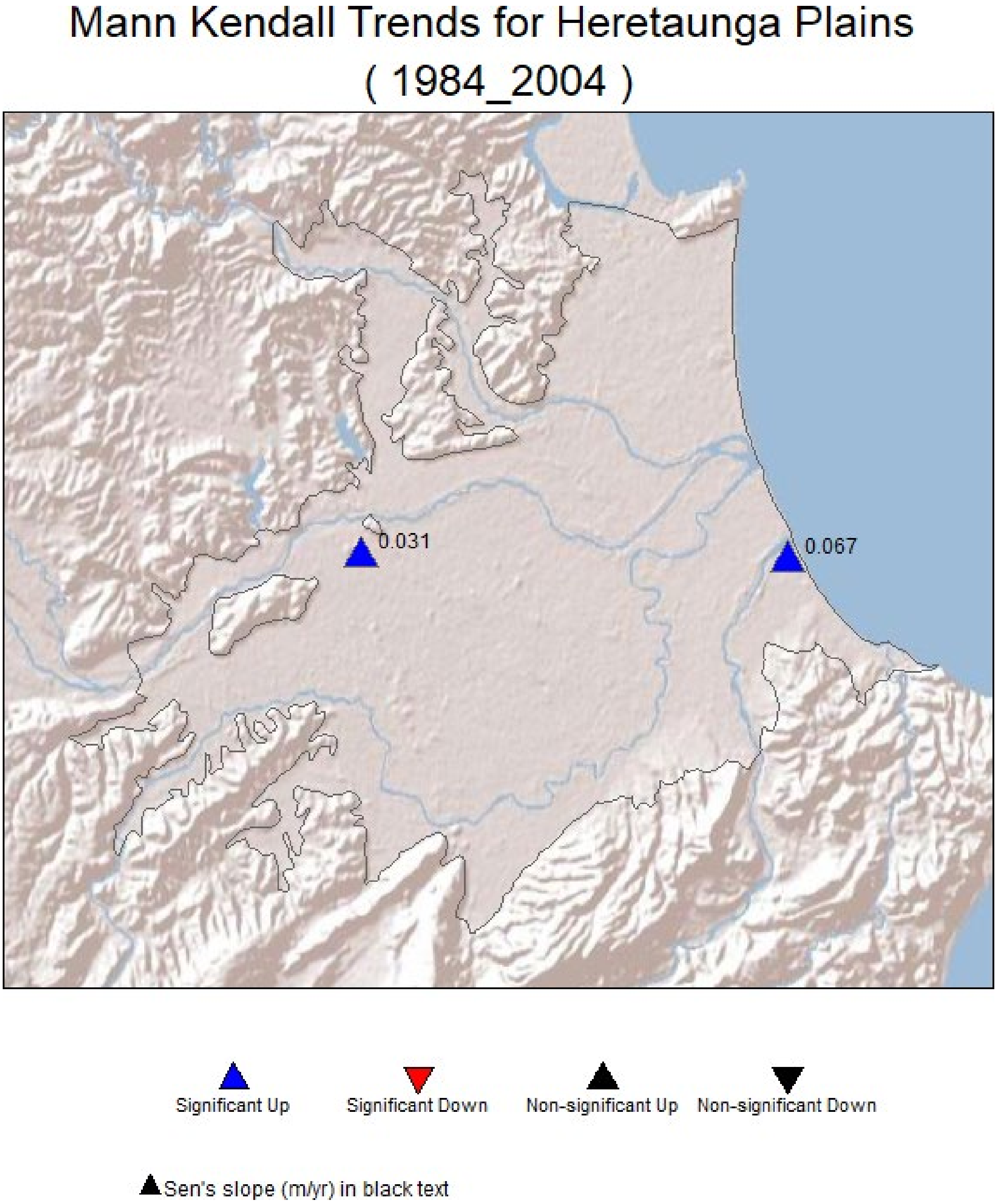


Figure 8-35: Groundwater level trends on the Heretaunga Plains for the 20-year period beween 1984-2004.

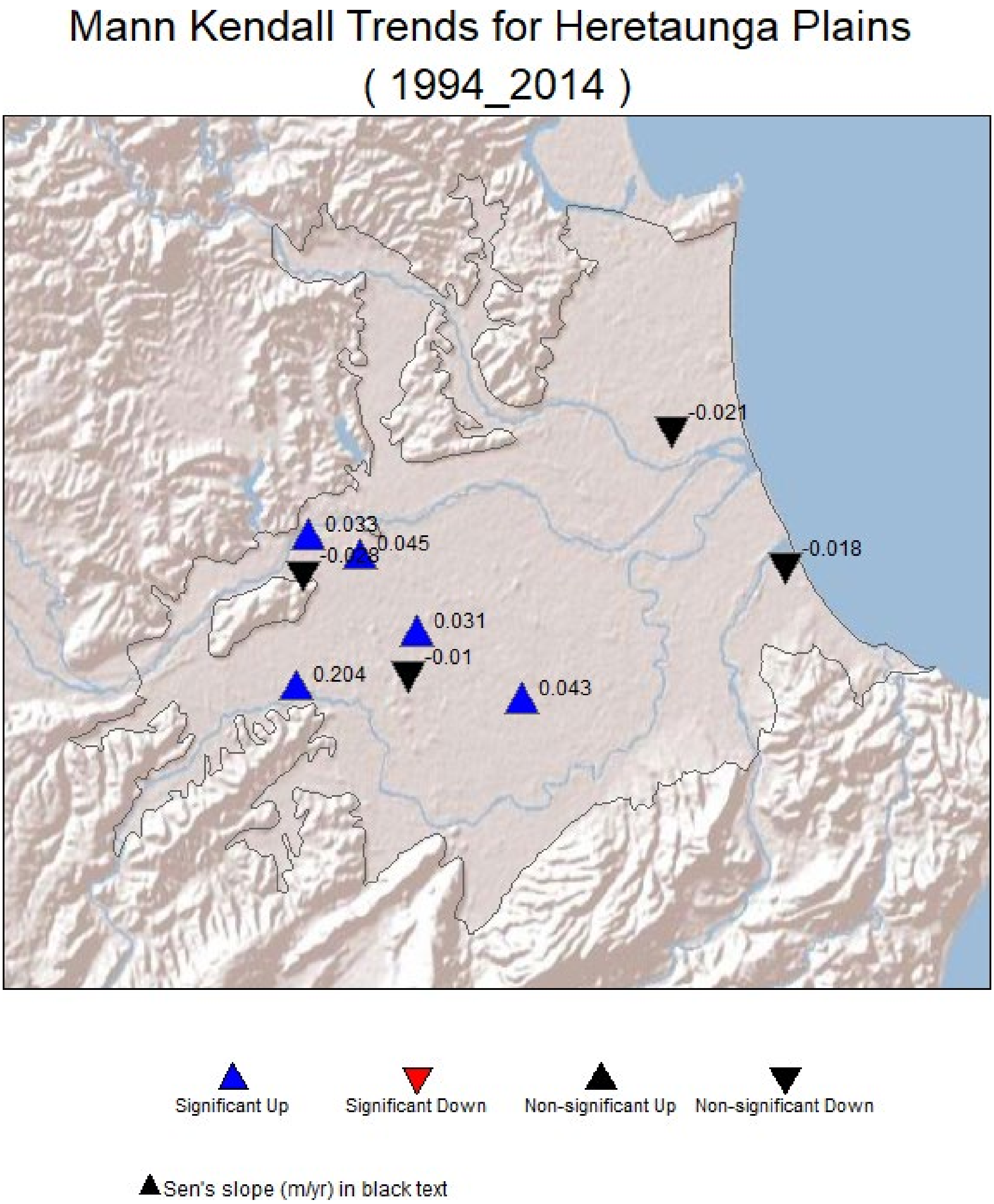


Figure 8-36: Groundwater level trends on the Heretaunga Plains for the 20-year period beween 1994-2014.

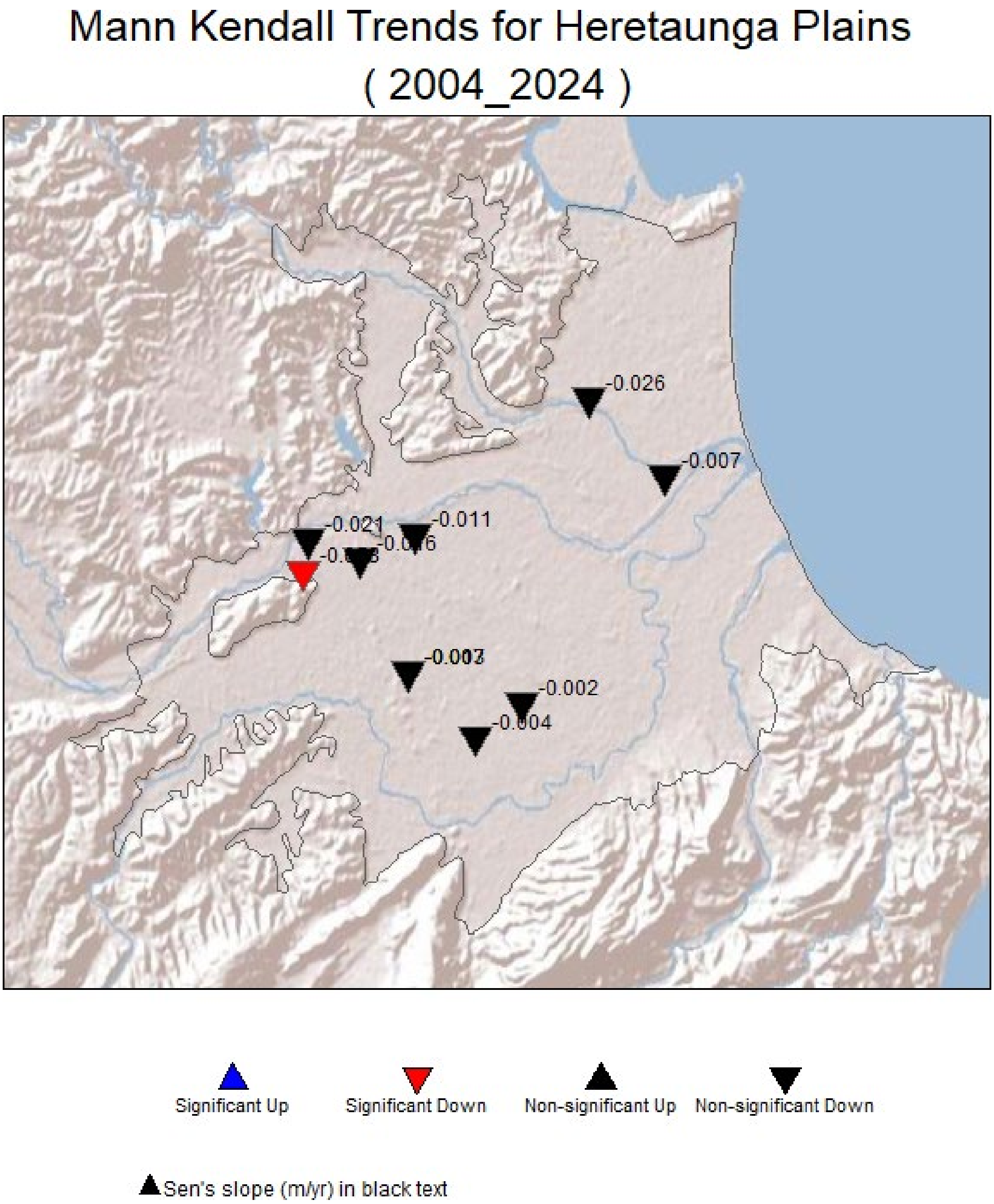


Figure 8-37: Groundwater level trends on the Heretaunga Plains for the 20-year period beween 2004-2024.

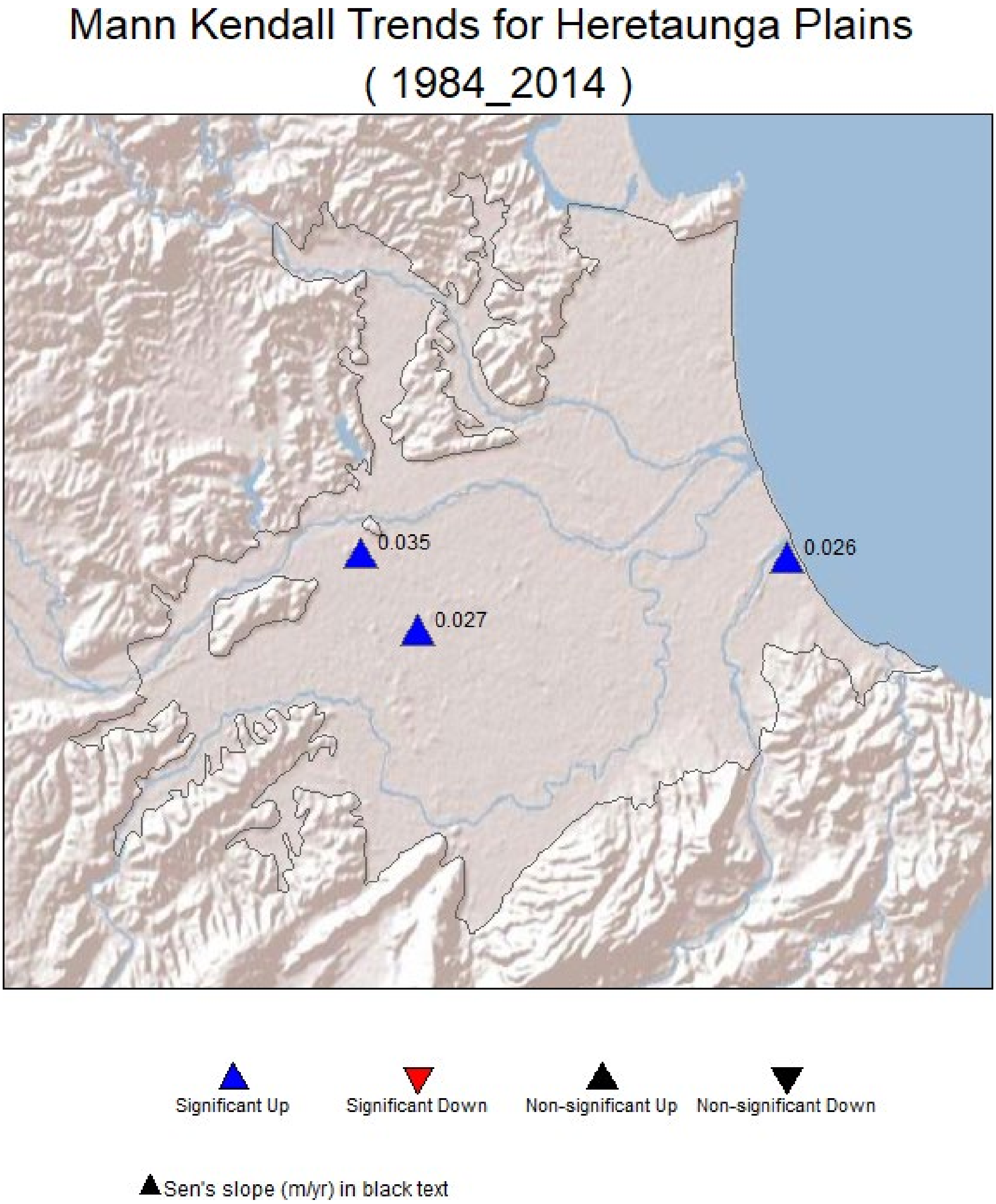


Figure 8-38: Groundwater level trends on the Heretaunga Plains for the 30-year period beween 1984-2014.

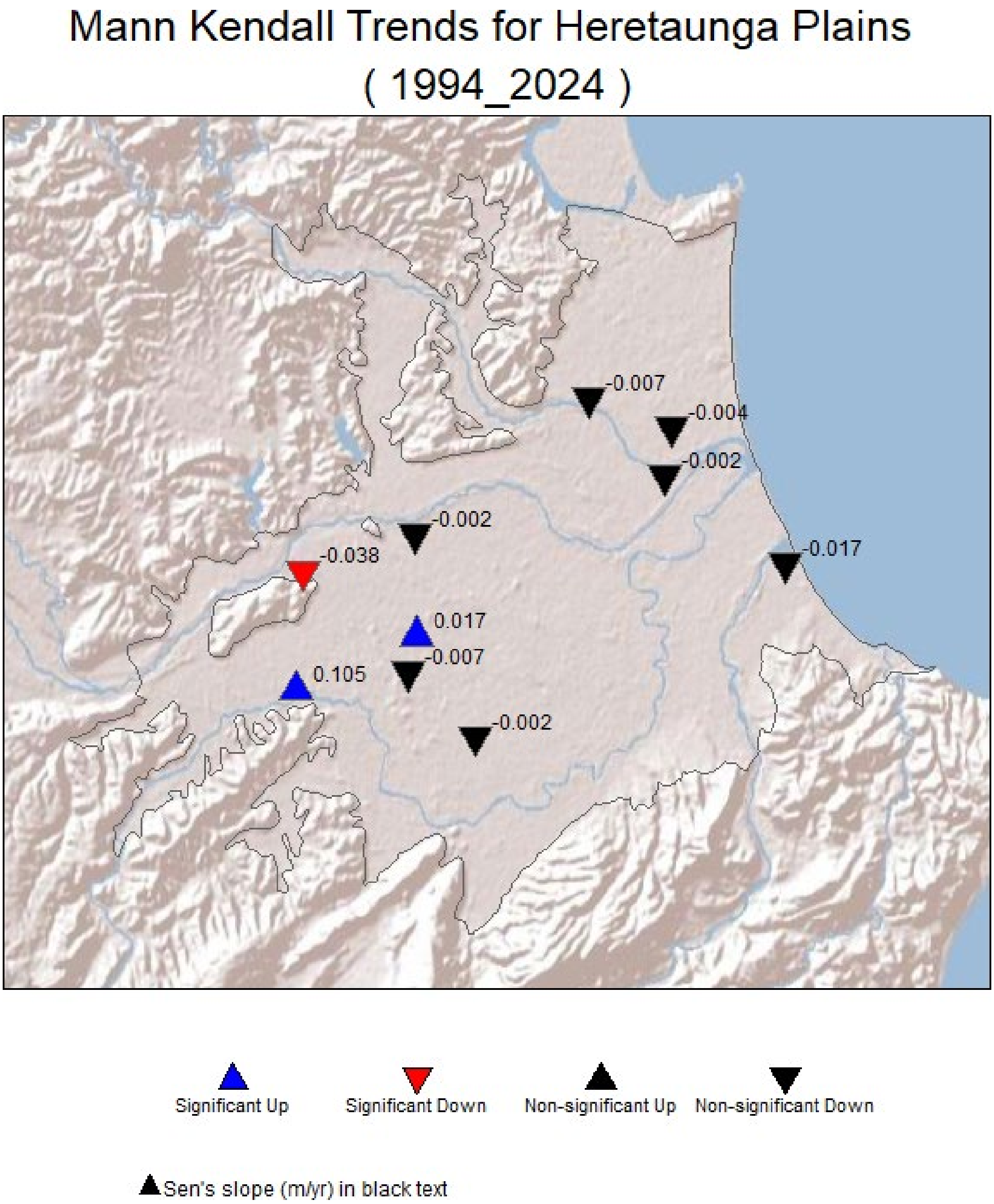


Figure 8-39: Groundwater level trends on the Heretaunga Plains for the 30-year period beween 1994-2024.

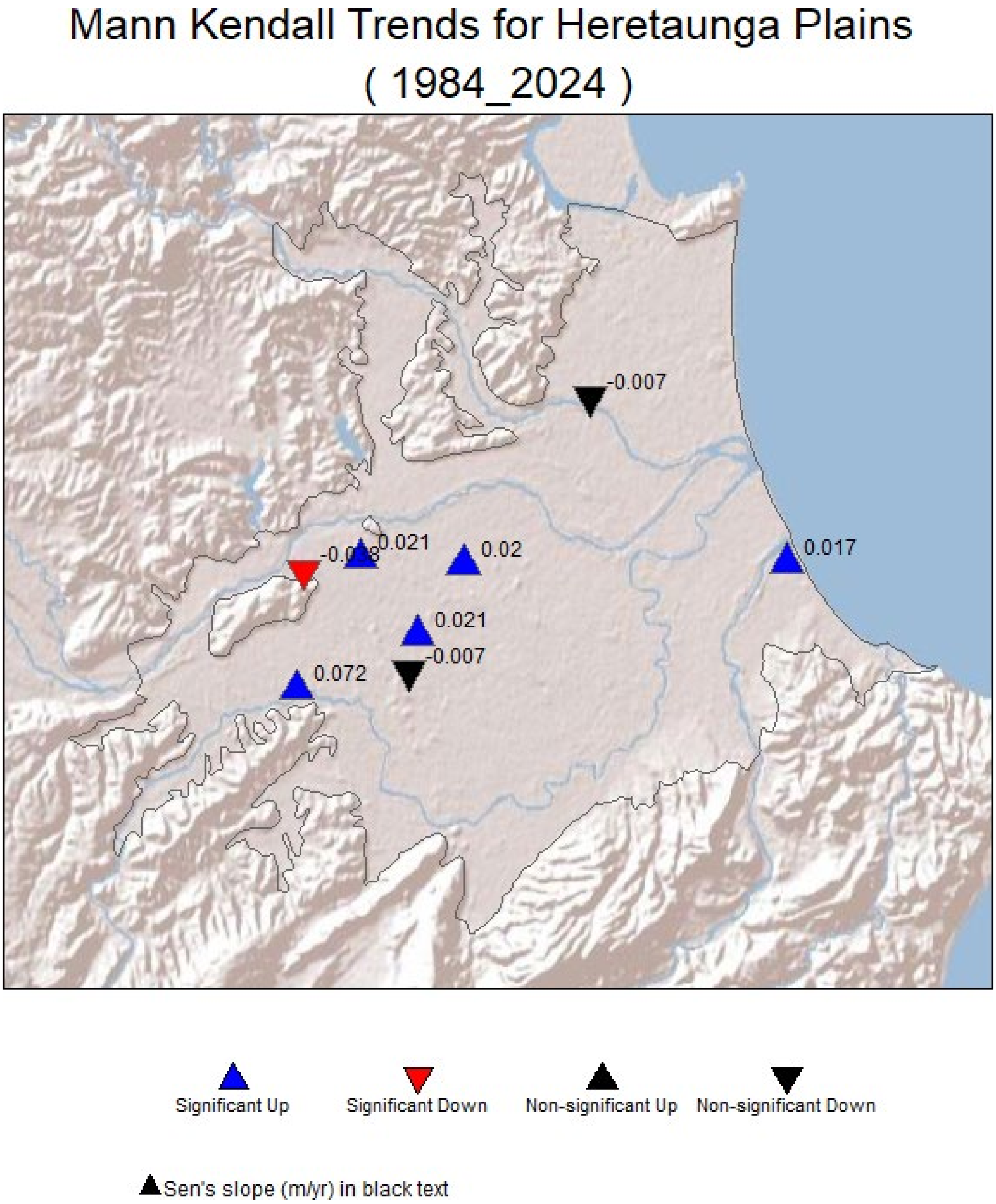


Figure 8-40: Groundwater level trends on the Heretaunga Plains for the 40-year period beween 1984-2024.

NO DATA

Figure 8-41: Groundwater level trends on the Ruataniwha Plains for the 10-year period beween 1984-1994.

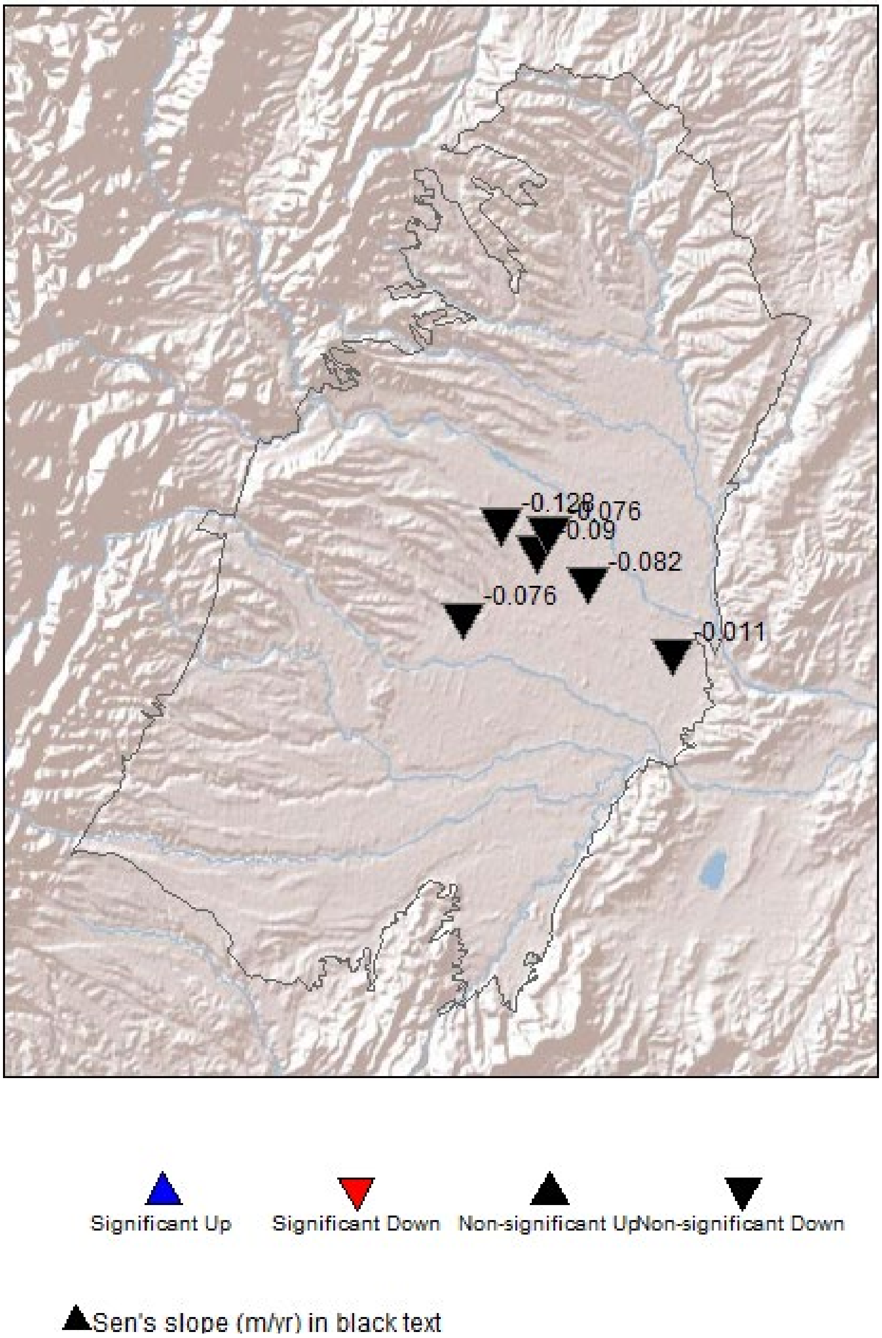


Figure 8-42: Groundwater level trends on the Ruataniwha Plains for the 10-year period beween 1994-2004.

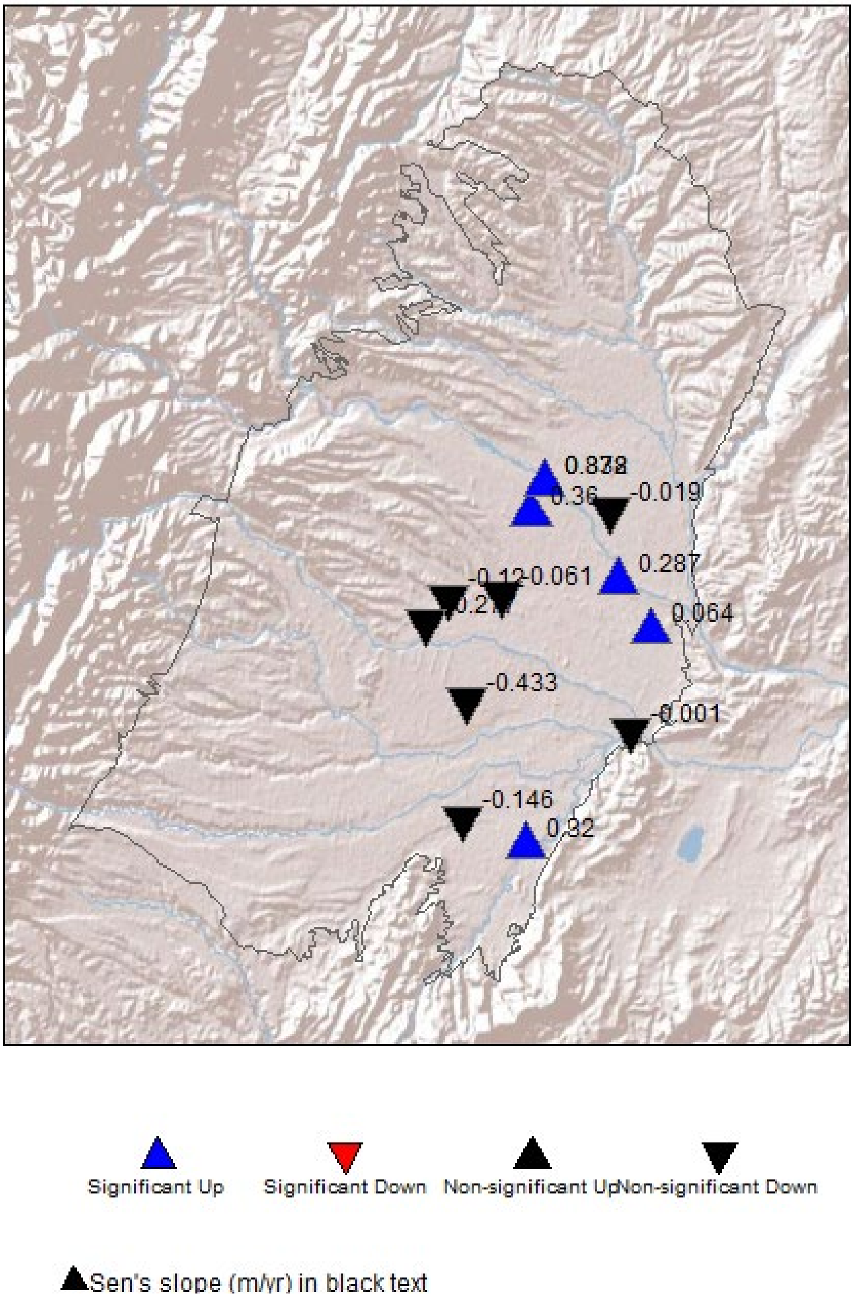


Figure 8-43: Groundwater level trends on the Ruataniwha Plains for the 10-year period beween 2004-2014.

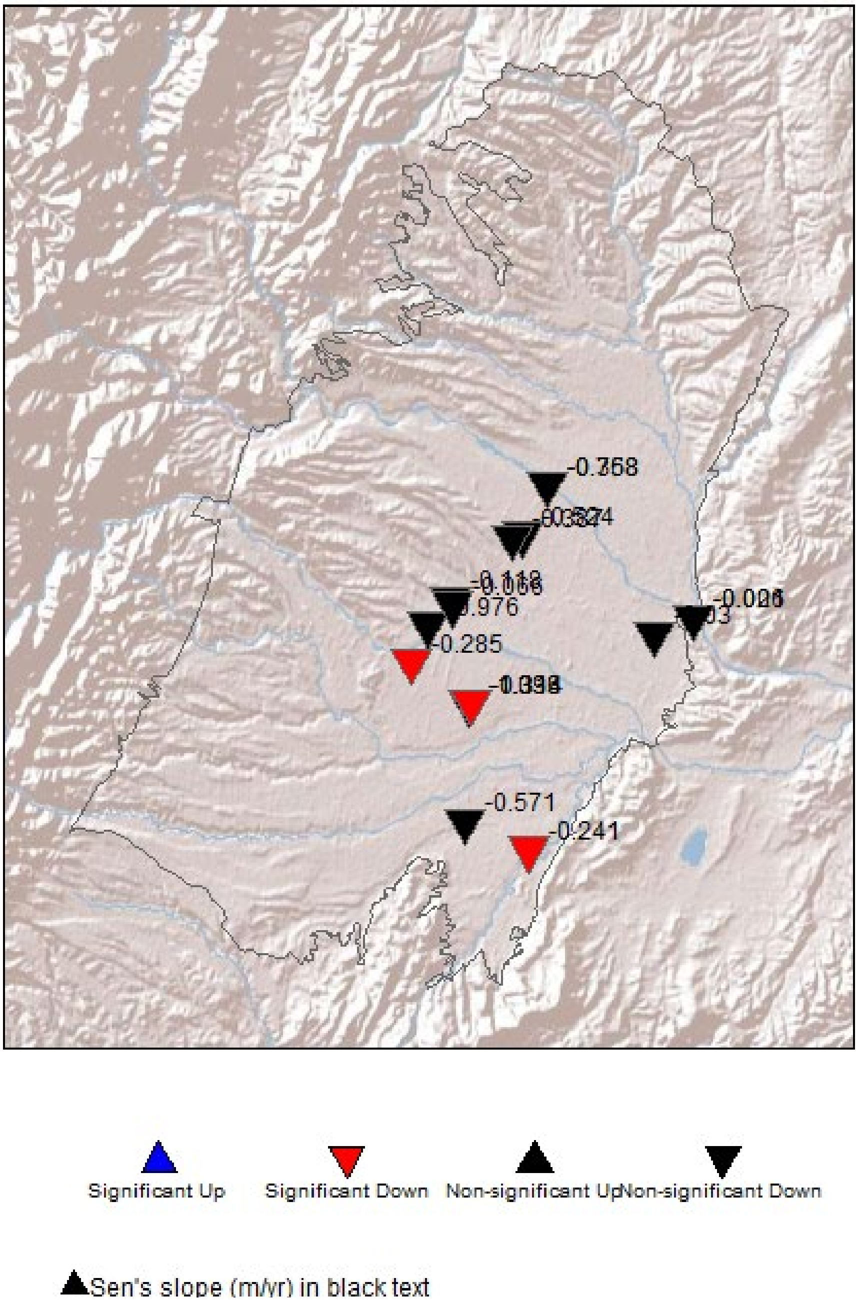


Figure 8-44: Groundwater level trends on the Ruataniwha Plains for the 10-year period beween 2014-2024.

NO DATA

Figure 8-45: Groundwater level trends on the Ruataniwha Plains for the 20-year period beween 1984-2004.

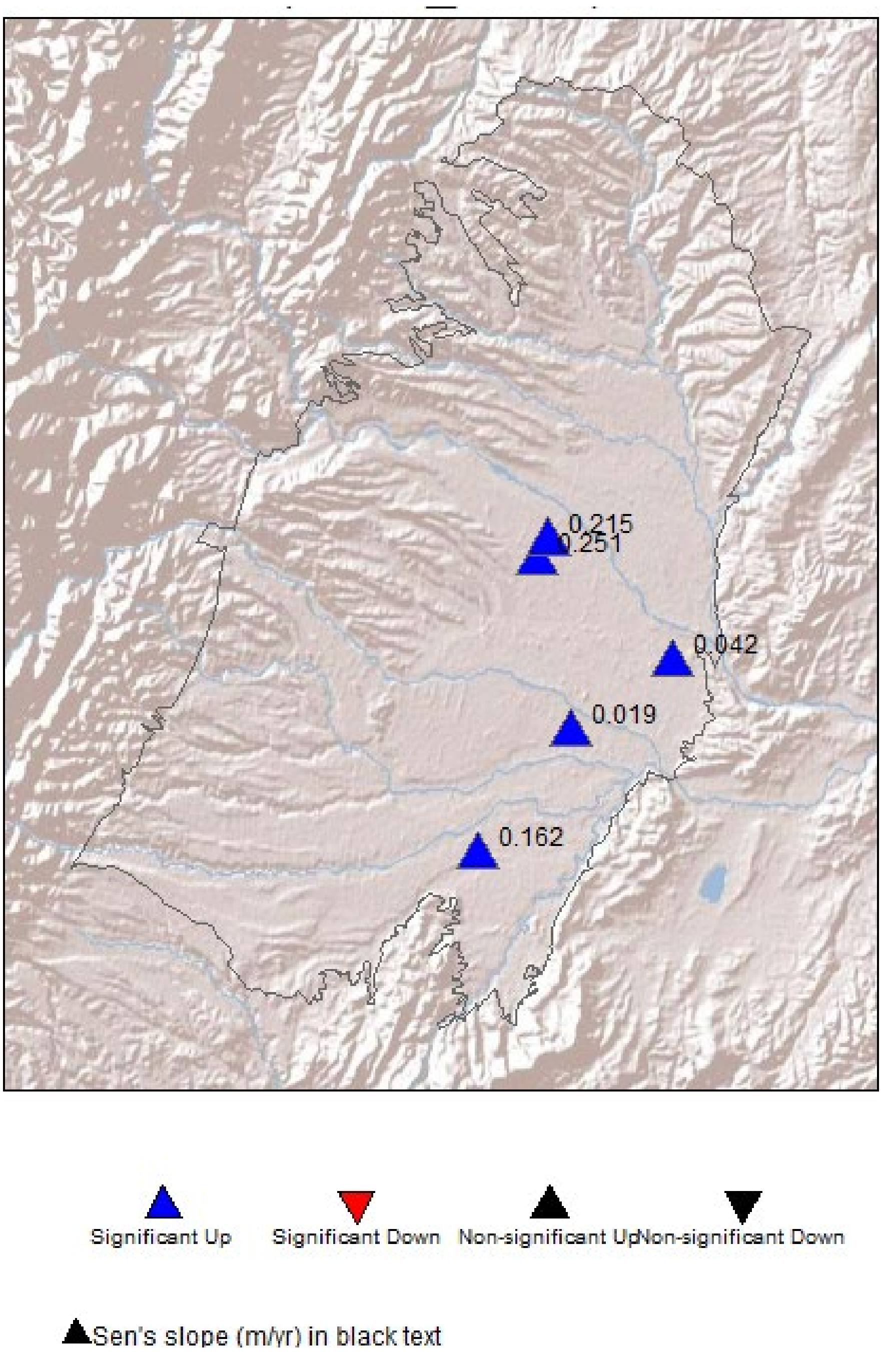


Figure 8-46: Groundwater level trends on the Ruataniwha Plains for the 20-year period beween 1994-2014.

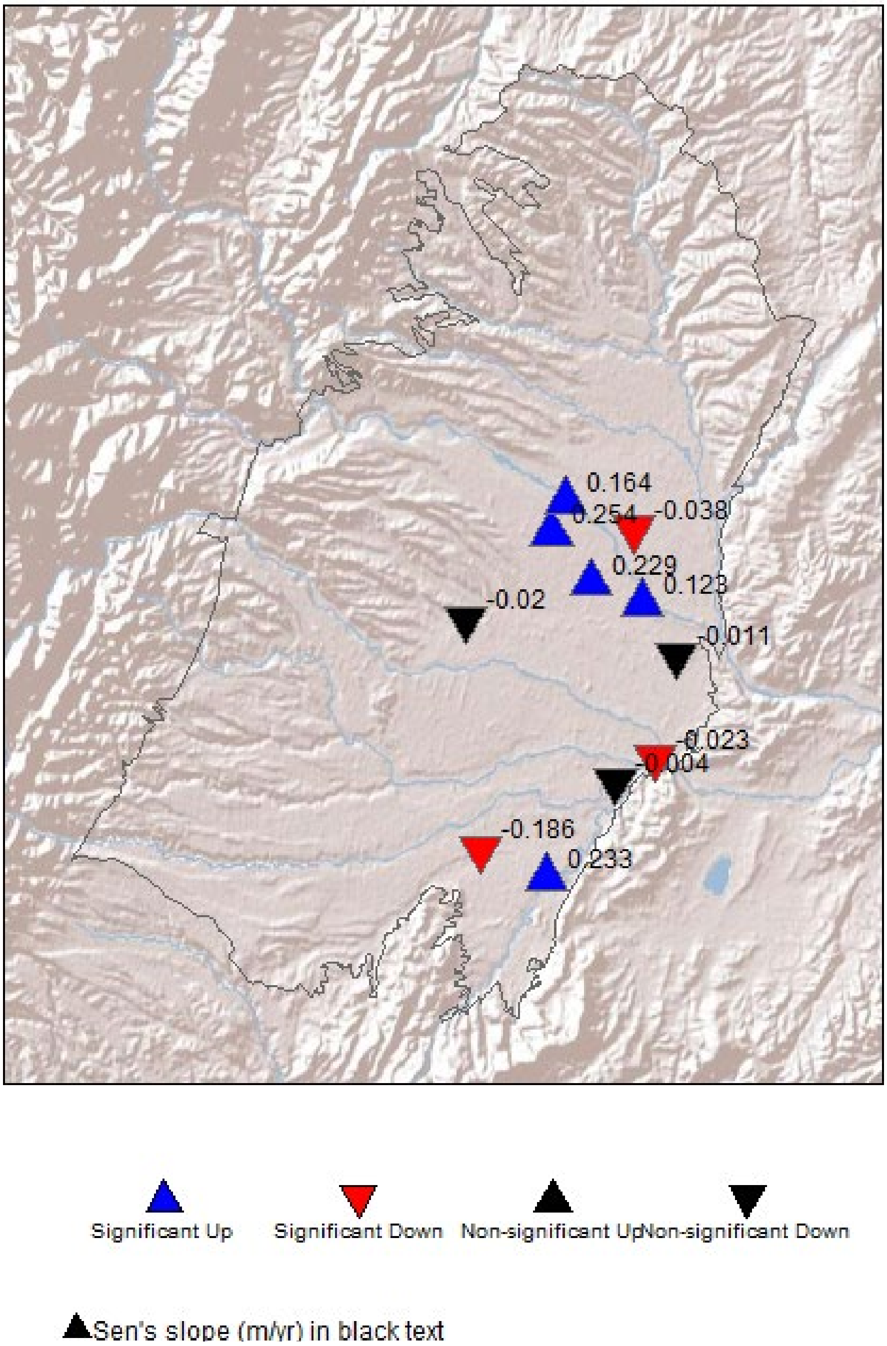


Figure 8-47: Groundwater level trends on the Ruataniwha Plains for the 20-year period beween 2004-2024.

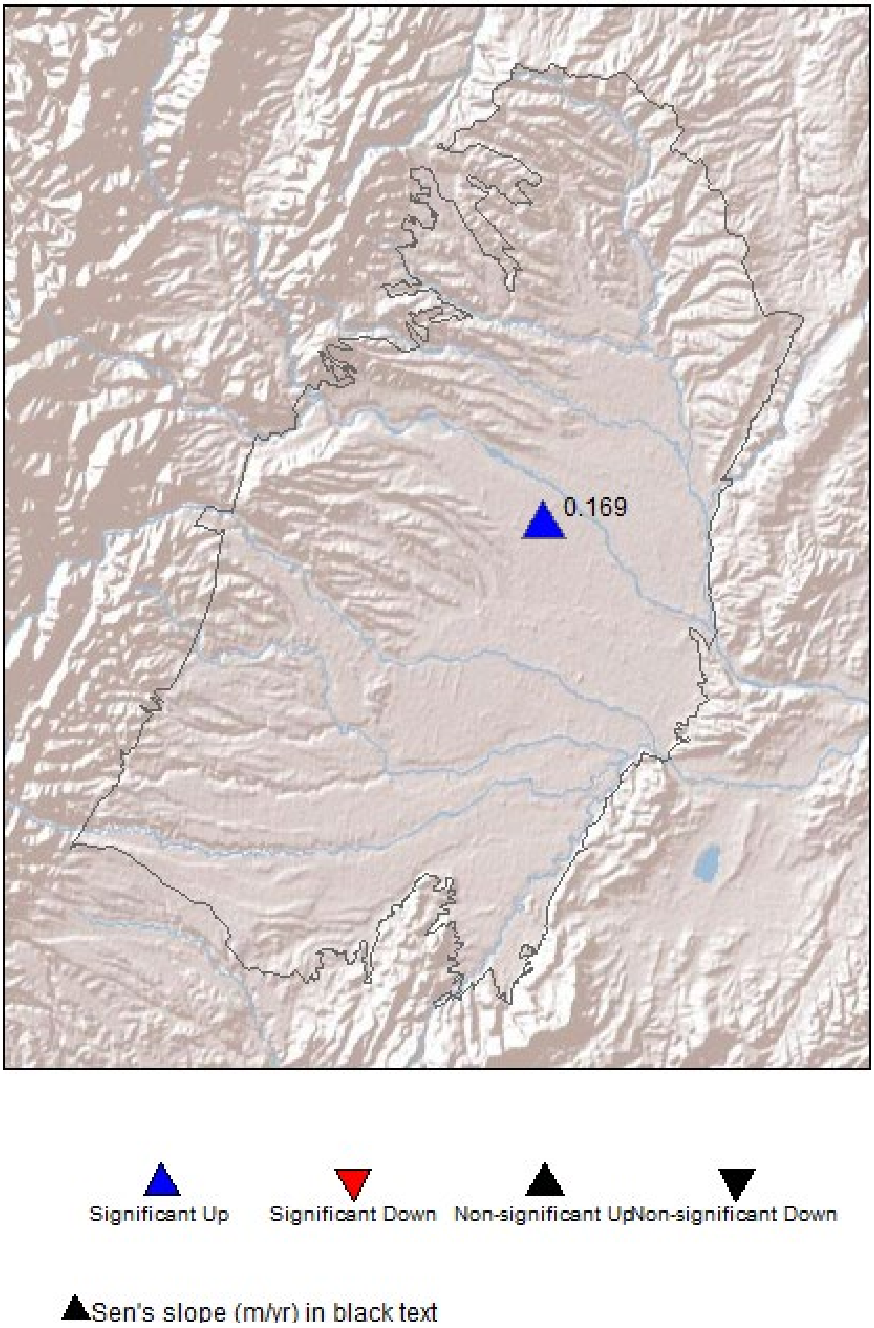
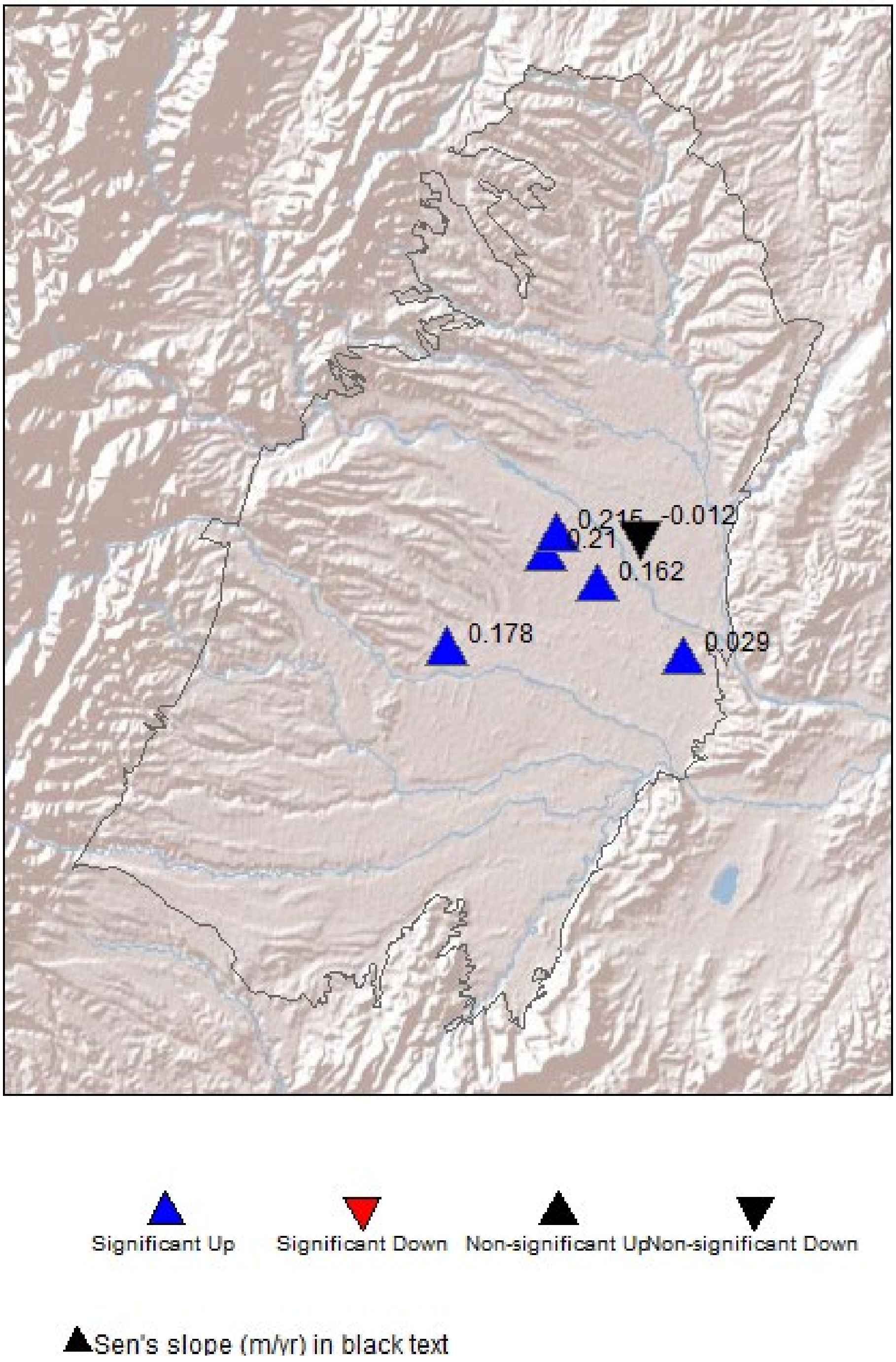


Figure 8-48: Groundwater level trends on the Ruataniwha Plains for the 30-year period beween 1984-2014.



igure 8-49: Groundwater level trends on the Ruataniwha Plains for the 30-year period beween 1994-2024

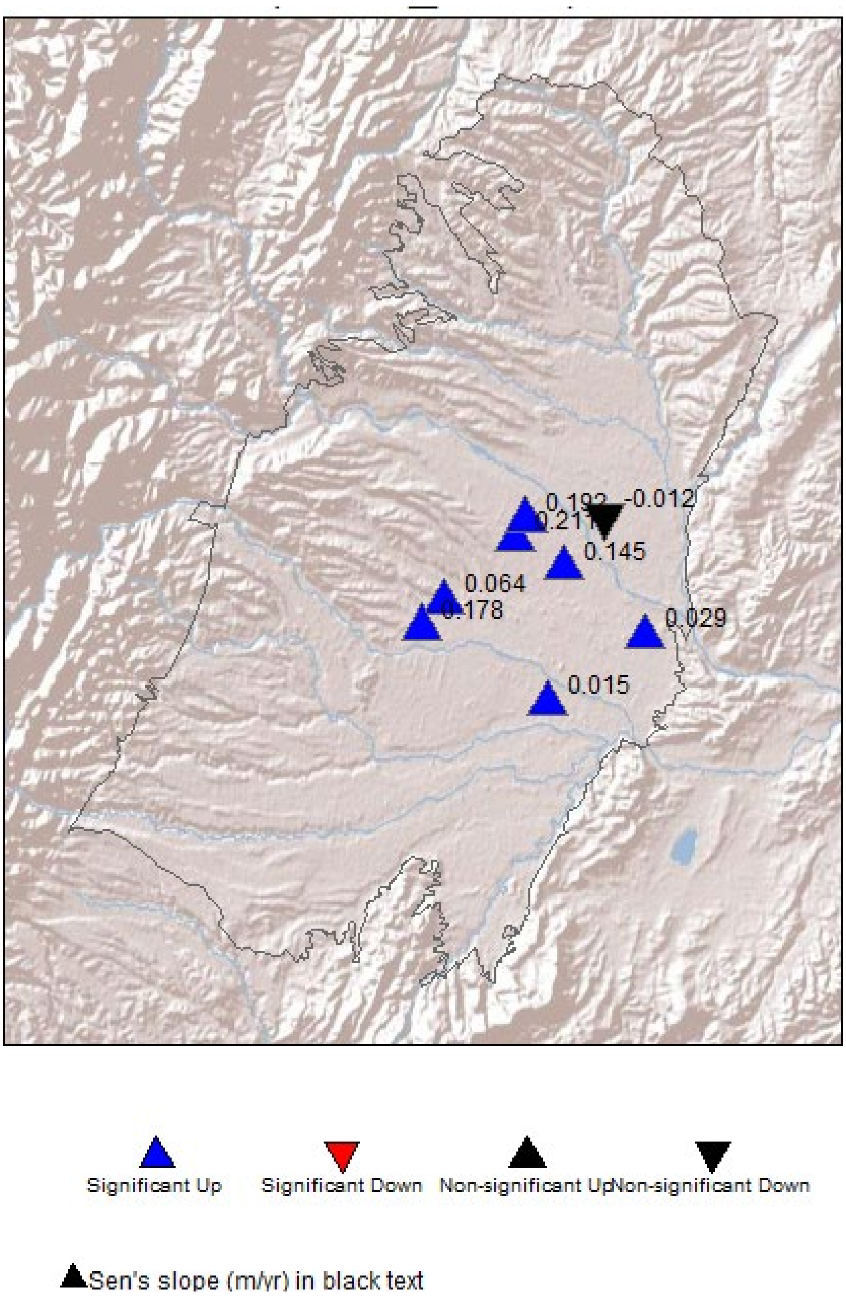


Figure 8-50: Groundwater level trends on the Ruataniwha Plains for the 40-year period beween 1984-2024.

NO DATA

Figure 8-51: Groundwater level trends on minor aquifers for the 10-year period beween 1984-1994.

NO DATA

Figure 8-52: Groundwater level trends on minor aquifers for the 10-year period beween 1994-2004.

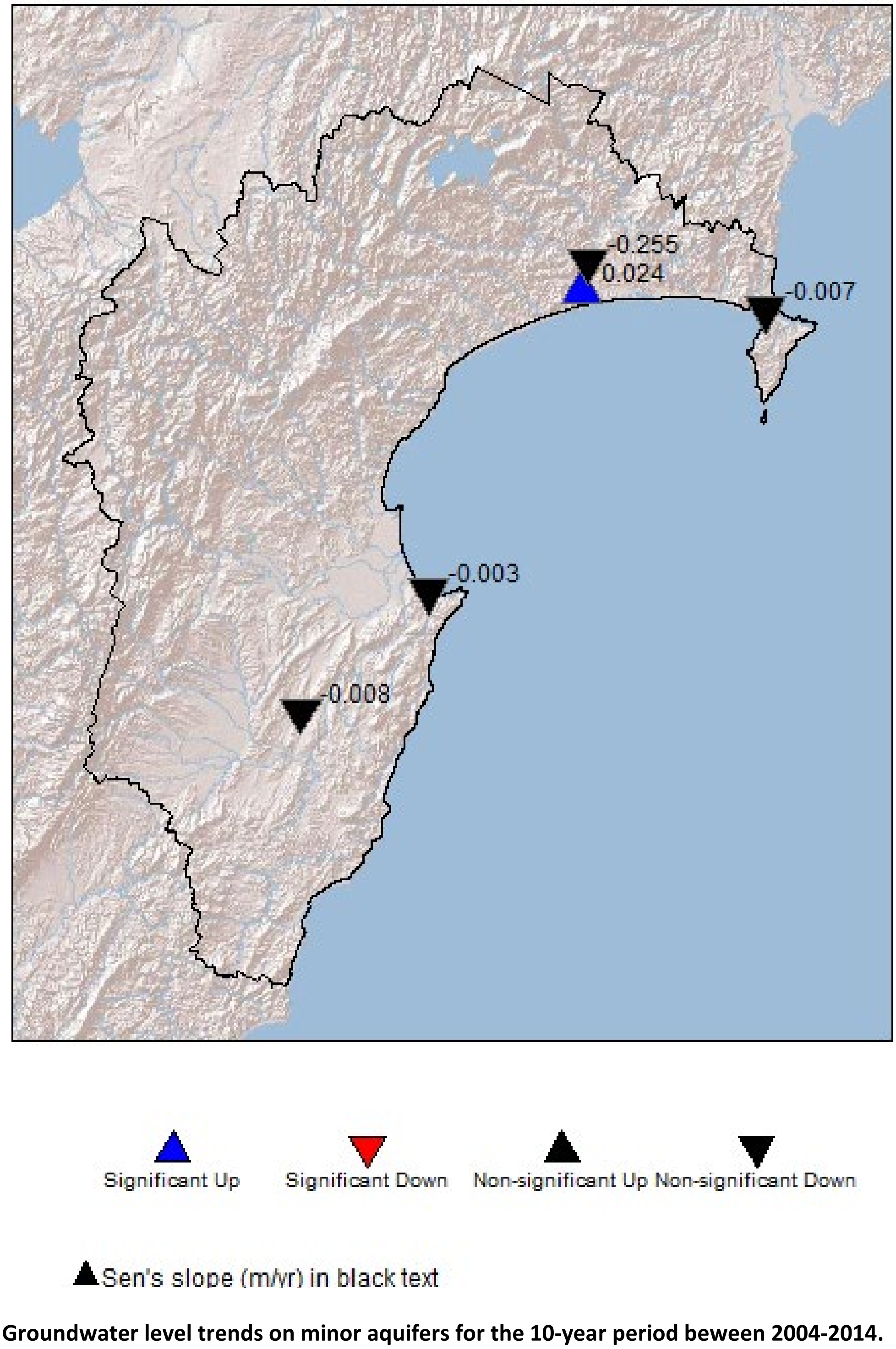


Figure 8-53: Groundwater level trends on minor aquifers for the 10-year period beween 2004-2014.

Figure 8-54: Groundwater level trends on minor aquifers for the 10-year period beween 2014-2024.

NO DATA

Figure 8-55: Groundwater level trends on minor aquifers for the 20-year period beween 1984-2004.

NO DATA

Figure 8-56: Groundwater level trends on minor aquifers for the 20-year period beween 1994-2014.

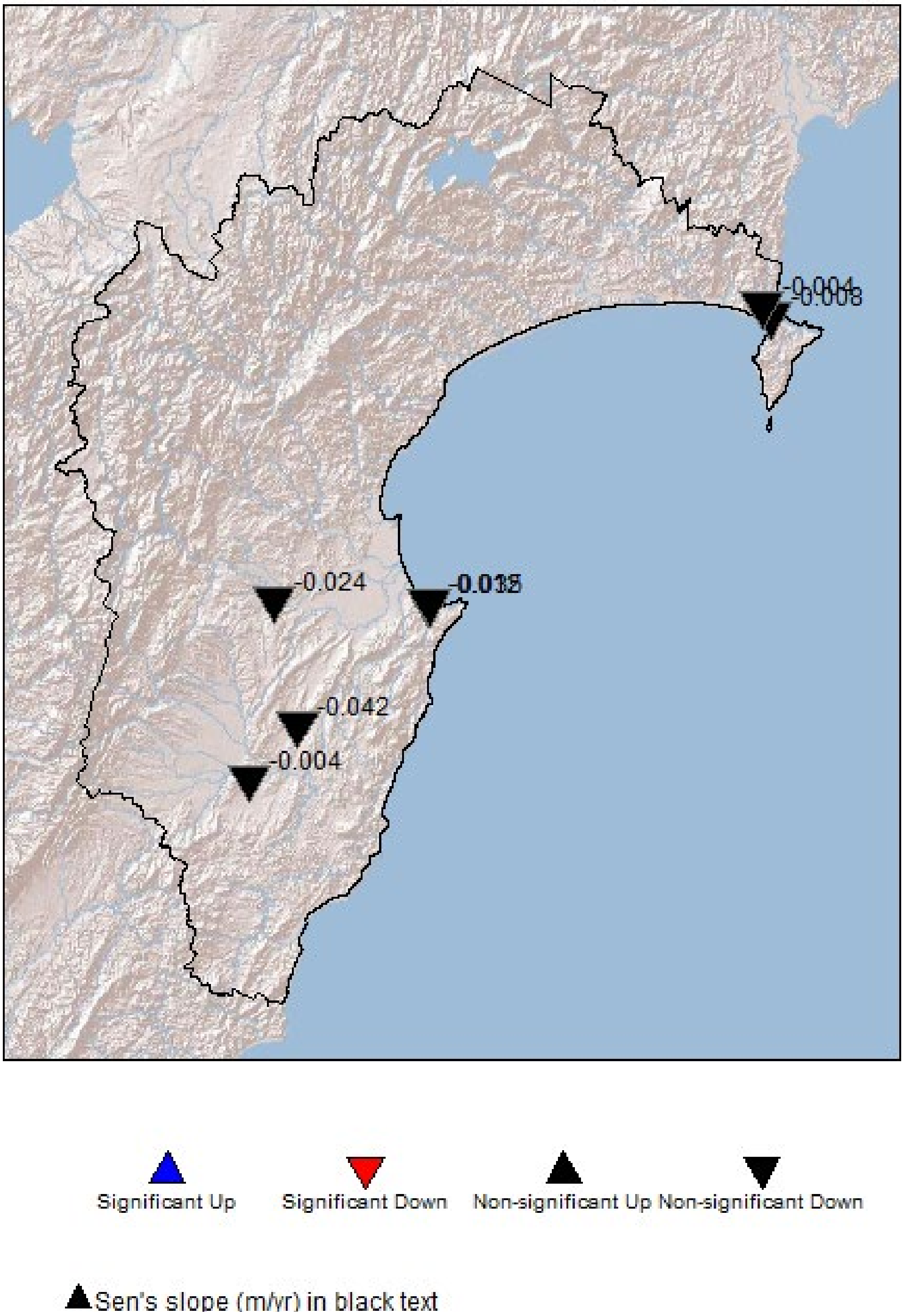


Figure 8-57: Groundwater level trends on minor aquifers for the 20-year period beween 2004-2024.

NO DATA

Figure 8-58: Groundwater level trends on minor aquifers for the 30-year period beween 1984-2014.

NO DATA

Figure 8-59: Groundwater level trends on minor aquifers for the 30-year period beween 1994-2024.

NO DATA

Figure 8-60: Groundwater level trends on minor aquifers for the 40-year period beween 1984-2024.

8.3 Seasonal-Kendall trend results – changes in long-term groundwater levels

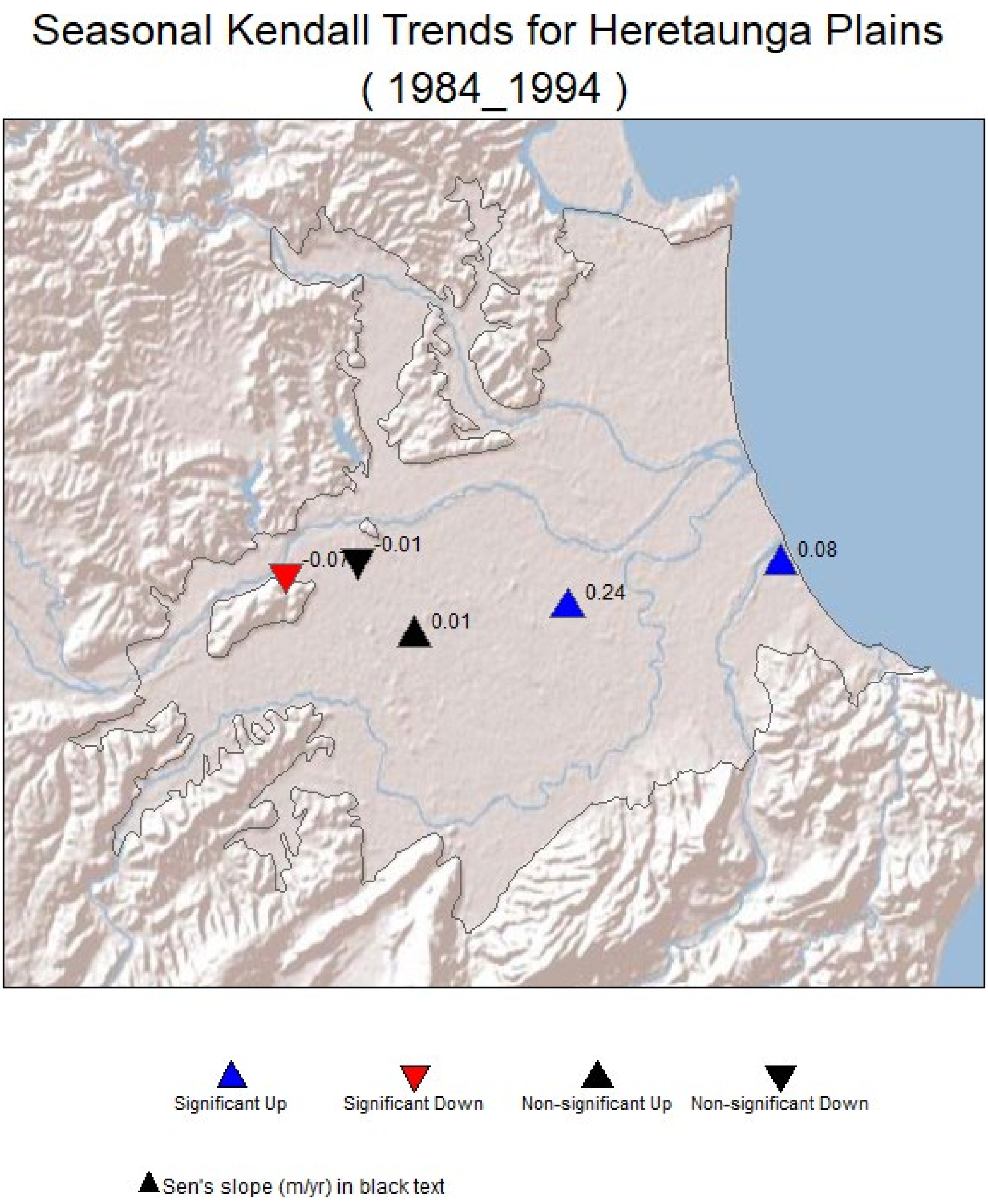


Figure 8-61: Groundwater level trends on the Heretaunga Plains for the 10-year period beween 1984-1994.

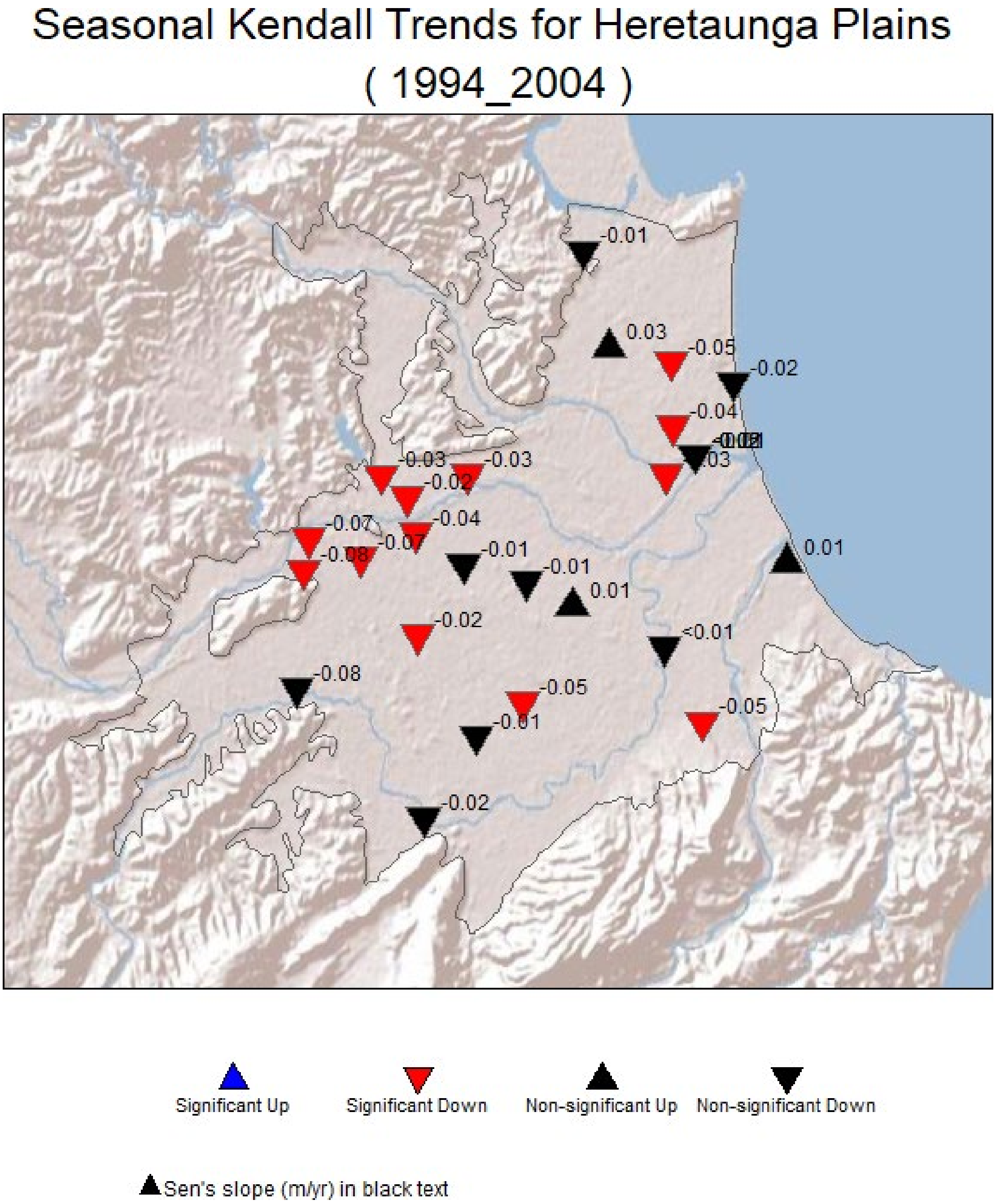


Figure 8-62: Groundwater level trends on the Heretaunga Plains for the 10-year period beween 1994-2004.

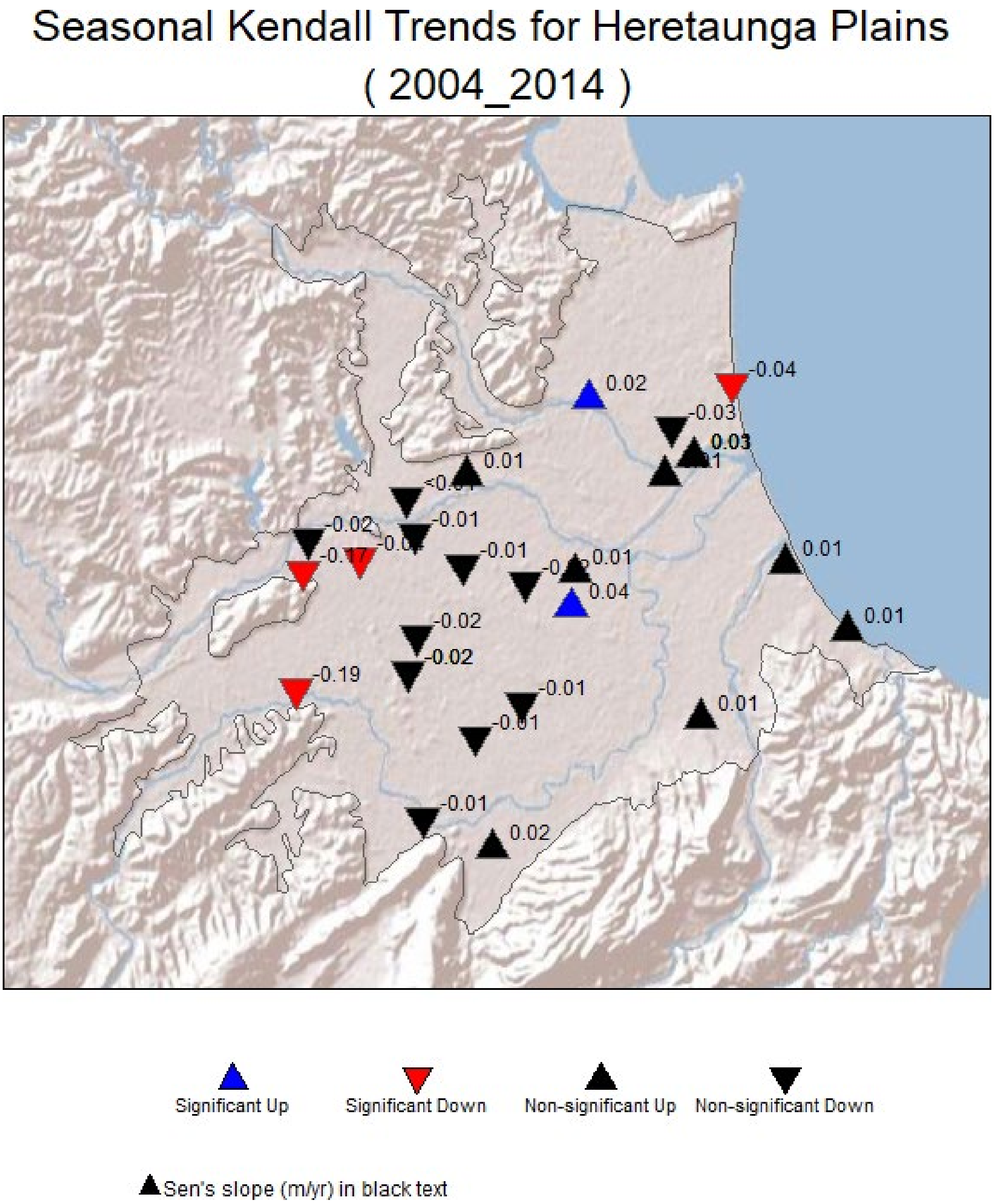


Figure 8-63: Groundwater level trends on the Heretaunga Plains for the 10-year period beween 2004-2014.

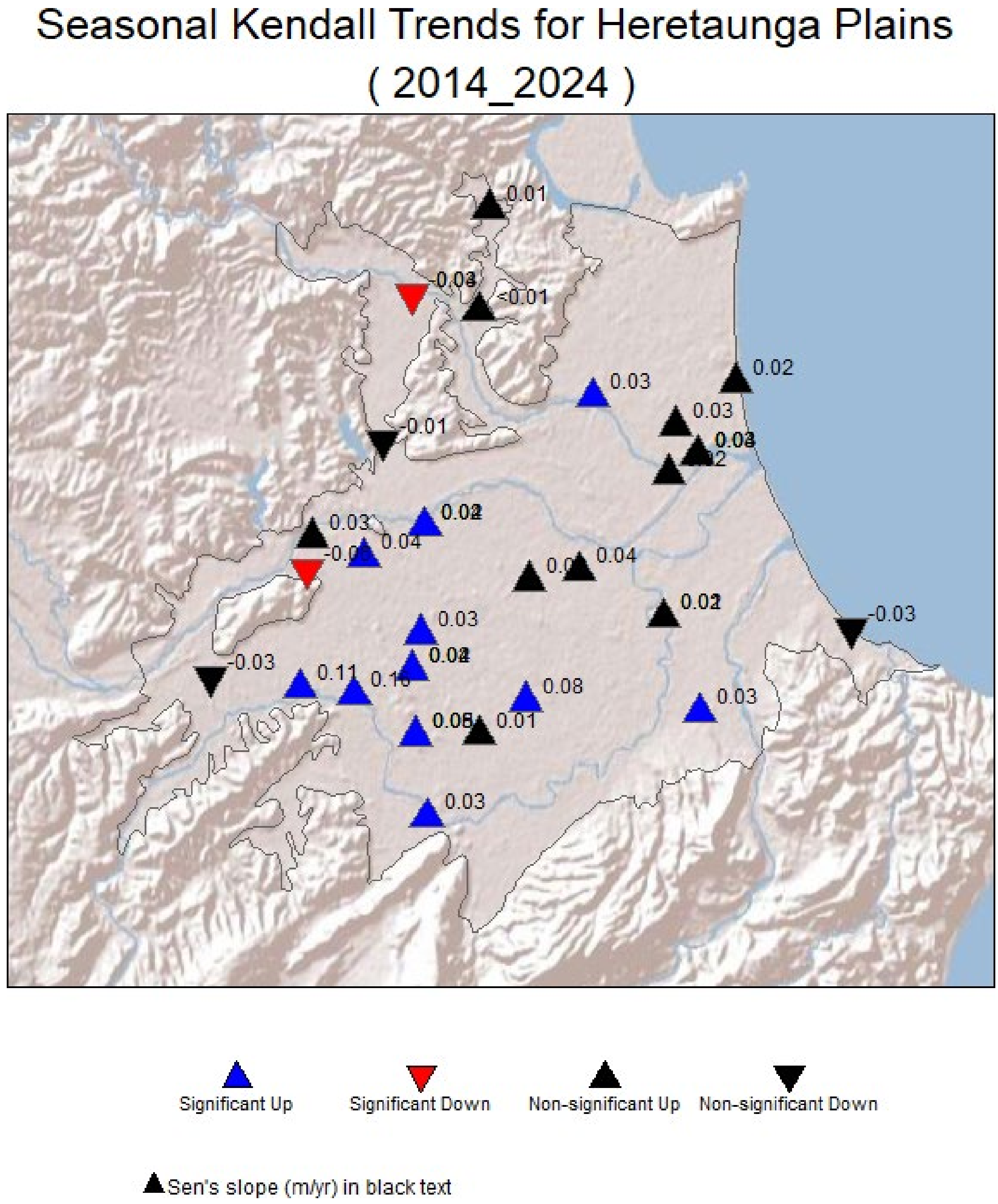


Figure 8-64: Groundwater level trends on the Heretaunga Plains for the 10-year period beween 2014-2024.

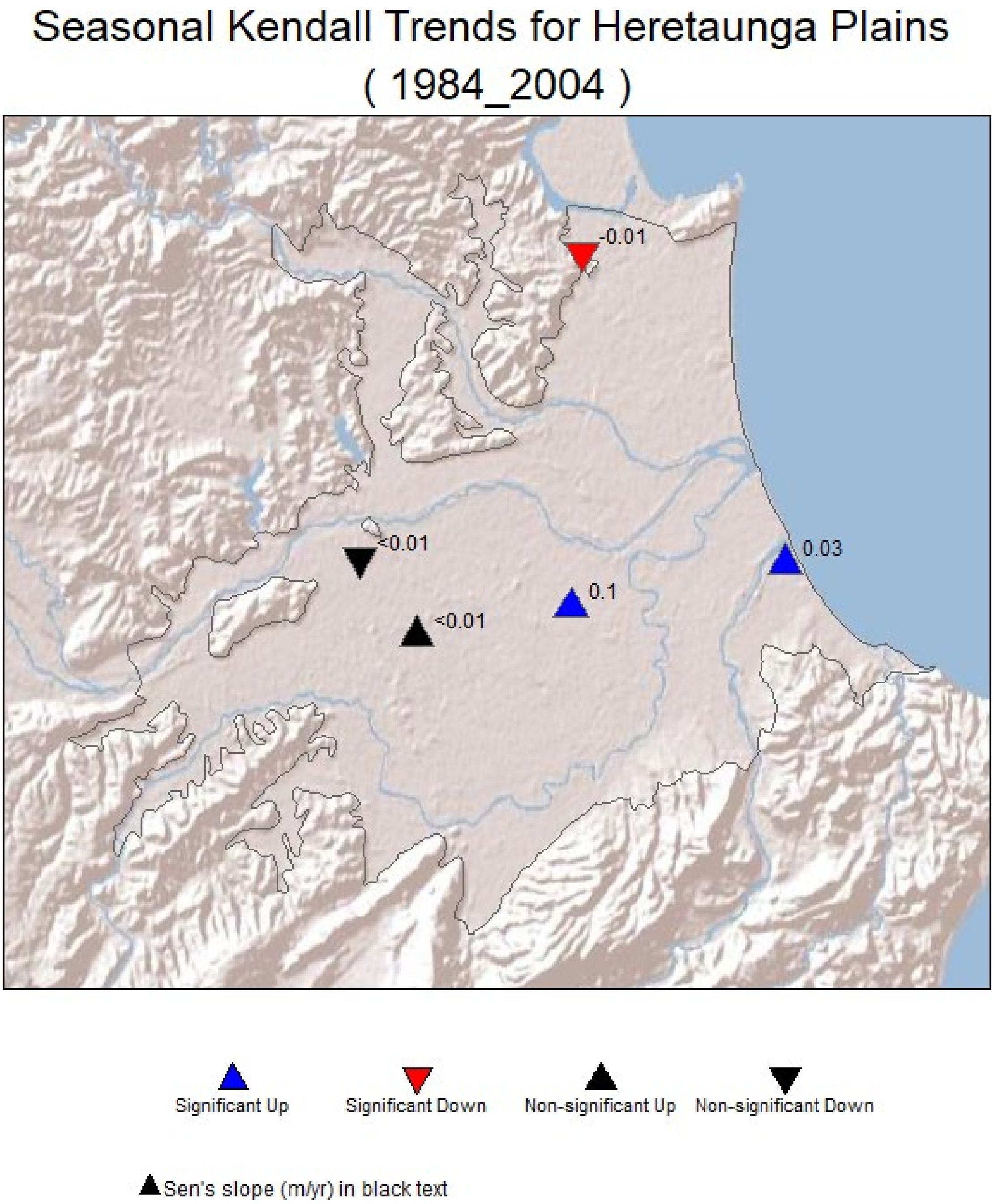


Figure 8-65: Groundwater level trends on the Heretaunga Plains for the 20-year period beween 1984-2004.

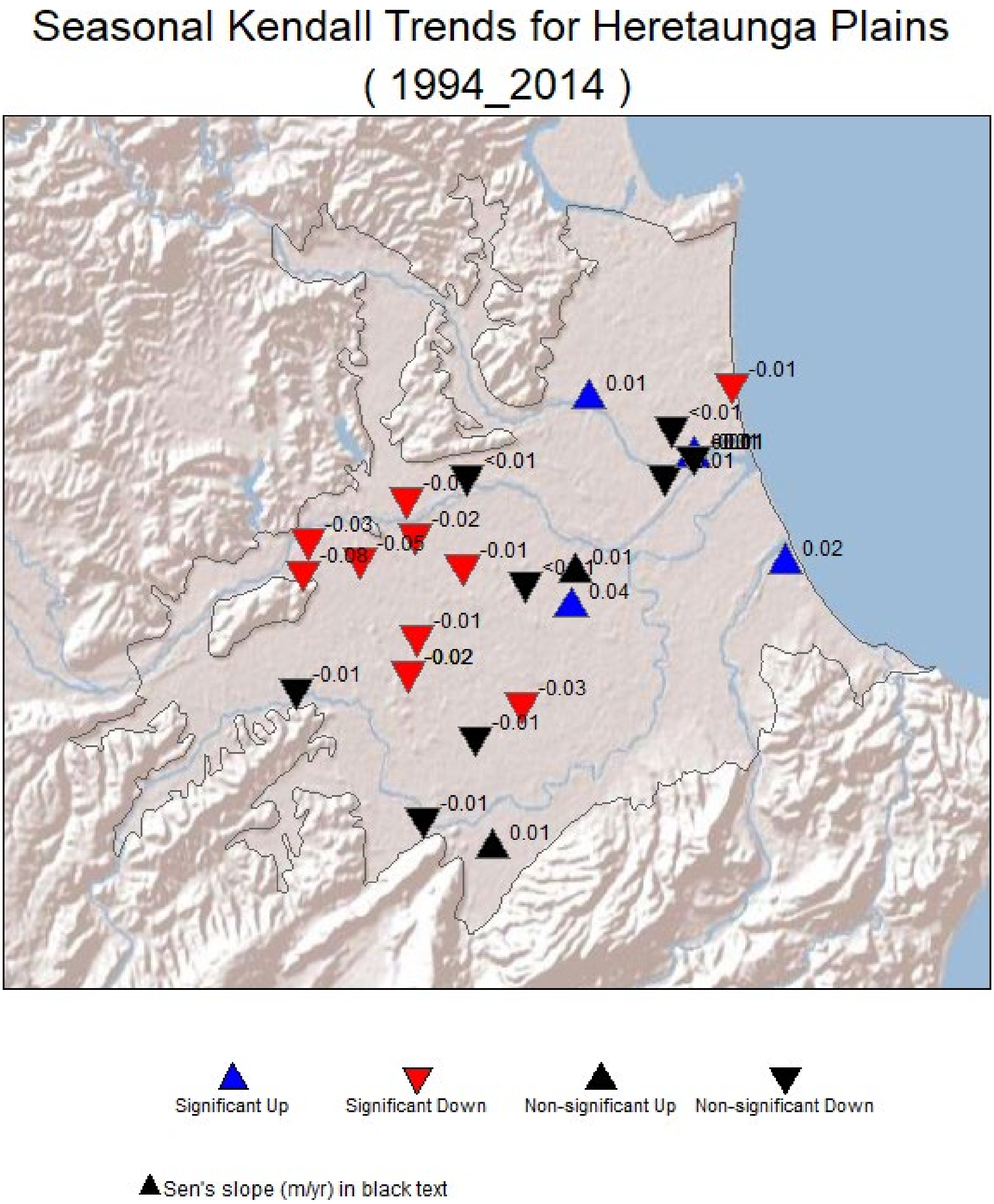


Figure 8-66: Groundwater level trends on the Heretaunga Plains for the 20-year period beween 1994-2014.

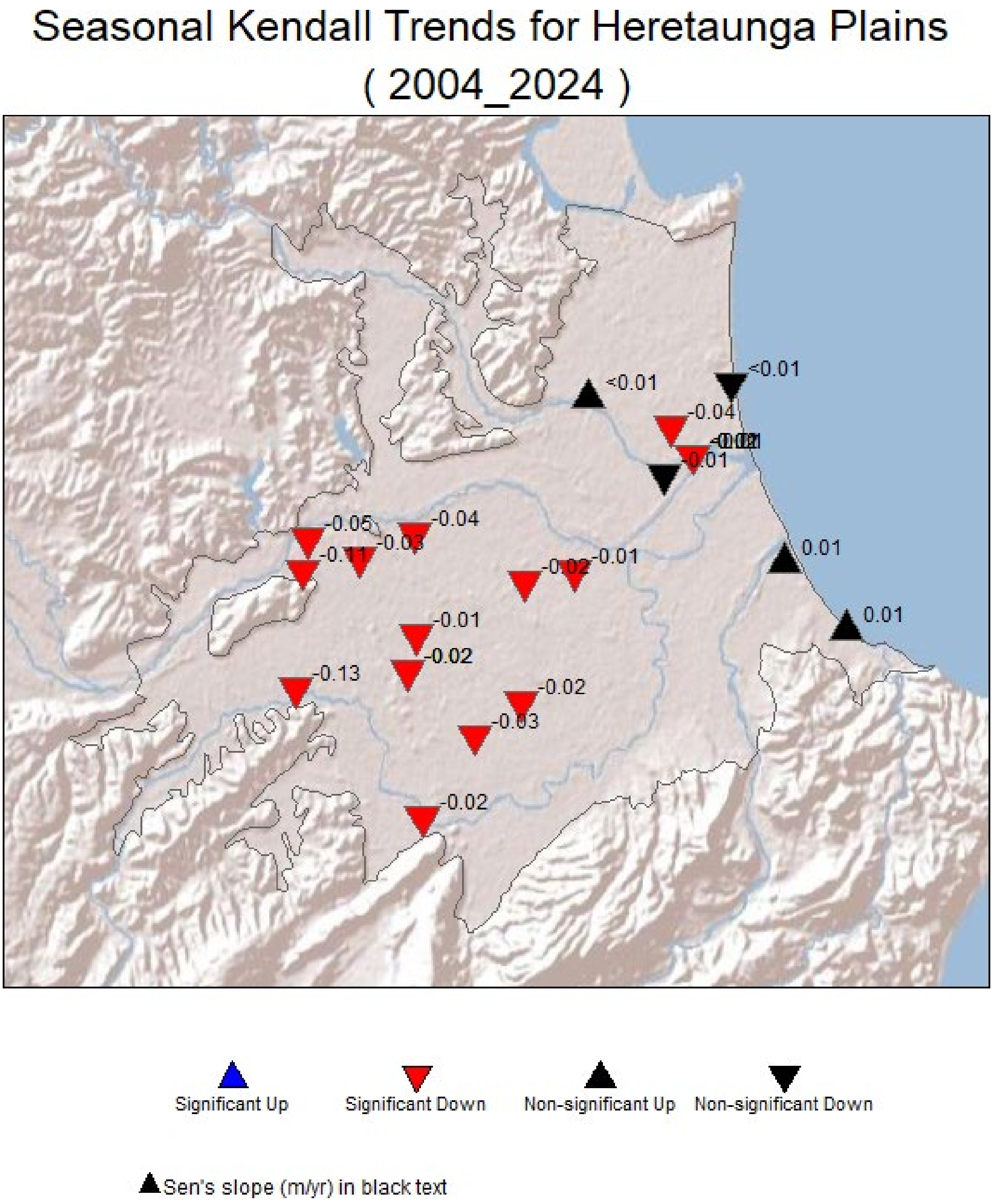


Figure 8-67: Groundwater level trends on the Heretaunga Plains for the 20-year period beween 2004-2024.

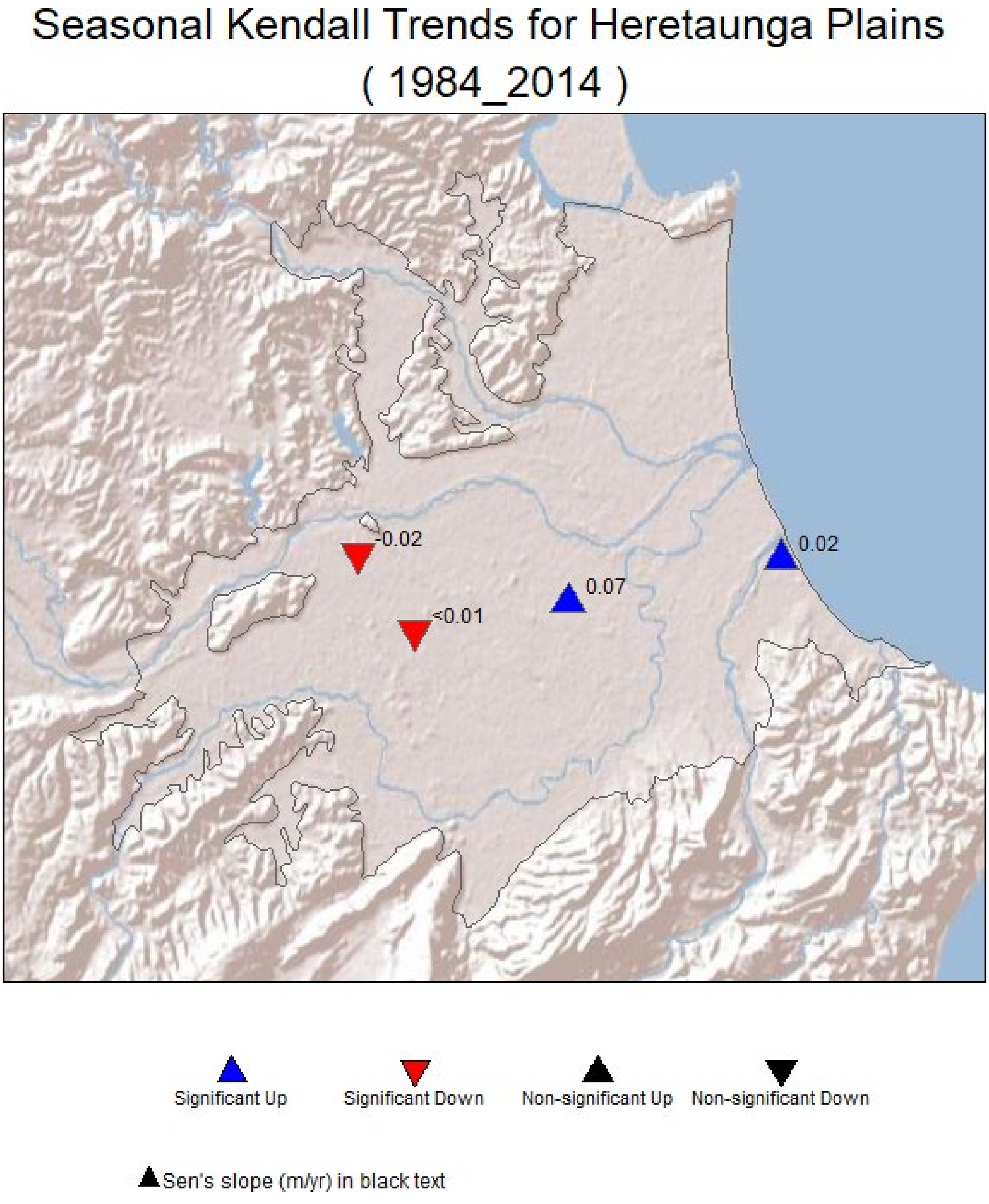


Figure 8-68: Groundwater level trends on the Heretaunga Plains for the 30-year period beween 1984-2014.

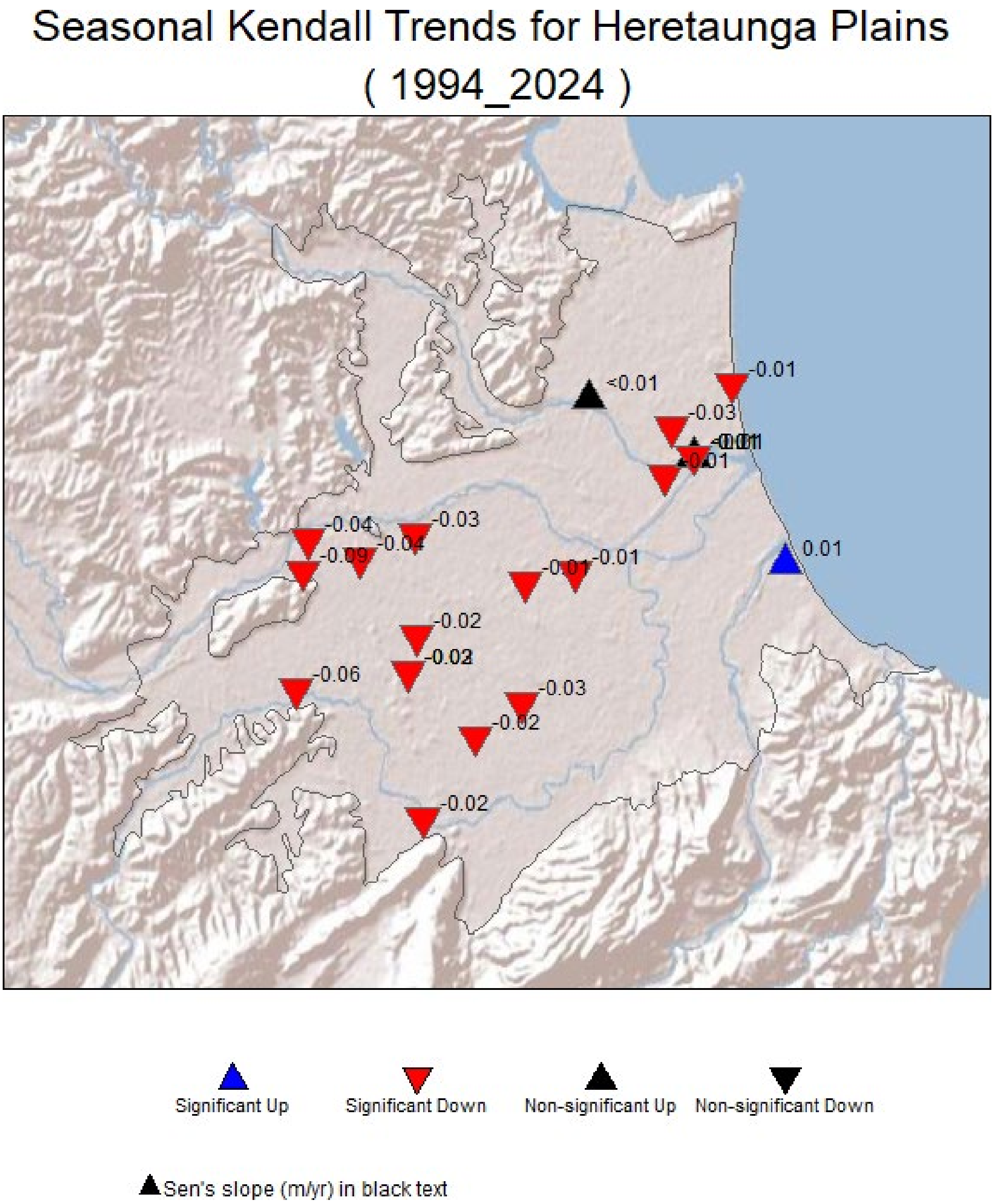


Figure 8-69: Groundwater level trends on the Heretaunga Plains for the 30-year period beween 1994-2024.

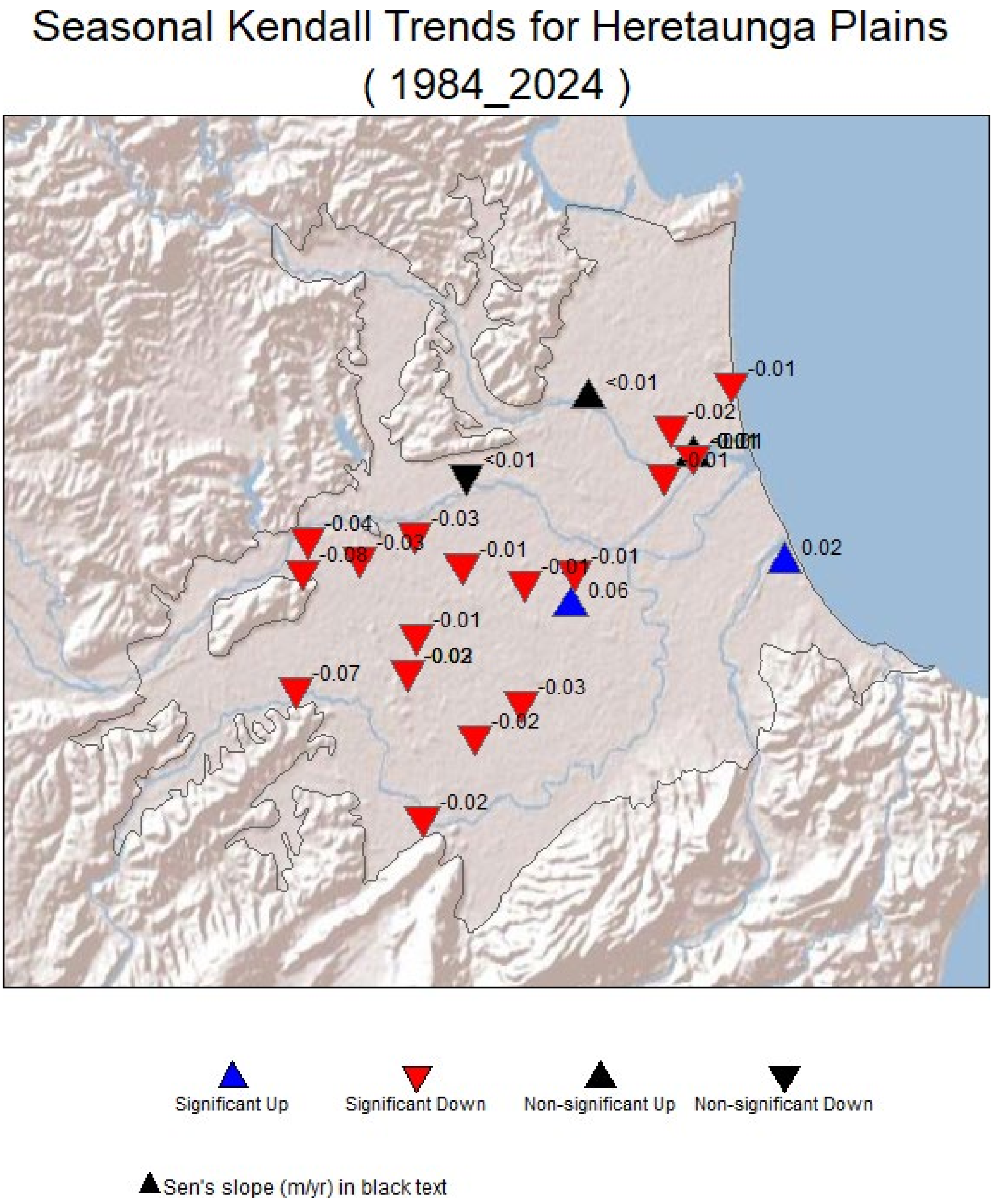


Figure 8-70: Groundwater level trends on the Heretaunga Plains for the 40-year period beween 1984-2024.

NO DATA

Figure 8-71: Groundwater level trends on the Ruataniwha Plains for the 10-year period beween 1984-1994.

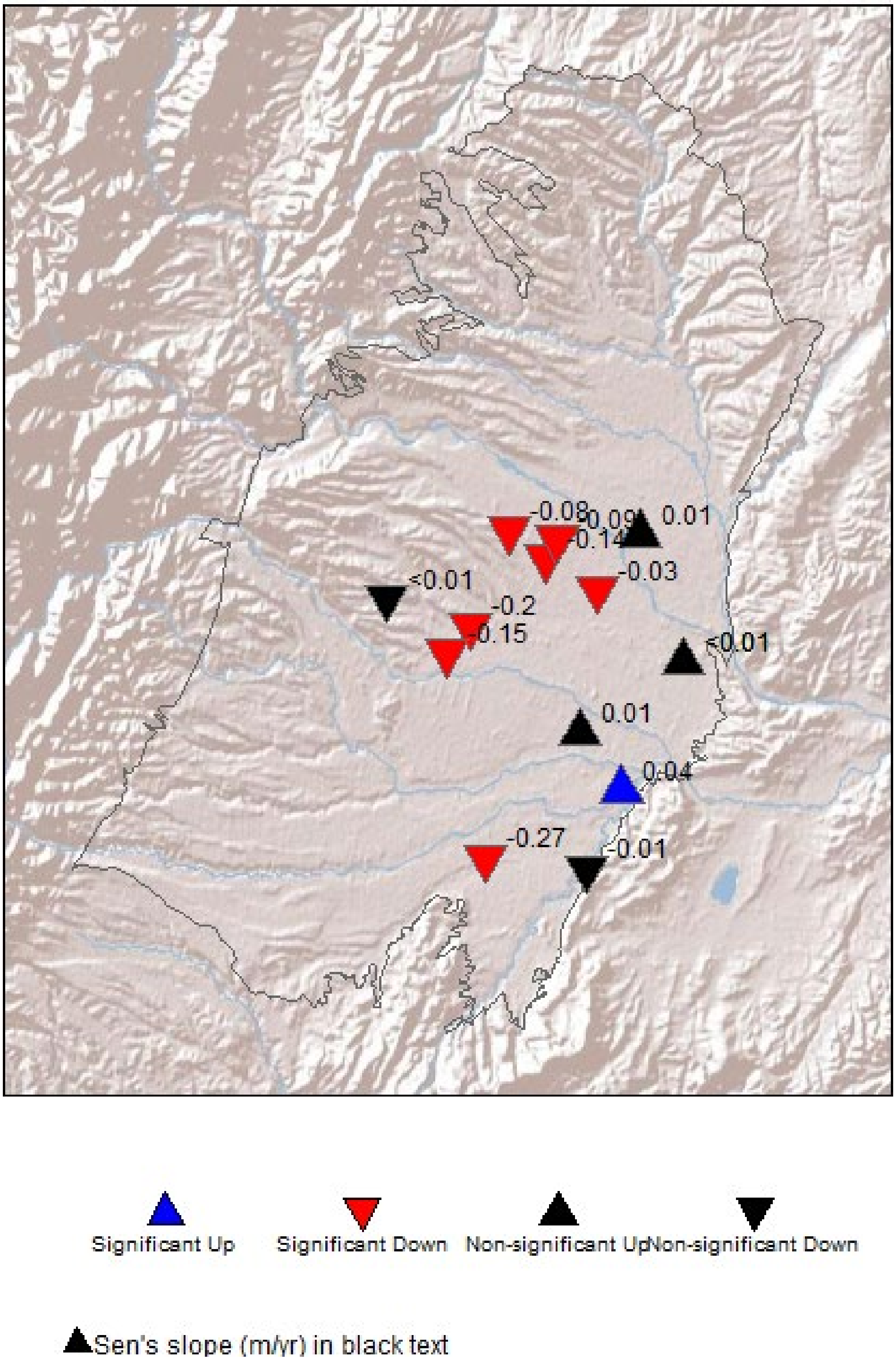


Figure 8-72: Groundwater level trends on the Ruataniwha Plains for the 10-year period beween 1994-2004.

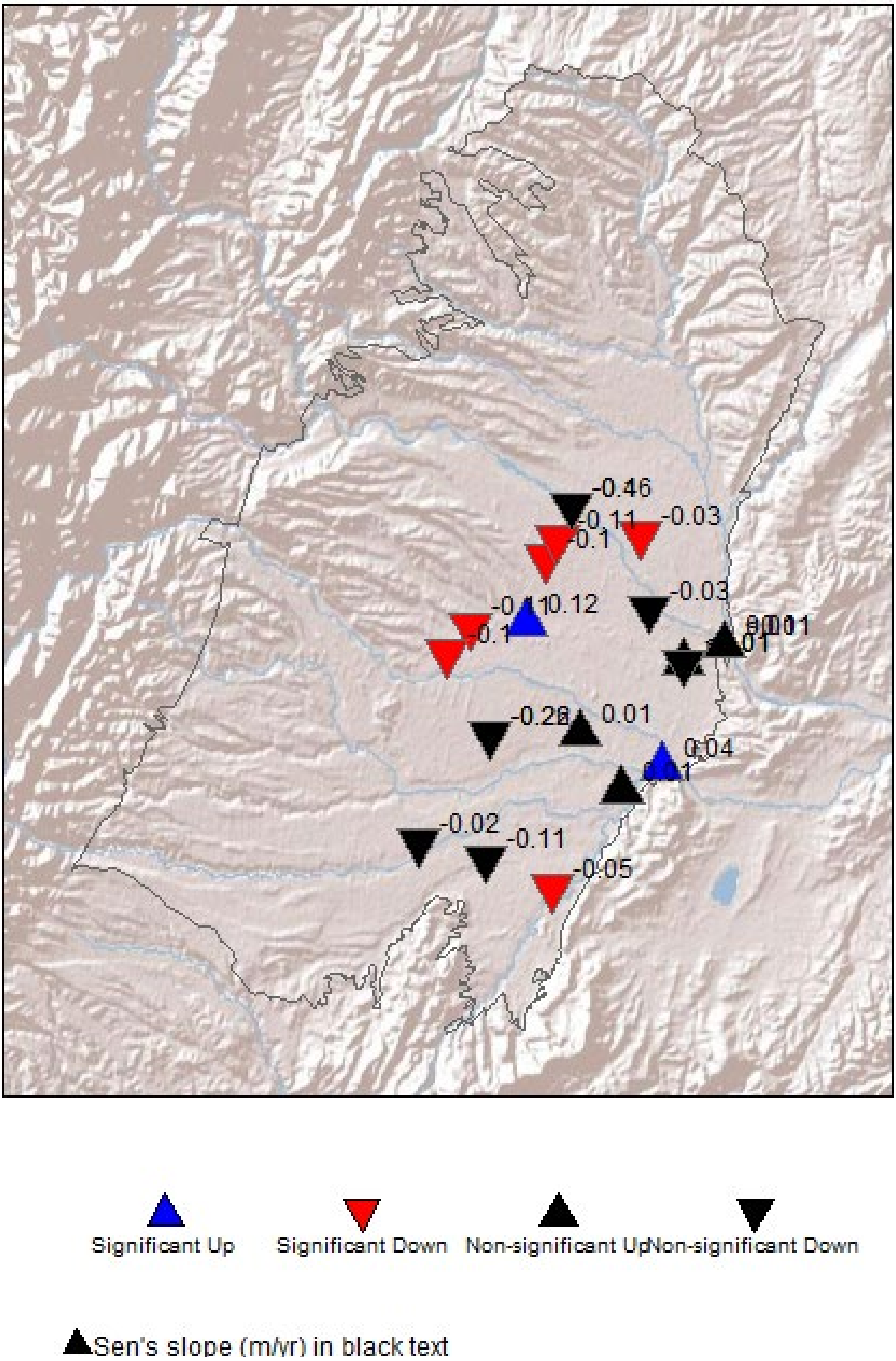


Figure 8-73: Groundwater level trends on the Ruataniwha Plains for the 10-year period beween 2004-2014.

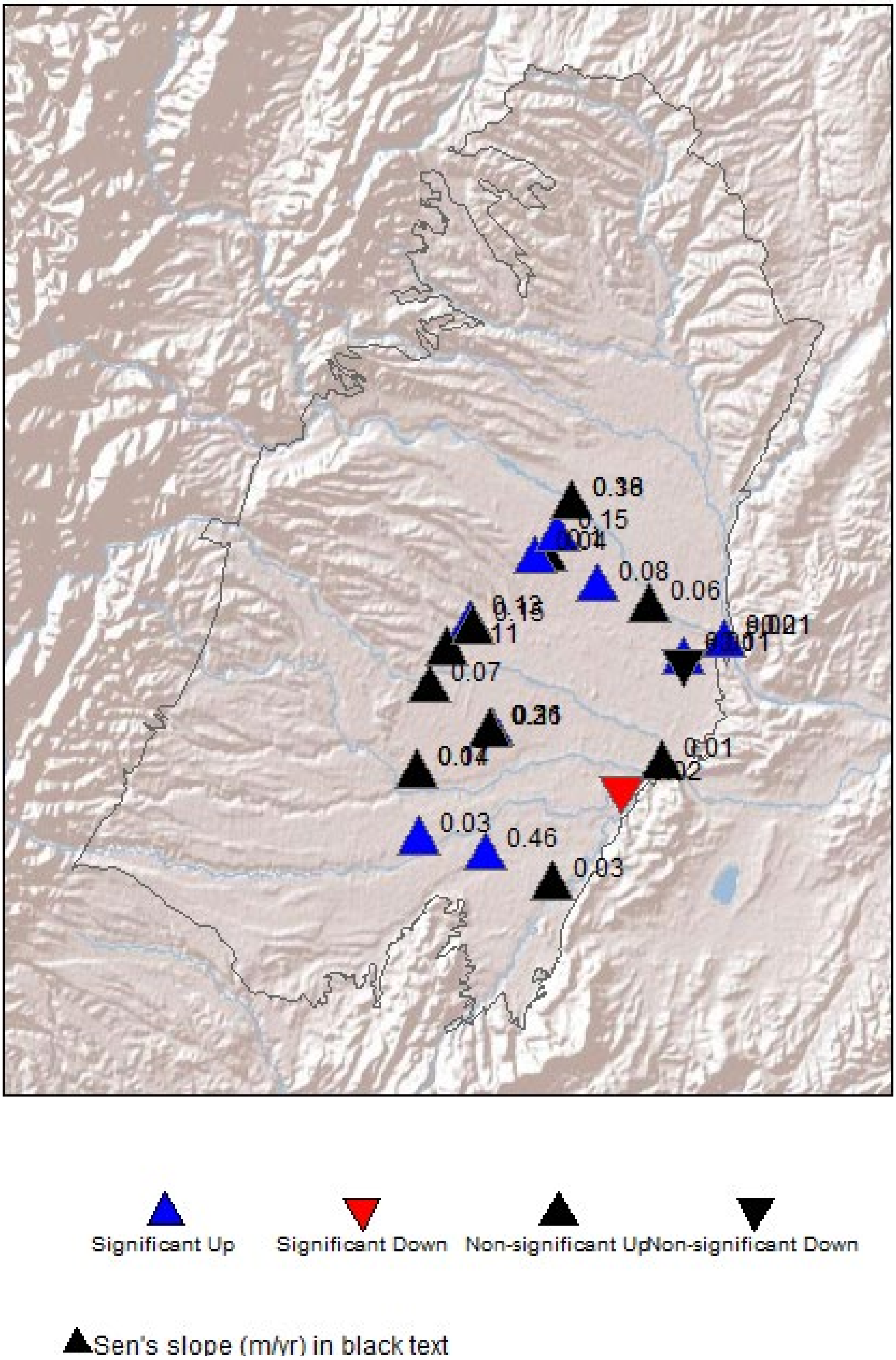


Figure 8-74: Groundwater level trends on the Ruataniwha Plains for the 10-year period beween 2014-2024.

NO DATA

Figure 8-75: Groundwater level trends on the Ruataniwha Plains for the 20-year period beween 1984-2004.

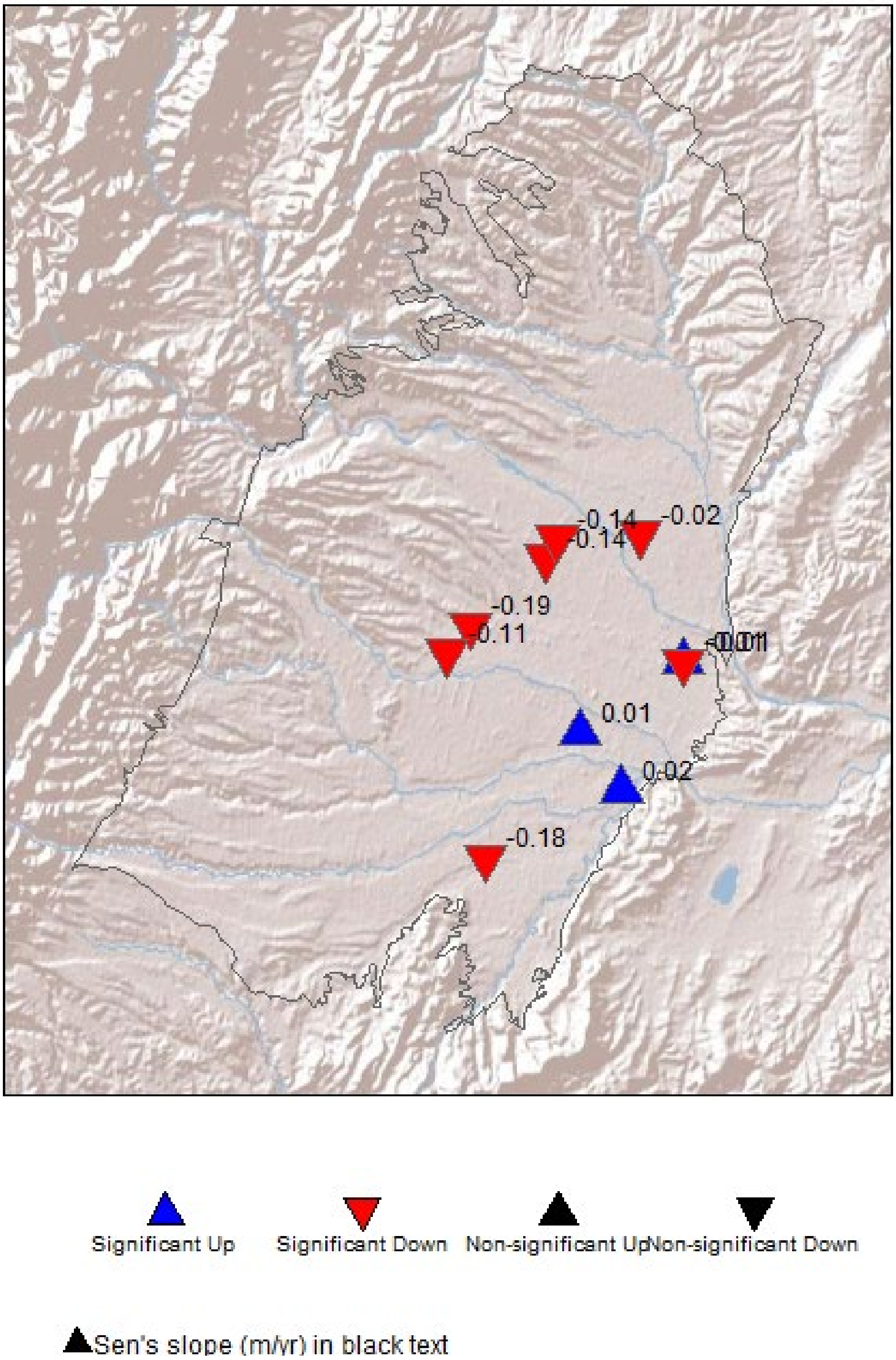


Figure 8-76: Groundwater level trends on the Ruataniwha Plains for the 20-year period beween 1994-2014.

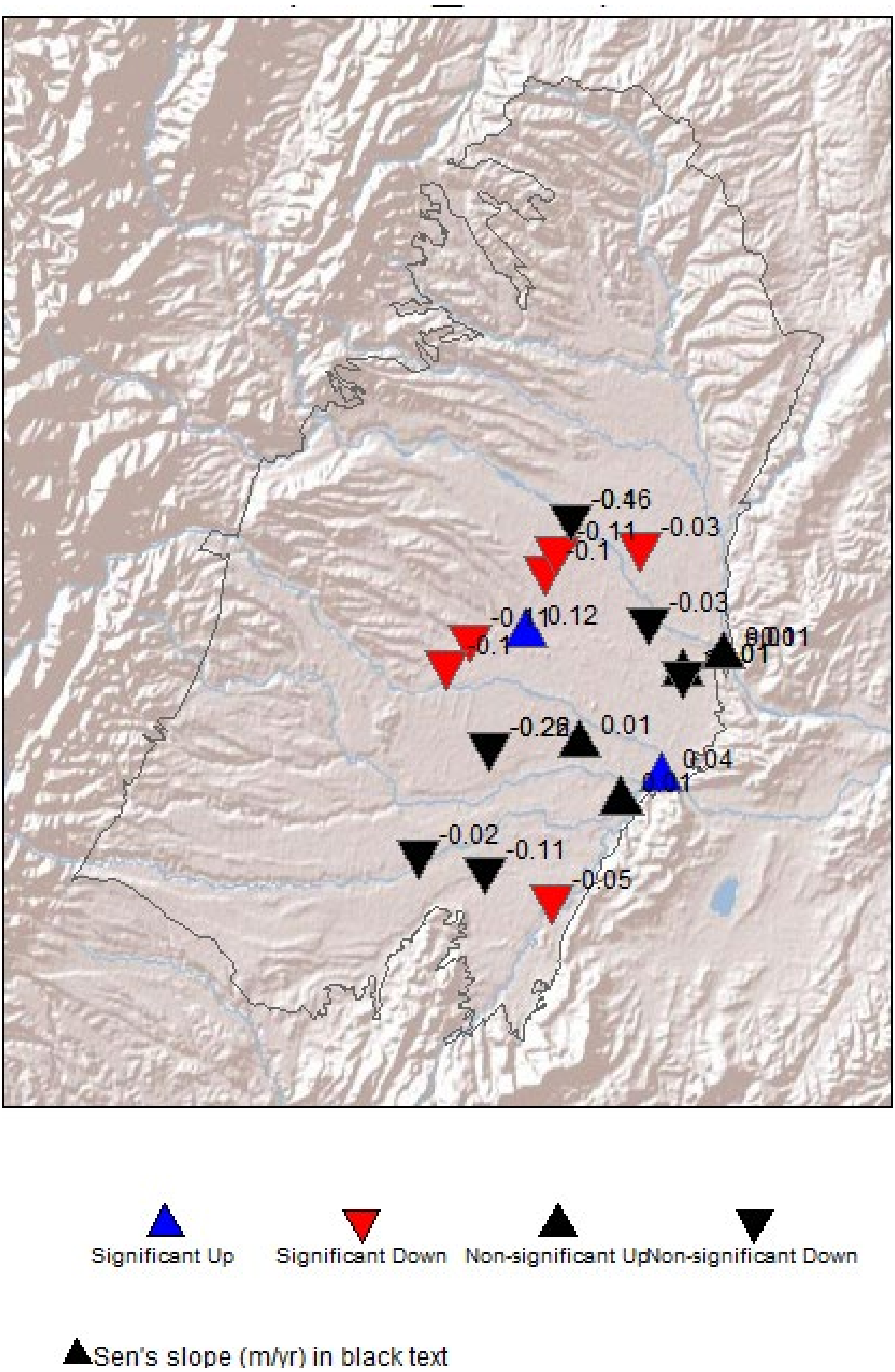


Figure 8-77: Groundwater level trends on the Ruataniwha Plains for the 20-year period beween 2004-2024.

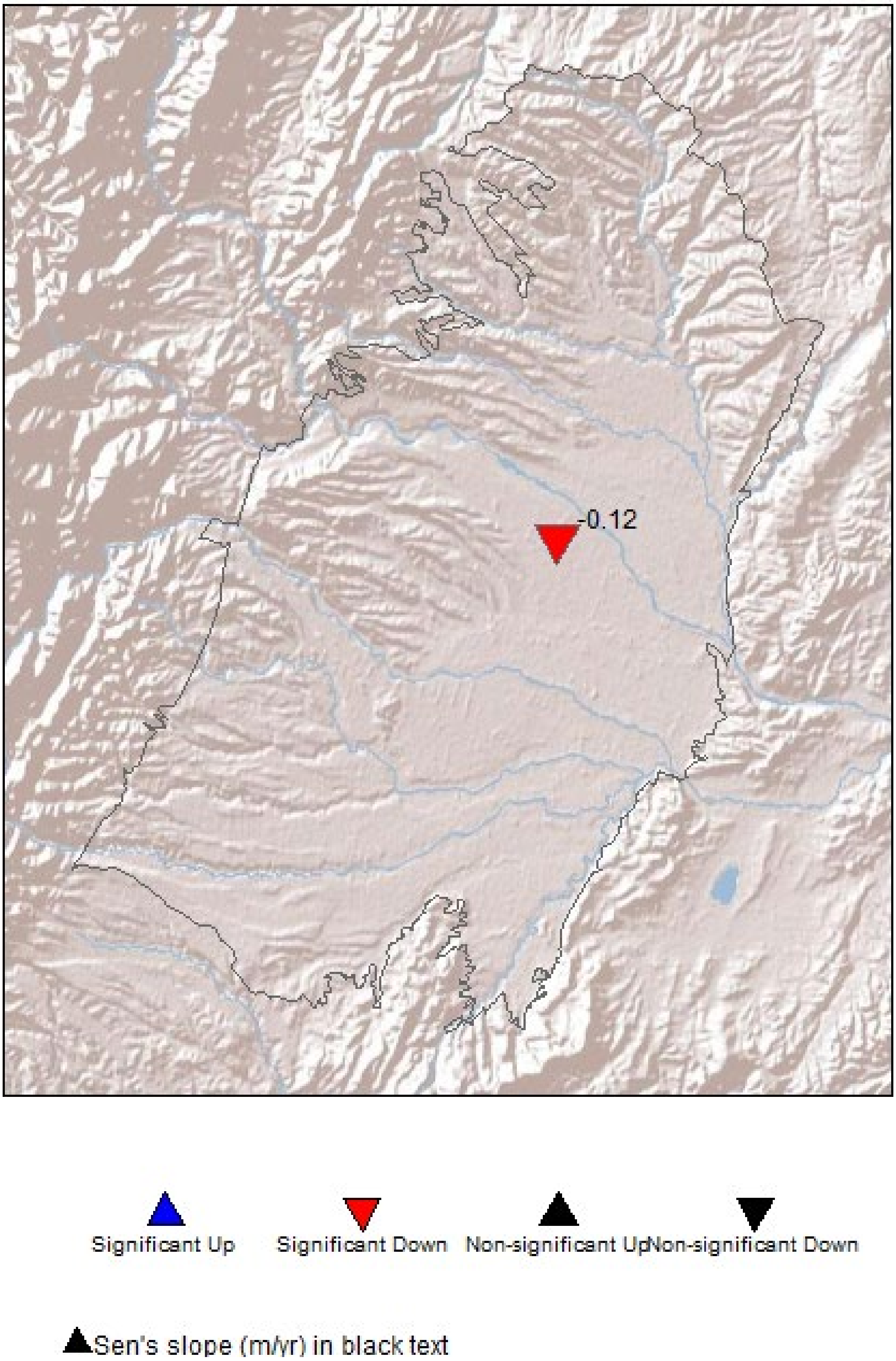


Figure 8-78: Groundwater level trends on the Ruataniwha Plains for the 30-year period beween 1984-2014.

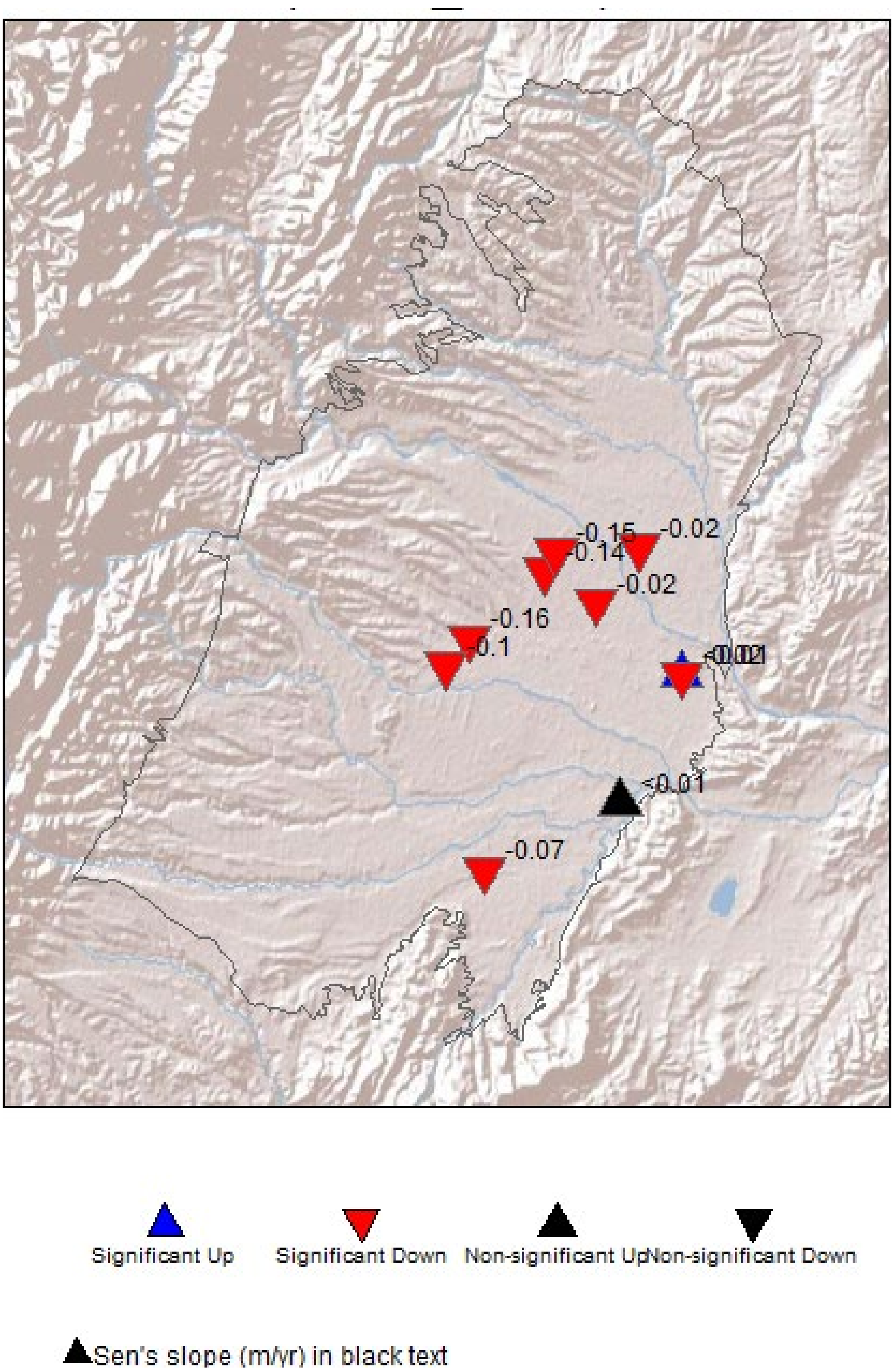


Figure 8-79: Groundwater level trends on the Ruataniwha Plains for the 30-year period beween 1994-2024.

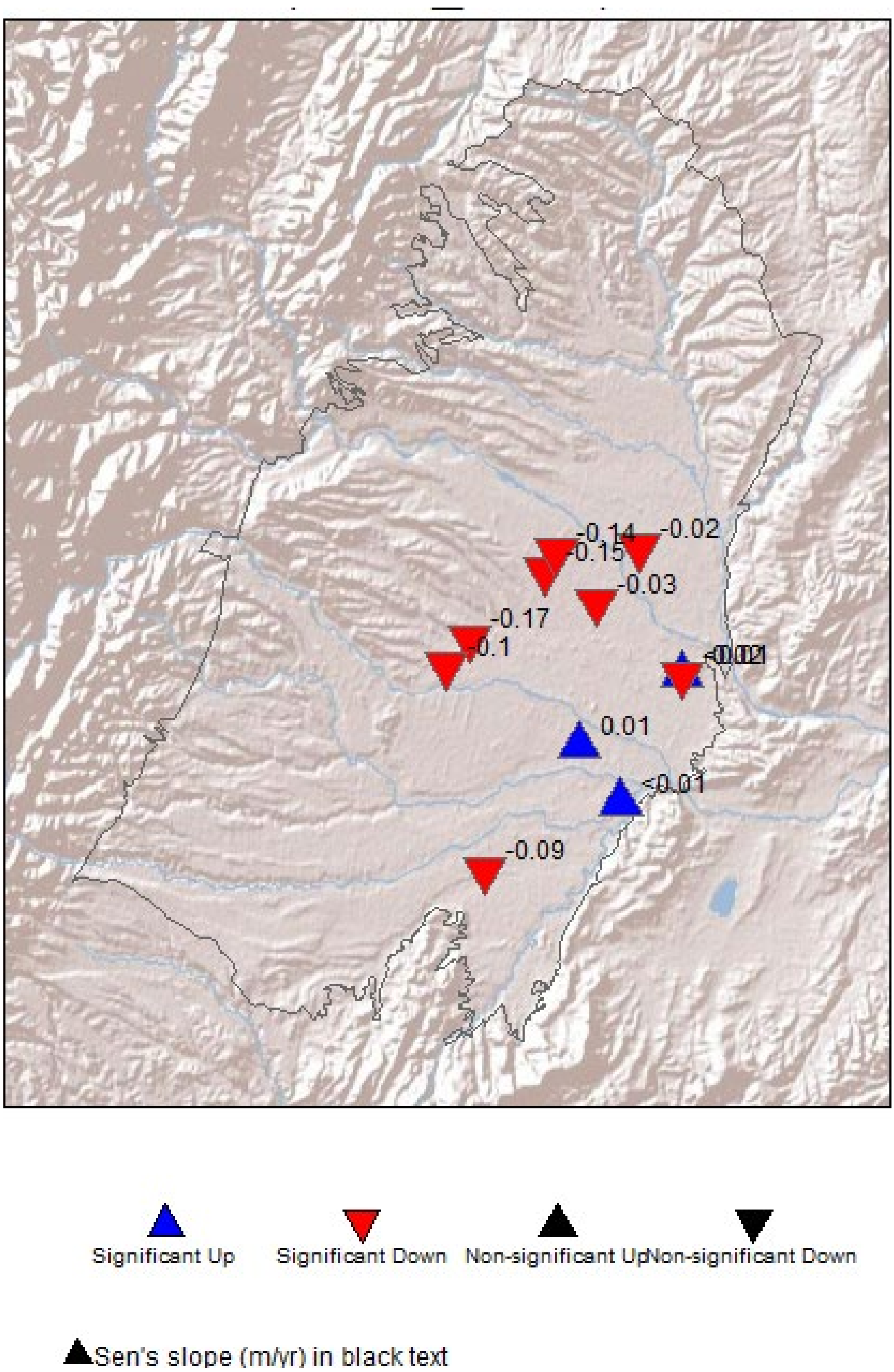


Figure 8-80: Groundwater level trends on the Ruataniwha Plains for the 40-year period beween 1984-2024.

NO DATA

Figure 8-81: Groundwater level trends on minor aquifers for the 10-year period beween 1984-1994.

NO DATA

Figure 8-82: Groundwater level trends on minor aquifers for the 10-year period beween 1994-2004.

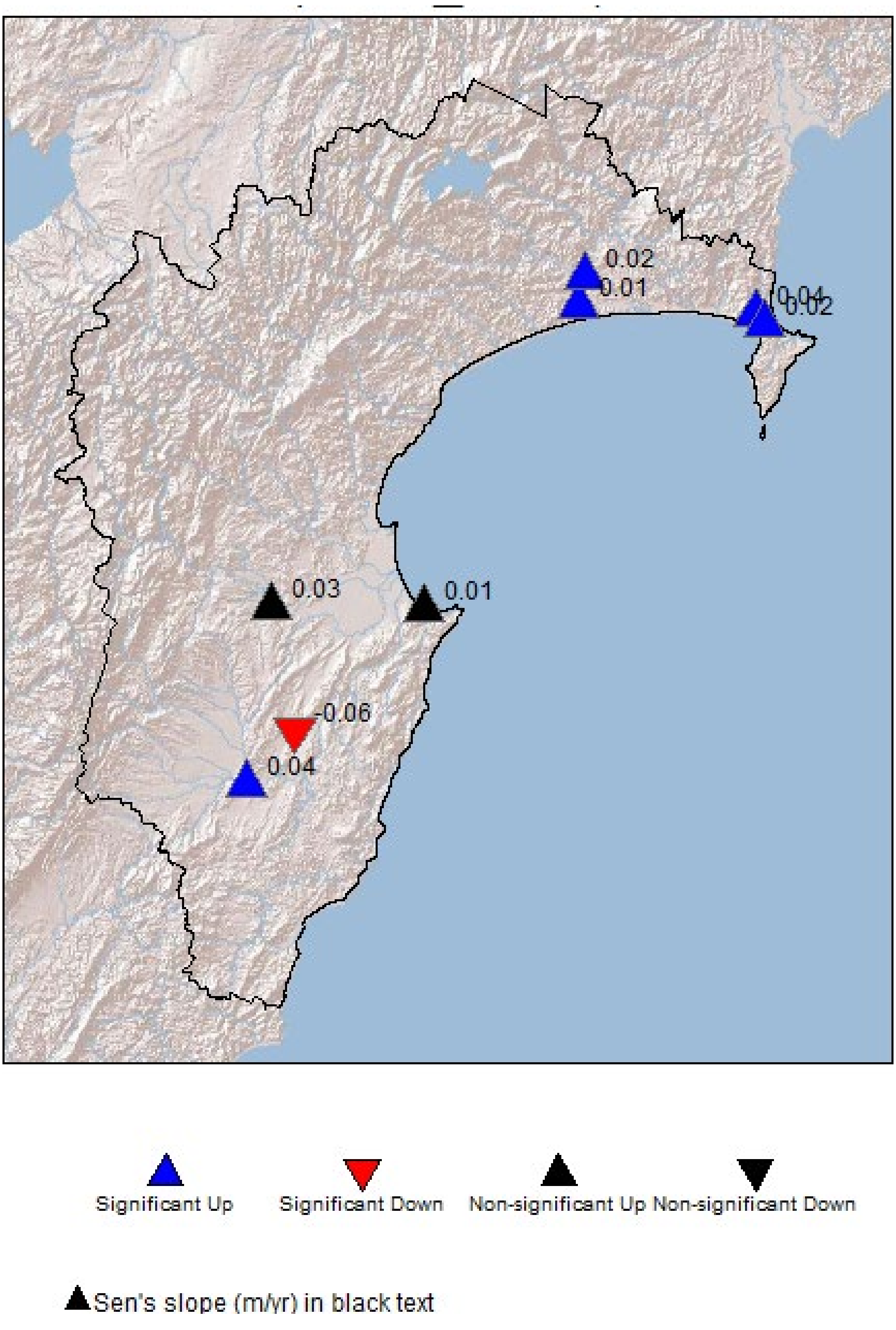


Figure 8-83: Groundwater level trends on minor aquifers for the 10-year period beween 2004-2014.

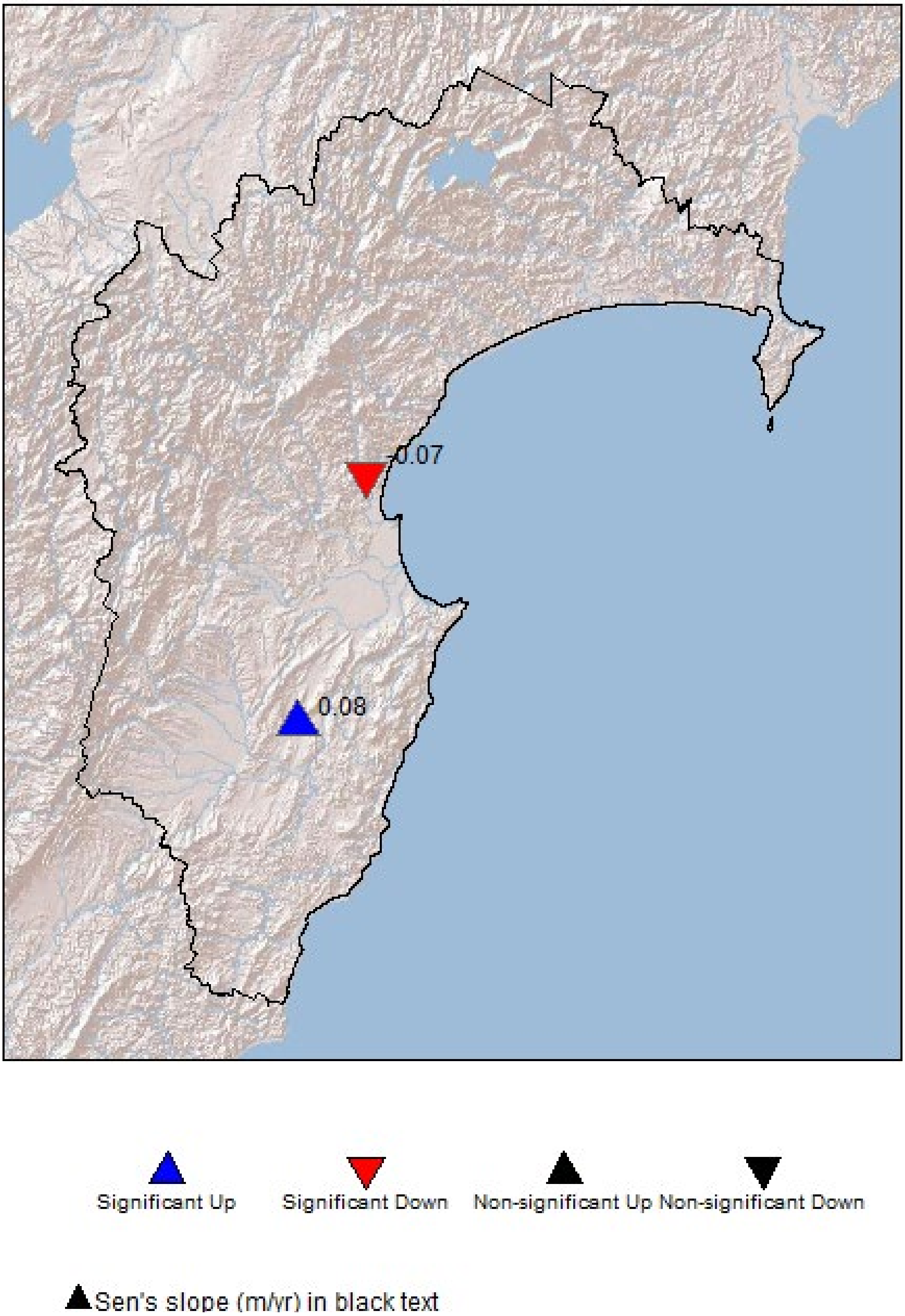


Figure 8-84: Groundwater level trends on minor aquifers for the 10-year period beween 2014-2024.

NO DATA

Figure 8-85: Groundwater level trends on minor aquifers ins for the 20-year period beween 1984-2004.

NO DATA

Figure 8-86: Groundwater level trends on minor aquifers for the 20-year period beween 1994-2014.

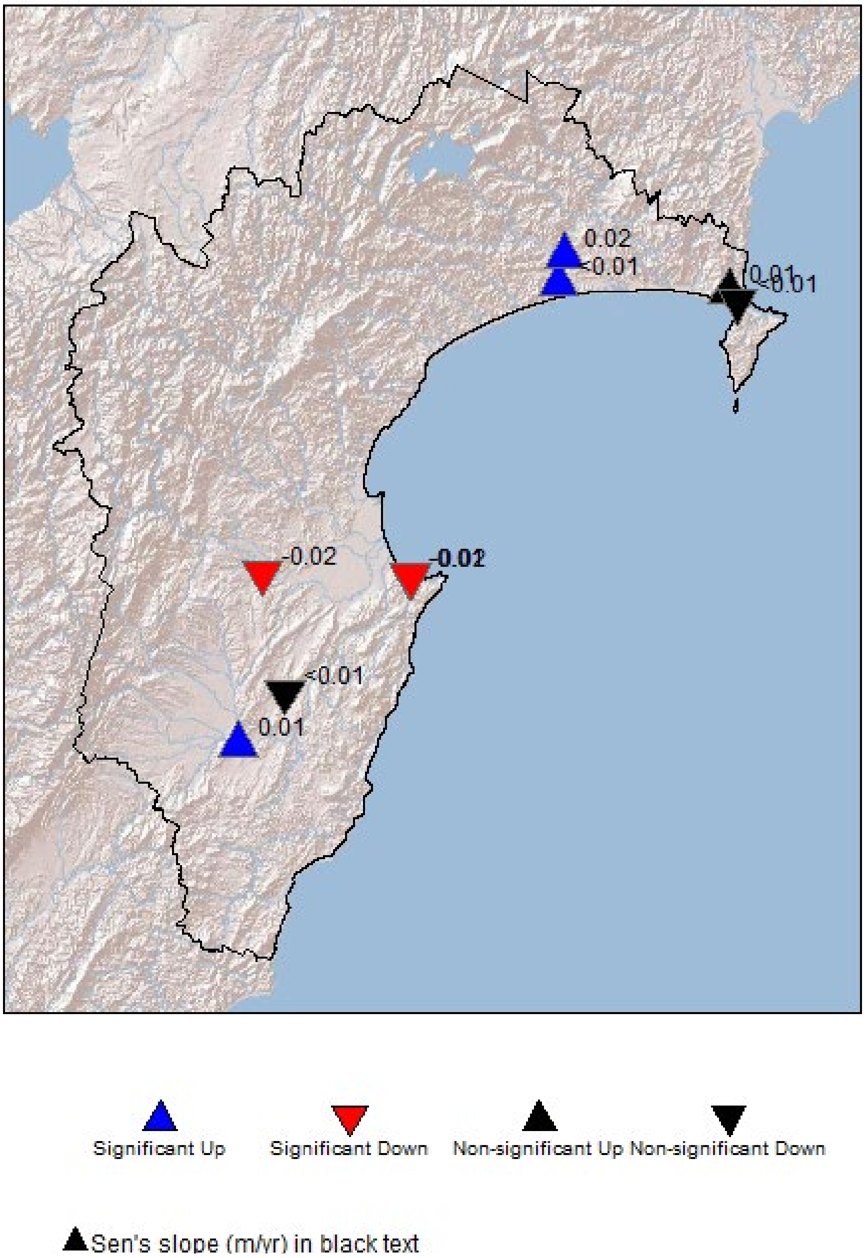


Figure 8-87: Groundwater level trends on minor aquifers for the 20-year period beween 2004-2024.

NO DATA

Figure 8-88: Groundwater level trends on minor aquifers for the 30-year period beween 1984-2014.

NO DATA

Figure 8-89: Groundwater level trends on minor aquifers for the 30-year period beween 1994-2024.

NO DATA

Figure 8-90: Groundwater level trends on minor aquifers for the 40-year period beween 1984-2024.

9 Downloadable files

Due to the size of the data files generated during the analysis of groundwater, several appendices are available as downloadable files only. These files require the installation of R to execute the scripts and run the files.

All R scripts utilised in this analysis are available on GitHub. These scripts provide access to the original dataset, perform all necessary data wrangling, execute the statistical tests, and include supplementary analyses and visualisations to help assess data quality and interpret the results.

To access and download the files, please visit the following repository:

https://github.com/hawkes-bay-rc/GW_3yearly_SoE.git

Downloading Instructions:

- Click on the **Code** button on the repository page.
- Select **Download ZIP** to obtain all files at once.
- Alternatively, you may clone the repository using Git.

The repository also includes a README file that provides detailed instructions on how to run the scripts and reproduce the analyses. Please ensure that you have R (version 3.6 or later) installed, along with any required packages as listed in the scritps.

9.1 Mann-Kendall test results

After running scripts, the Mann-Kendall results can be found in the directory:

…4_Trend_analysis/Results_tables

YYYY-MM_DD_Mann_Kendall_results.csv

9.2 Seasonal-Kendall test results

After running scripts, Seasonal-Kendall results can be found in the directory:

…4_Trend_analysis/Results_tables

YYYY-MM_DD_Seaonal_Kendall_results.csv

9.3 Mann-Kendall test results (seasonal variation)

After running scripts, Mann-Kendall results for changes in the difference between the annual minimum and maximums (seasonal variation) can be found in the directory:

…5_Trend_analysis/Results_tables

YYYY-MM_DD_SV_Mann_Kendall_results.csv