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Effects of Land Development and Season on Heavy Metal Concentrations in Urban Streams

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Computational Modeling Serving the City REU

Abstract

Although it is generally understood that urban development can impact the quality of urban streams, there are many factors that affect the concentrations of pollutants being transferred from the built environment to a given output. This study examines the impact of land use surrounding urban streams, specifically, the degree of development and presence or absence of green infrastructure (GI) in these areas on heavy metal (HM) concentrations in Portland, Oregon. After collecting 1021 water quality samples from 2010-2018, we examined the difference in concentrations of HM pollutants across different combinations of land use and season. Increased levels of calcium, magnesium, and hardness were found in highly developed areas compared to lowly developed areas as well as dry season compared to wet season. More controlled studies are necessary in determining the effects of GI on HM pollutants in urban areas.

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Introduction

While there has been research to determine how green infrastructure interacts with the environment in terms of absorbing rainfall and retaining sediments (Allen et al., 2017; Bedan & Clausen, 2009; Davis et al., 2010), this study looks specifically into land use and its effects on the quality of urban watercourses. This involves examining different levels of development and the presence or absence of green infrastructure in areas where stormwater runoff is directed to a nearby stream. Because the quality of stormwater runoff can directly affect the makeup of elements in nearby streams, we must understand seasonal differences, as the wet season on average has more frequent rainfall events than the dry. We believe examining seasonal differences is a necessary component in breaking down the relationship between land use and urban water quality.

Table 1: Review of literature

Author (year)	Area(s) of Focus	Data collection	Location	Key findings
Allen et al. (2017)	Sand sediment movement through different SuDS assets in multiple rainfall events	Samples collected every other week for a 12 month period	Bathgate, Scotland	SuDSs not as effective at retaining sediments over time; linear wetlands more successful at sediment retention than wetlands and swales
Beasley and Kneale (2002)	Pollutant movement through ecosystem, from the water and to macroinvertebrates in urban streams	n/a	Yorkshire, England, UK	Reduced species diversity found in some sites. More information necessary in

				understanding sediments and HMs in urban streams.
Bedan and Clausen (2009)	Stormwater runoff volume and quality Control, traditional, and LID residential watersheds	Watershed runoff monitored continuously Samples collected weekly before, during, and after neighborhood construction	Waterford, Connecticut, USA	LID watershed had 42% reduction of storm flow with no increase in peak flow; traditional water increased streamflow
Davis et al. (2010)	Flow velocity Adsorption of pollutants	n/a	n/a	Effectiveness of LID depends on its design and site characteristics as well as management
Ignatavičius et al. (2017)	Sources of HM in urban catchments Pollutant concentrations between seasons	42 samples collected after rainfall events from 7 drainage pipes between Sept. 29, 2014-Jan. 31, 2015	Vilnius, Lithuania	Seasons had significantly different levels of HM pollutants. Highest concentrations of suspended solids and highest volume of runoff located in highly active urban areas.
Janes et al. (2017)	Sediment quality and flood management	Sediment quality samples collected at outfalls.	Johnson Creek Catchment, Oregon, USA	Natural reaches have greater habitat quality and a greater likelihood of lower pollutant levels

Liu and Borst (2018)	Runoff from 3 permeable pavements, traditional asphalt, and rainwater.	Water quality samples collected over a period of 6 years from runoff of different pavements.	Edison, New Jersey, USA	Higher concentrations of specific HM pollutants found in runoff than rainwater. Specific metals behaved differently among different permeable pavements
Mu et al. (2014)	Different types of land use in relation to water quality.	Water quality samples collected over May 22-June 10, 2010 and Sept 10-19, 2010. 87 sampling sites on rivers and 23 in Lake Taihu.	Lake Taihu, China	Nutrients attributed to agricultural land use; sodium and chloride with urban areas; calcium and magnesium with natural weathering.

Literature suggested the need for more research on specific low impact development (LID) approaches for reducing pollutants in water. Studies overwhelmingly acknowledge the impact of urbanization on water quality, noting specific ways in which pollutants can be transported to urban streams. Research on water quality showed higher concentrations of HM pollutants were attributed to urban areas, and more natural areas or those with GI or LID had lower concentrations of pollutants and lower volumes of stormwater runoff.

Background

Pollutants in urban watersheds often arise from nearby urban and industrial activities. The HMs of focus in this study are, calcium, copper, magnesium, mercury, lead, and zinc. A common source heavy metal pollutants in urban streams is stormwater runoff, as pollutants can be traced back to surface sediments on impermeable urban surfaces such as pavement (Beasley

& Kneale, 2002; Ignatavičius et al., 2017). Copper, iron, lead and zinc can be found in pavement runoff and can be traced back to urban factors such as automobiles and buildings, as they are worn away from brake pads and construction materials (Beasley & Kneale, 2002; Davis et al., 2010). Calcium and magnesium in streams can be attributed to natural weathering (Mu et al., 2014). These pollutants build up on impermeable surfaces during dry periods and are washed into nearby water systems during rainfall events (Beasley & Kneale, 2002).

Opposed to gray infrastructure, green infrastructure (GI) is designed to mimic the behavior of natural systems. In a time of increasing urbanization, GI is used to implement best management practices (BMPs) when it comes to the control and treatment of stormwater runoff. Due to increased surface area of impermeable materials in urban areas, there is increased volume of stormwater runoff (US EPA, 2015). Additionally, urban stormwater runoff tends to have higher concentrations of pollutants due to a variety of urban factors (US EPA, 2015). It is generally understood that the use of GI can be helpful in mitigating stormwater runoff volume, as the natural elements will absorb a portion of the water before the runoff reaches an output, a nearby watercourse. However, the design and organization of low impact development (LID) systems involving green infrastructure impact the degree of effectiveness.

There is no single LID strategy guaranteed to be most effective when it comes to treating water quality and mitigating stormwater runoff, as there are many variables that impact the functions of the system (Davis et al., 2010). Generally, effectiveness of LID or a sustainable urban drainage system (SuDS) is determined by how well the system is able to retain fine sediments (Allen et al., 2017). In a paired watershed study, Bedan and Clausen (2009) designed LID and traditional residential neighborhoods and compared each to a control watershed. Their study found the LID neighborhood – which included rain gardens and grass swales among other

BMPs and GI assets – to have a significantly lower volume of stormwater runoff than the control, and found the traditional neighborhood to have increased runoff (Bedan and Clausen, 2009). Along with decreased volume of stormwater runoff, in the post construction period, concentrations of Zn and Pb in the LID watershed decreased by 77 and 67% respectively (Bedan and Clausen, 2009). Although they did not specifically test the ability of specific GI assets at retaining heavy metal pollutants, the study suggests a LID network is effective at retaining pollutants to a certain degree.

Methods

Data Organization

Water quality data was collected from 131 locations around the greater Portland area. The number of samples taken at each site varied for a total of 1021 samples of each HM in question. Samples were collected sporadically from 12/1/2010-3/21/2018. Collection months, days, and times varied such that there were data collected for wet and dry seasons across multiple years to normalize seasonal anomalies. For the 1021 samples, 346 were collected in the dry season (April-September) and 675 in the wet season (October-March). For distribution of development level, 298 samples were collected in lowly developed areas, 339 in moderately developed areas, and 383 in highly developed areas. There were far more samples collected in areas with no GI presence than those with GI, where counts are 771 and 249, respectively.

Hourly precipitation data, recorded per 0.01 inch, is publicly available by the United States Geological Survey (USGS) through the City of Portland HYDRA rainfall network. The HYDRA rain gages are labeled numerically on a map of Portland and are provided with specific addresses for each station. Sample and stream locations were stored using ArcMap, in which we could retrieve the coordinates of each sample site. Upon identifying rain gages in the general area of the sample location, Google Maps was used to determine the exact nearest station. For rain gage stations that did not collect data on a water quality sample date, data from the second nearest gage was used. Sample collection times were recorded to the minute. Rounding the sample collection begin times to the nearest hour allowed us to find the approximate total rainfall at the sample location for 24, 48, and 72 hours prior to sample collection using data from the nearest HYDRA rain gage station.

Beginning with data for Johnson Creek stations, we used SPSS to examine whether or not season or wetness had an effect on heavy metal pollutants. We coded for season and wetness. Water quality samples taken anywhere from October-March, the wet season in the Pacific Northwest, were marked 2 and those taken from April-September, the dry season, were marked 1. Similarly, we coded for wetness, defined by whether or not there was significant rainfall prior to the sample collection. During a given period of 24, 48, or 72 hours, if there was less than 0.04in (approximately 1 mm) of precipitation it was considered a dry period. For each time period we assigned values of wetness (wetness24, wetness48, and wetness72) where 1 represented a dry period and 2 represented a wet period. This process was repeated to include all 131 sample collection sites around Portland.

After collating precipitation and water quality data. We added information on the land use surrounding each water quality sample location. This included data on the density of green infrastructure and the percent of land development within a radius of 500 meters from the sampling location. This information was coded for the presence or absence of GI and its level of development. If there was any form of GI present, it was marked 2 for the category. All absence of GI was marked 1. For development, levels were separated to for a generally equal distribution of sample locations between each level. A location that was less than 40% developed was considered low, 40-80% was considered moderate, and greater than 80% was considered high. Low, moderate, and high levels of development were marked 1, 2, and 3 respectively.

Statistical Analysis

The first step in interpreting the data was determining whether or not season has an effect on water quality. Using SPSS 25, an independent-samples t-test was performed for concentrations of each HM with grouping by season. Because the development level or absence/presence of GI could affect these results, we separate analyses for each combination of development level and GI presence. To understand the effects of development level on HM concentrations, we separated data by season and GI and performed independent samples t-tests with grouping by development level. Finally, we looked within each season and within each development level to determine the significance of the presence or absence of GI on water quality. The t-test included Levene's test for equality of variances. P-values listed in this study are from t-tests with equal variances assumed. For any significant results, those with equal variance and $p < 0.05$, we created box plots to show the different populations' range of values for the each pollutant.

Results

Season

For all types of land use, there were no statistically significant seasonal differences in concentrations of copper, dissolved copper, lead, dissolved lead, mercury, zinc, and dissolved zinc. All t-tests on these pollutants either had unequal variance or there was no significant difference in concentrations of these elements during wet and dry seasons. Results for t-tests with seasonal grouping are provided in Table 2.

Concentrations of calcium and magnesium were significantly lower in the wet season than dry season for highly and moderately developed sampling locations, both with and without GI present. In highly developed areas with no GI present, seasonal differences in concentrations of calcium and magnesium were 18.39% ($p < 0.001$) and 22.8% ($p < 0.001$), respectively, and seasonal differences in concentrations of calcium and magnesium in highly developed areas with GI present were 18.57% ($p = 0.003$) and 20.5% ($p = 0.002$), respectively. In moderately developed areas with no GI, seasonal differences in concentrations of calcium and magnesium were 15.99% ($p = 0.007$) and 19.5% ($p = 0.001$), respectively, and seasonal differences for calcium and magnesium in moderately developed areas with GI present were 25.04 ($p < 0.001$) and 26.7% ($p < 0.001$), respectively. Lowly developed areas with no GI had significantly ($p < 0.001$) lower concentrations of calcium in the wet season than dry season; however, the groups had unequal variance. Concentrations of calcium in lowly developed areas with GI present were lower in the wet season than dry season, but the difference was not significant ($p = 0.063$). Average concentration of magnesium in lowly developed areas with GI present was 28.8% ($p = 0.040$) lower in the wet season than dry season. Variance for concentrations of magnesium was unequal in the case of low development with no GI.

Similar to trends in concentration of calcium and magnesium, average water hardness levels were lower in the wet season than dry season for all land use combinations. Differences between average water hardness during dry and wet seasons for highly developed areas with and without GI present was 19.3% ($p = 0.002$) and 20.2% ($p < 0.001$), respectively. Differences between average water hardness during dry and wet seasons for moderately developed areas with and without GI present were 25.7% ($p < 0.001$) and 17.3% ($p = 0.003$), respectively. There was unequal variance in water hardness from collection sites in lowly developed areas with no GI for seasonal groupings. Season had no significant ($p = 0.51$) effect on hardness in lowly developed areas with GI present. Mean concentration and p-values are listed in Table 2. Significant percent differences in concentration during dry and wet seasons are provided in Table 3 along with respective p-values. Ranges of concentrations of calcium, magnesium and hardness in areas which showed statistically significant differences between seasons can be visualized through box plots given in figures 1-13.

Degree of Development

Calcium, magnesium, and hardness were the only variables with cases whose variances were equal and had significant differences between development levels. Concentrations of calcium and magnesium as well as water hardness were significantly higher in highly developed areas than lowly developed areas during the dry season. During the dry season, in areas with no GI, the differences in average concentrations of calcium, magnesium, and water hardness between lowly and highly developed areas were 29.24% ($p < 0.001$), 35.11% ($p < 0.001$), and 31.72% ($p < 0.001$). During the dry season, in areas with GI present, the differences in average concentrations of calcium, magnesium, and water hardness between lowly and highly developed areas were 27.31% ($p = 0.010$), 24.75% ($p = 0.021$), and 26.25% ($p = 0.013$). During the wet season, in areas with GI present, the differences in average concentrations of calcium, magnesium and water hardness between lowly and highly developed areas were 34.17% ($p < 0.001$), 32.61% ($p = 0.001$), and 33.54% ($p < 0.001$). For these metals, samples taken during the wet season in areas with GI present had unequal variance for low and high development grouping. Of the elements with significant differences between low and high development groupings, the majority also had significant differences between lowly and moderately developed areas and moderately and highly developed areas. These details are given in Table 5. All other elements either did not have equal variance of concentrations in lowly and highly developed areas, or had no significant difference between groupings. Results of all t-tests performed with development groupings are given in Table 4. Ranges of concentrations of calcium, magnesium, and hardness for combinations of season and GI presence which showed statistically significant differences between development levels can be visualized through box plots given in figures 14-23.

Presence of Green Infrastructure

No elements tested had significant difference in concentrations between GI groups. The concentrations either had unequal variance, insignificant difference between groupings, or both. All t-test results of GI groupings are provided in Table 6.

Summary

Figures 24-29 summarize the seasonal and developmental trends in levels of calcium, magnesium, and hardness for all samples across all locations. Locations with an without GI present were included in these plots, as there were no significant results which indicated a difference between the GI populations.

Discussion

The significant difference between concentrations of calcium, magnesium, and hardness in the wet and dry season suggests an accumulation of the pollutants on impermeable surfaces. For highly and moderately developed areas, concentrations in the dry season were 15-30% higher than those in the wet season for these elements. Because the seasonal difference was not significant in lowly developed areas, which theoretically have less impermeable surfaces, it is possible the difference in seasonal groupings is dependent on the type of land use. More information is necessary to understand the cause of this difference. It is possible these trends could be attributed to an accumulation of calcium and magnesium from impermeable surfaces during dry periods, causing the concentration to spike after a rainfall event when stormwater runoff carries pollutants and weathers the pavement, carrying sediments to the streams. It is also possible that there is a negative correlation between concentrations of calcium, magnesium and hardness with rainfall, if frequent addition of stormwater runoff in the wet season is merely diluting the concentrations of the elements in streams. Determining the reason for decreased concentrations in the dry season would require an analysis of the effects of precipitation on pollutant concentrations within each season.

Results from the t-test with development level groupings show a positive correlation between concentration of calcium, magnesium, and hardness and degree of development. Concentrations generally increased from low, to moderate, to high development levels. Some differences between concentrations of calcium and magnesium in low and moderate or moderate and high development levels were insignificant, though this could be due to the differences in the sizes of the groups being compared, yielding unequal variance between groups. The increase in concentrations from low to moderate to high development levels within the dry and wet season suggests a relationship between impermeable surfaces and concentrations of calcium and magnesium.

In order to understand the effect of GI on concentration of pollutants, we need to be more specific in our study. We specifically looked at density of GI within a given area. Not only were there far fewer samples being taken near areas with GI, but we had no data on specifically what types of assets were implemented in those areas or how the facilities were maintained. Future studies could focus on this topic of GI effects by controlling more parameters and increasing the number of samples taken in areas with GI. Instead of simply comparing the absence and presence of GI, one could also compare levels of GI density as we did with development.

Conclusions

Tables and Figures

Table 2: Results from independent samples t-test with grouping by season

	Land Use		Mean Concentration			Levene's test for equality of variances	Independent Samples test
Element Analyte	Development Level	GI	Dry Season	Wet season	unit	p-value	p-value
Calcium	High	no	17.07	13.93	mg/L	0.707	< 0.001
		yes	18.27	14.88		0.906	0.003
	Medium	no	15.18	12.75		0.859	0.007
		yes	14.67	10.99		0.084	<0.001
	Low	no	12.06	9.05		0.002	<0.001
		yes	13.28	9.80		0.190	0.063
Copper	High	no	1.754	2.846	ug/L	0.003	0.028
		yes	1.090	1.834		<0.001	0.001
	Medium	no	1.668	2.406		<0.001	0.009
		yes	1.545	2.271		0.007	0.109
	Low	no	1.631	1.669		0.308	0.892
		yes	4.139	2.200		0.043	0.334
Dissolved Copper	High	no	1.127	1.310	ug/L	0.091	0.203
		yes	0.655	0.975		0.003	0.006
	Medium	no	0.937	1.147		0.001	0.022
		yes	1.003	1.047		0.389	0.781
	Low	no	0.739	0.738		0.134	0.997
		yes	2.705	1.223		0.040	0.257
Hardness	High	no	72.5	57.8	mg CaCO3	0.731	<0.001
		yes	76.0	61.3		0.626	0.002
	Medium	no	62.0	51.3		0.691	0.003
		yes	60.8	45.2		0.122	<0.001
	Low	no	49.5	37.5		0.008	<0.001
		yes	56.0	40.8		0.157	0.051
Lead	High	no	0.491	1.203	ug/L	<0.001	0.001
		yes	0.323	0.749		<0.001	<0.001
	Medium	no	0.723	1.141		0.012	0.057
		yes	0.377	0.894		0.077	0.066
	Low	no	0.744	0.798		0.4346	0.792
		yes	0.375	0.758		0.068	0.104
Dissolved Lead	High	no	0.118	0.158	ug/L	<0.001	0.018
		yes	0.100	0.120		<0.001	0.034
	Medium	no	0.123	0.167		<0.001	0.021
		yes	0.107	0.124		0.010	0.158
	Low	no	0.122	0.140		0.021	0.099
		yes	0.137	0.173		0.116	0.317
Magnesium	High	no	7.25	5.60	mg/L	0.770	<0.001
		yes	7.38	5.87		0.390	0.002
	Medium	no	5.86	4.71		0.774	0.001
		yes	5.86	4.30		0.067	<0.001
	Low	no	4.70	3.61		0.046	<0.001
		yes	5.55	3.95		0.145	0.040

Mercury	High	no	0.00221	0.00396	ug/L	<0.001	<0.001
		yes	0.00173	0.00341		<0.001	<0.001
	Medium	no	0.00299	0.00458		<0.001	0.005
		yes	0.00245	0.00428		0.009	0.040
	Low	no	0.00420	0.00466		0.952	0.551
		yes	0.00317	0.00964		0.170	0.343
Zinc	High	no	7.66	18.03	ug/L	0.004	0.013
		yes	4.52	12.73		<0.001	0.001
	Medium	no	7.66	11.72		0.018	0.020
		yes	5.05	19.17		0.113	0.229
	Low	no	4.98	5.63		0.179	0.618
		yes	5.66	5.44		0.430	0.939
Dissolved Zinc	High	no	4.30977	8.91084	ug/L	0.030	0.048
		yes	2.33757	7.84406		<0.001	0.005
	Medium	no	3.78740	4.82517		0.682	0.303
		yes	2.33938	12.37246		0.167	0.356
	Low	no	1.51513	1.79319		0.461	0.577
		yes	3.54369	2.24160		0.125	0.441

Table 3: Significant differences in seasonal groupings

Element Analyte	Development Level	GI	Percent difference	p-value
Calcium	High	no	18.39	< 0.001
		yes	18.57	0.003
	Medium	no	15.99	0.007
		yes	25.04	<0.001
Magnesium	High	no	22.8	<0.001
		yes	20.5	0.002
	Medium	no	19.5	0.001
		yes	26.7	<0.001
	Low	yes	28.8	0.040
Hardness	High	no	20.2	<0.001
		yes	19.3	0.002
	Medium	no	17.3	0.003
		yes	25.7	<0.001

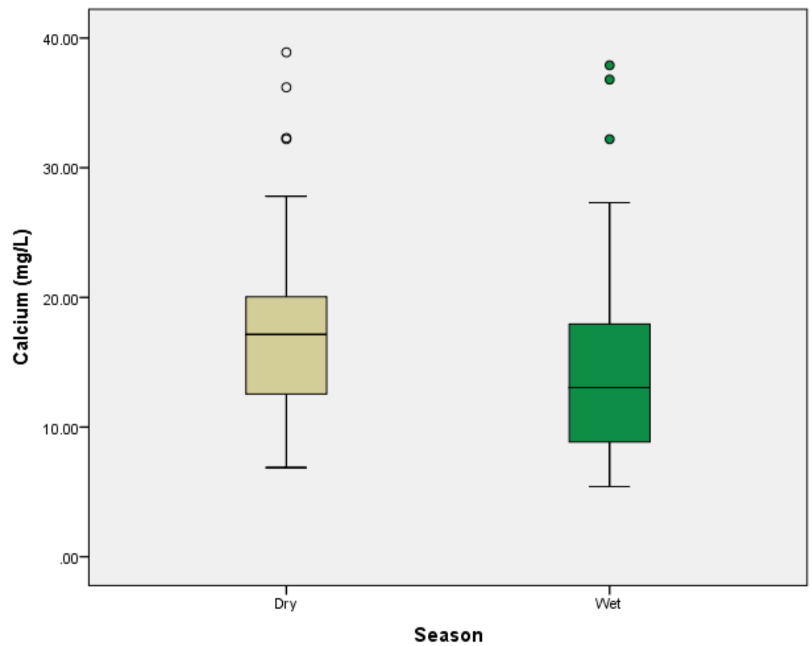

Figure 1: Box plot showing ranges of calcium concentrations during dry and wet seasons in highly developed areas with no GI present

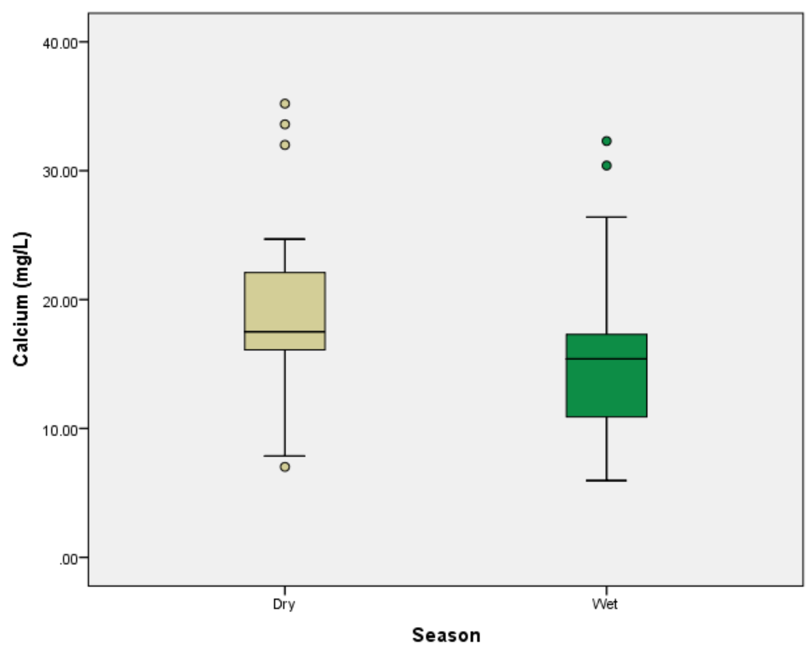

Figure 2: Box plot showing ranges of calcium concentrations during dry and wet seasons in highly developed areas with GI

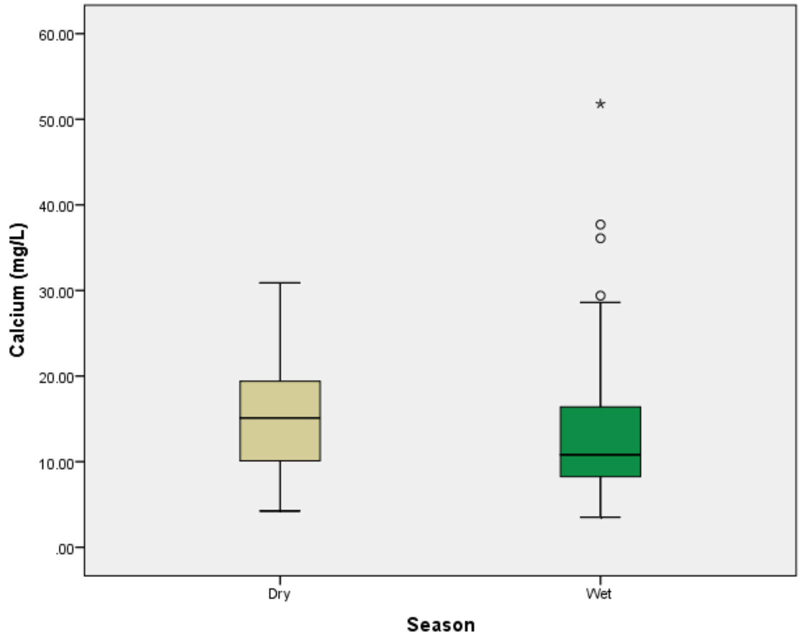

Figure 3: Box plot showing ranges of calcium concentrations during dry and wet seasons in moderately developed areas with no GI present

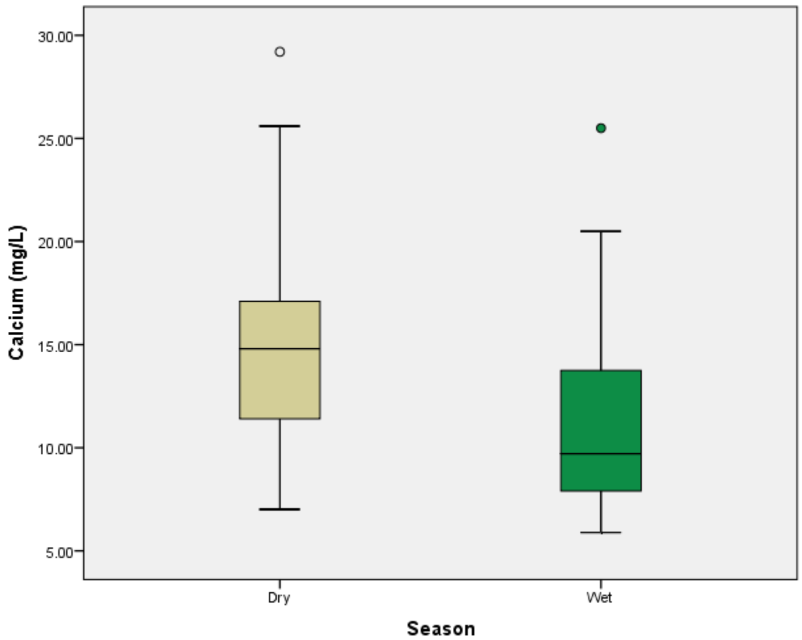

Figure 4: Box plot showing ranges of calcium concentrations during dry and wet seasons in moderately developed areas with GI

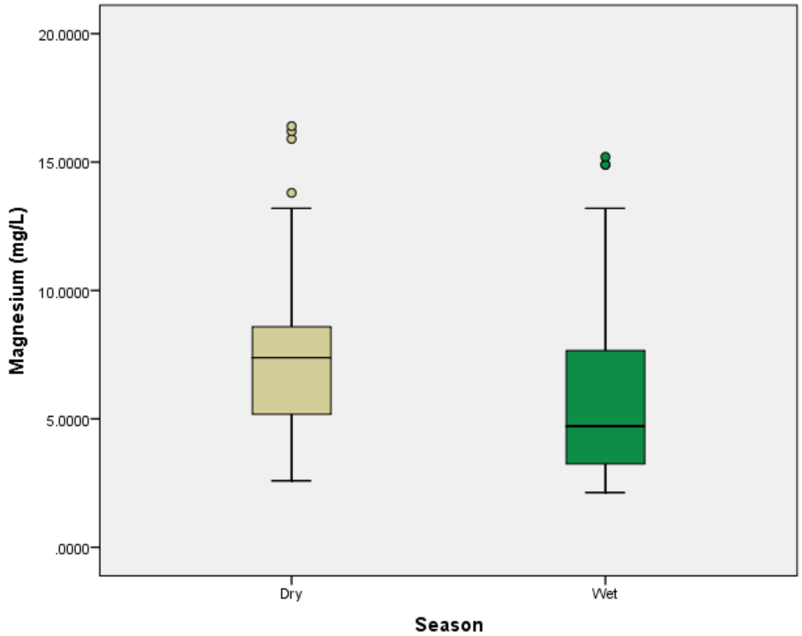

Figure 5: Box plot showing ranges of magnesium concentrations during dry and wet seasons in highly developed areas with no GI present

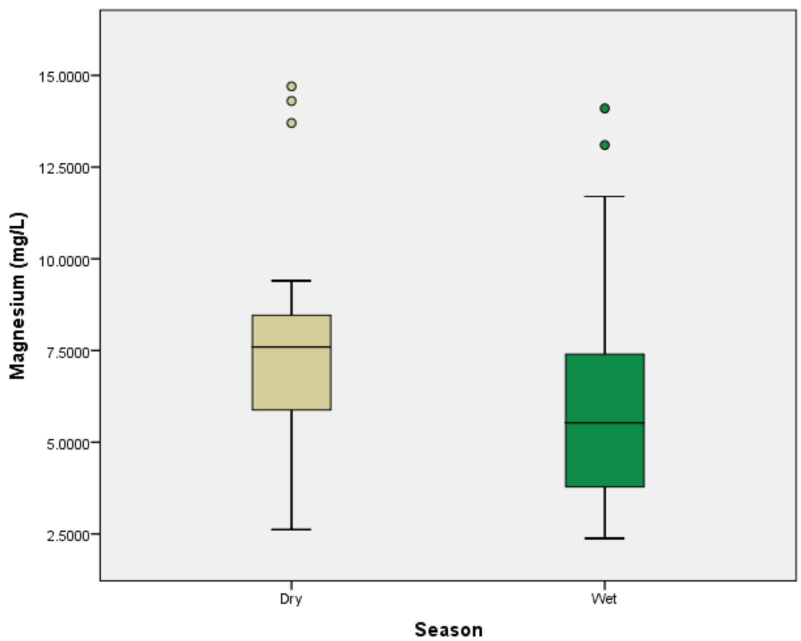

Figure 6: Box plot showing ranges of magnesium concentrations during dry and wet seasons in highly developed areas with GI

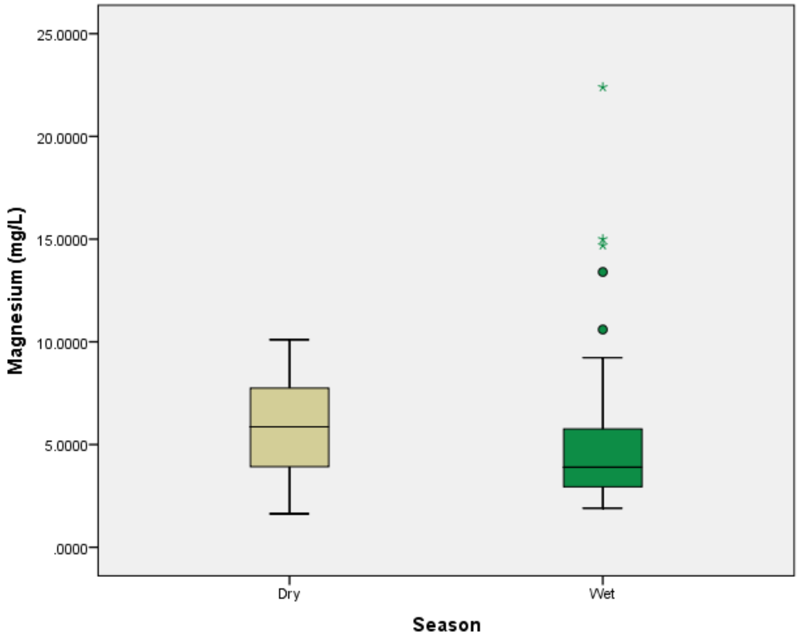

Figure 7: Box plot showing ranges of magnesium concentrations during dry and wet seasons in moderately developed areas with no GI present

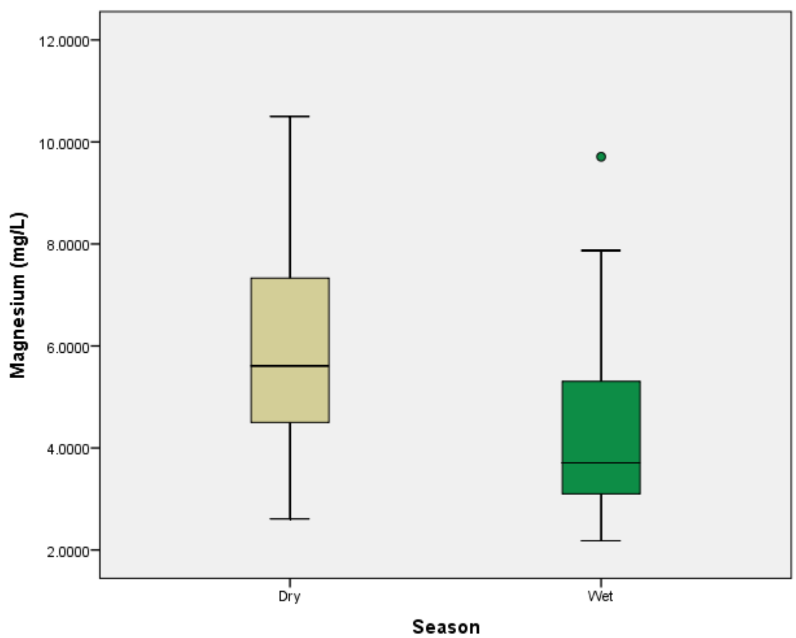

Figure 8: Box plot showing ranges of magnesium concentrations during dry and wet seasons in moderately developed areas with GI

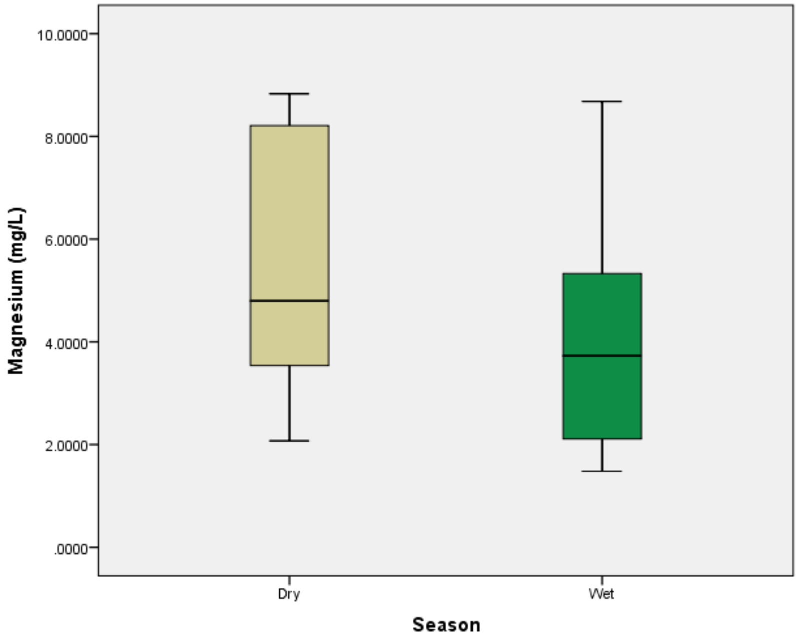

Figure 9: Box plot showing ranges of magnesium concentrations during dry and wet seasons in lowly developed areas with GI

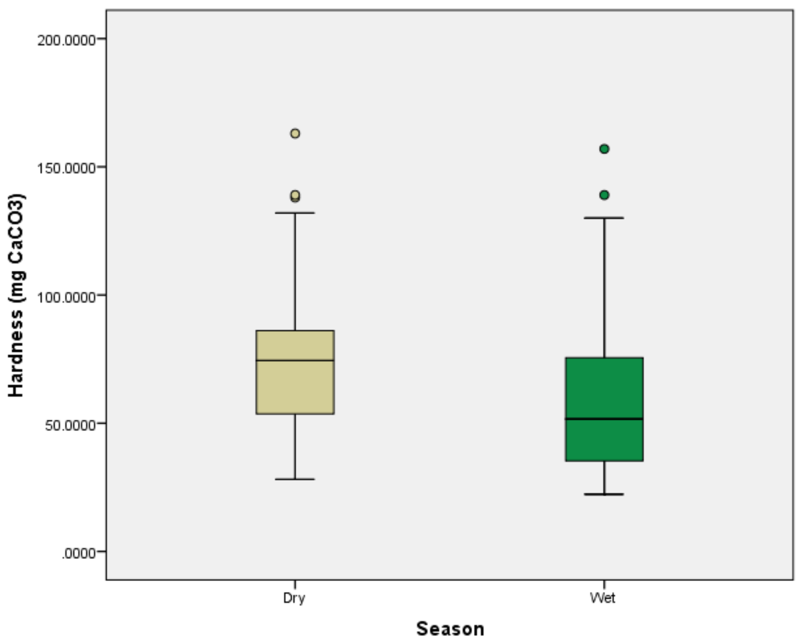

Figure 10: Box plot showing ranges of water hardness during dry and wet seasons in highly developed areas with no GI present

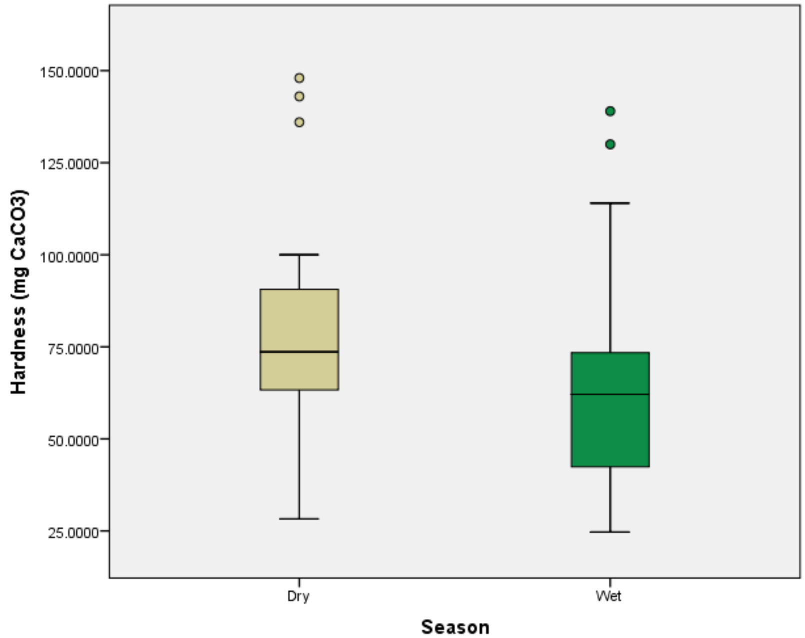

Figure 11: Box plot showing ranges of water hardness during dry and wet seasons in highly developed areas with GI

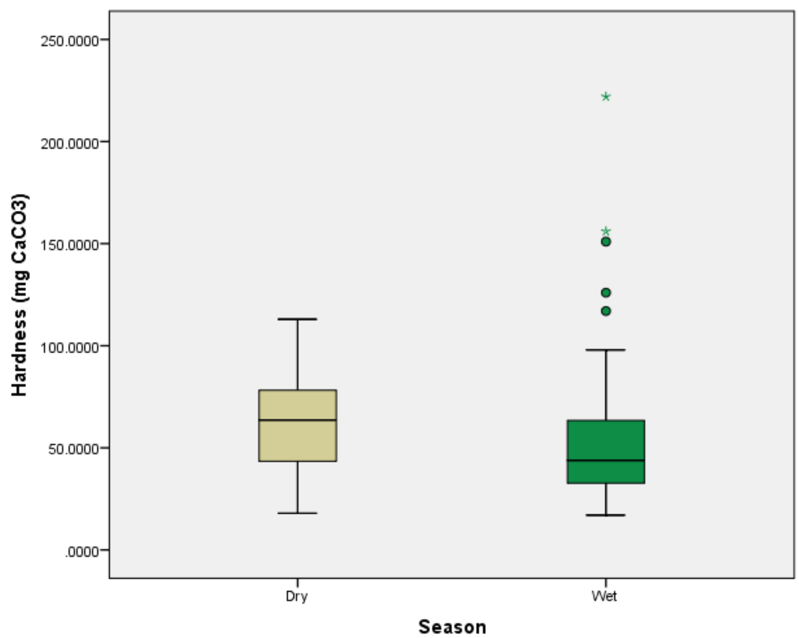

Figure 12: Box plot showing ranges of water hardness during dry and wet seasons in moderately developed areas with no GI present

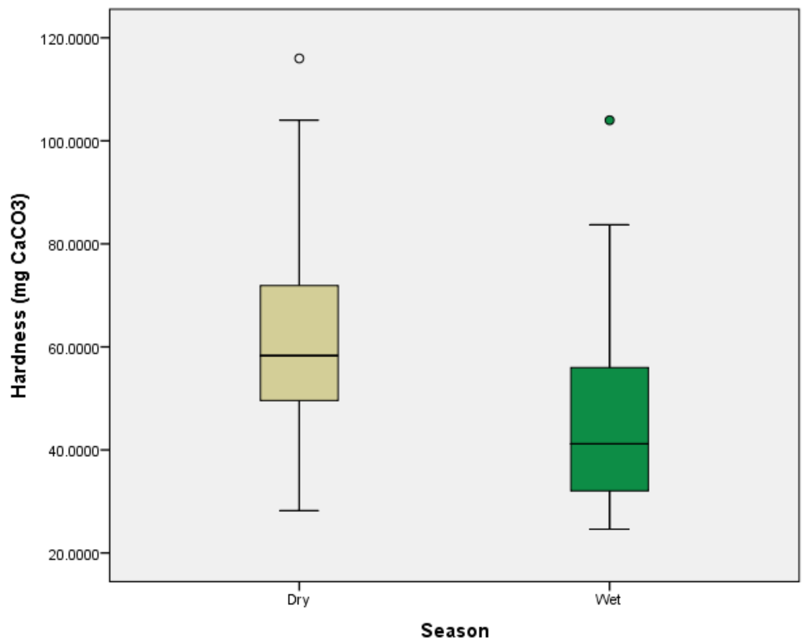

Figure 13: Box plot showing ranges of water hardness during dry and wet seasons in moderately developed areas with GI

Table 4: Results from independent samples t-test with grouping by development

			Mean Concentration				Grouping: low, medium		Grouping: medium, high		Grouping: low,high	
Element Analyte	Season	GI	Low	Medium	High	unit	p (Levene's test for equality of variances)	p (Independent Samples test)	p (Levene's test for equality of variances)	p (Independent Samples test)	p (Levene's test for equality of variances)	p (Independent Samples test)
Calcium	Dry	no	12.06	15.18	17.07	mg/L	0.987	0.001	0.428	0.035	0.447	<0.001
		yes	13.28	14.70	18.27		0.275	0.446	0.91	0.011	0.426	0.01
	Wet	no	9.05	12.75	13.93		0.001	<0.001	0.448	0.104	0.003	<0.001
		yes	9.80	10.99	14.88		0.096	0.242	0.024	<0.001	0.762	<0.001
Copper	Dry	no	1.631	1.668	1.754	ug/L	0.279	0.884	0.024	0.68	0.538	0.647
		yes	4.139	1.545	1.090		0.007	0.151	0.015	0.004	<0.001	0.033
	Wet	no	1.669	2.406	2.846		0.037	0.002	0.04	0.309	0.001	0.002
		yes	2.200	2.271	1.834		0.777	0.893	0.048	0.185	0.13	0.318
Dissolved Copper	Dry	no	0.739	0.937	1.127	ug/L	0.027	0.014	0.027	0.142	0.001	0.005
		yes	2.705	1.003	0.655		0.006	0.148	0.159	0.001	<0.001	0.028
	Wet	no	0.738	1.147	1.310		<0.001	<0.001	0.003	0.139	<0.001	<0.001
		yes	1.223	1.047	0.975		0.009	0.426	0.689	0.574	0.005	0.23
Hardness	Dry	no	49.5	62.0	72.5	mg CaCO3	0.722	0.001	0.668	0.005	0.932	<0.001
		yes	56.0	60.8	76.0		0.17	0.529	0.927	0.008	0.315	0.013
	Wet	no	37.5	51.3	57.8		0.005	<0.001	0.735	0.03	<0.001	<0.001
		yes	40.8	45.2	61.3		0.081	0.294	0.013	<0.001	0.675	<0.001
Lead	Dry	no	0.744	0.723	0.491	ug/L	0.951	0.931	0.136	0.151	0.137	0.141
		yes	0.374	0.377	0.323		0.532	0.982	0.004	0.366	0.146	0.45
	Wet	no	0.798	1.141	1.203		0.026	0.041	0.198	0.779	0.001	0.035
		yes	0.758	0.894	0.749		0.175	0.665	0.046	0.472	0.851	0.958
Dissolved Lead	Dry	no	0.122	0.123	0.118	ug/L	0.465	0.887	0.413	0.658	0.905	0.723
		yes	0.137	0.107	0.100		<0.001	0.015	<0.001	0.029	<0.001	<0.001
	Wet	no	0.140	0.167	0.158		<0.001	0.045	0.643	0.609	0.002	0.185
		yes	0.173	0.124	0.120		0.001	0.013	0.577	0.705	<0.001	0.006

Magnesium	Dry	no	4.70	5.86	7.25	mg/L	0.848	0.002	0.101	<0.001	0.27	<0.001
		yes	5.55	5.86	7.38		0.164	0.68	0.973	0.007	0.314	0.021
	Wet	no	3.61	4.71	5.60		0.028	<0.001	0.055	0.005	<0.001	<0.001
		yes	3.95	4.30	5.87		0.08	0.397	0.002	<0.001	0.394	0.001
Mercury	Dry	no	0.00420	0.00299	0.00221	ug/L	51	0.153	0.038	0.017	0.002	0.007
		yes	0.00317	0.00245	0.00173		0.617	0.165	<0.001	0.004	<0.001	<0.001
	Wet	no	0.00466	0.00458	0.00396		0.784	0.879	0.549	0.211	0.756	0.142
		yes	0.00964	0.00428	0.00341		0.013	0.083	0.031	0.176	0.003	0.035
Zinc	Dry	no	4.98	7.66	7.66	ug/L	0.125	0.12	0.724	0.998	0.033	0.094
		yes	5.66	5.05	4.52		0.136	0.794	0.588	0.639	0.192	0.606
	Wet	no	5.63	11.72	18.03		<0.001	<0.001	0.008	0.068	<0.001	<0.001
		yes	5.44	19.17	12.73		0.189	0.278	0.281	0.409	0.001	0.029
Dissolved Zinc	Dry	no	1.52	3.79	4.31	ug/L	0.013	0.067	0.856	0.715	0.004	0.018
		yes	3.54	2.34	2.34		0.043	0.425	0.204	0.998	0.136	0.422
	Wet	no	1.79	4.85	8.91		<0.001	<0.001	0.002	0.027	<0.001	<0.001
		yes	2.24	12.37	7.84		0.213	0.388	0.281	0.528	0.001	0.031

Table 5: Significant differences in development groupings

			Development Level Groupings					
			Low, Medium		Medium, High		Low, High	
Element Analyte	Season	GI	Percent Difference	p-value	Percent Difference	p-value	Percent Difference	p-value
Calcium	Dry	no	20.55	0.001	11.07	0.035	29.34	<0.001
		yes	9.62	0.446	19.57	0.011	27.31	0.010
Calcium	Wet	yes	10.90	0.242	26.1192425	unequal variance	34.17	<0.001
Magnesium	Dry	no	19.71	0.002	19.17	<0.001	35.11	<0.001
		yes	5.23	0.680	20.60	0.007	24.75	0.021
	Wet	yes	8.01	0.397	26.74	unequal variance	32.61	0.001
Hardness	Dry	no	20.20	0.001	14.43	0.005	31.72	<0.001
		yes	7.84	0.529	19.98	0.008	26.25	0.013
	Wet	yes	9.75	0.294	26.37	unequal variance	33.54	<0.001

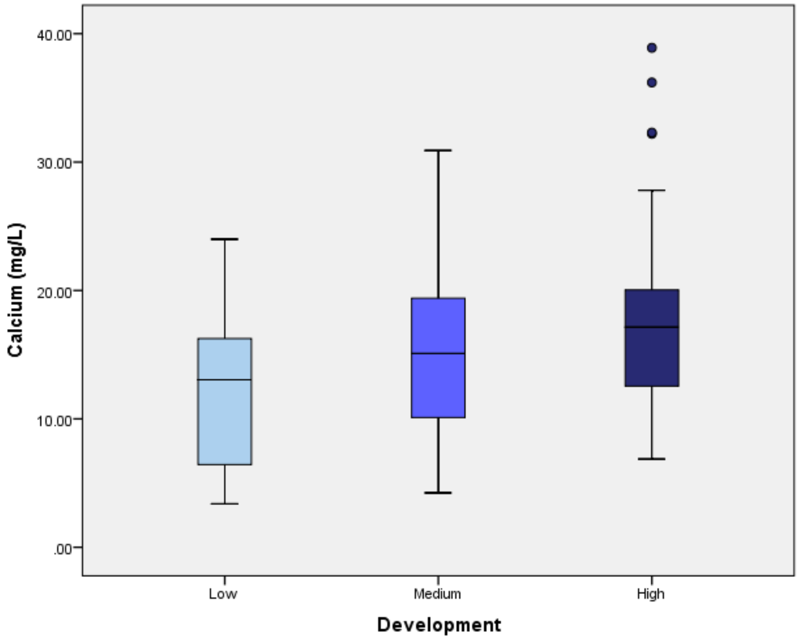

Figure 14: Box plot showing ranges of calcium concentrations in areas with low, medium, and high development levels with no GI present in the dry season

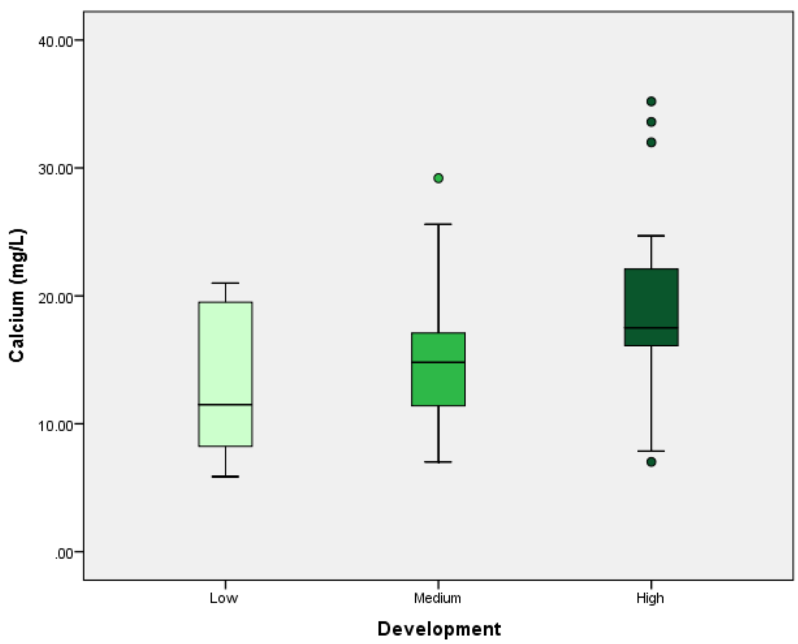

Figure 15: Box plot showing ranges of calcium concentrations in areas with low, medium, and high development levels with GI in the dry season

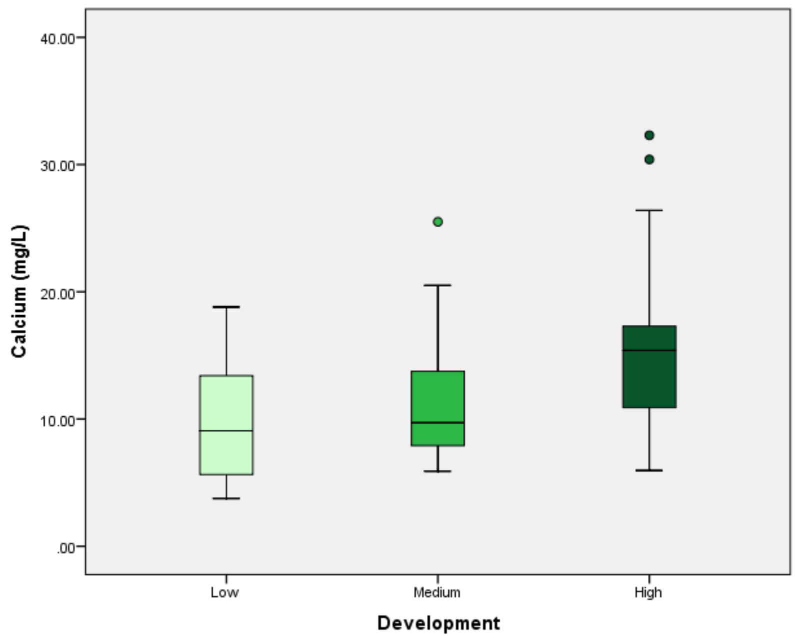

Figure 16: Box plot showing ranges of calcium concentrations in areas with low, medium, and high development levels with GI in the wet season

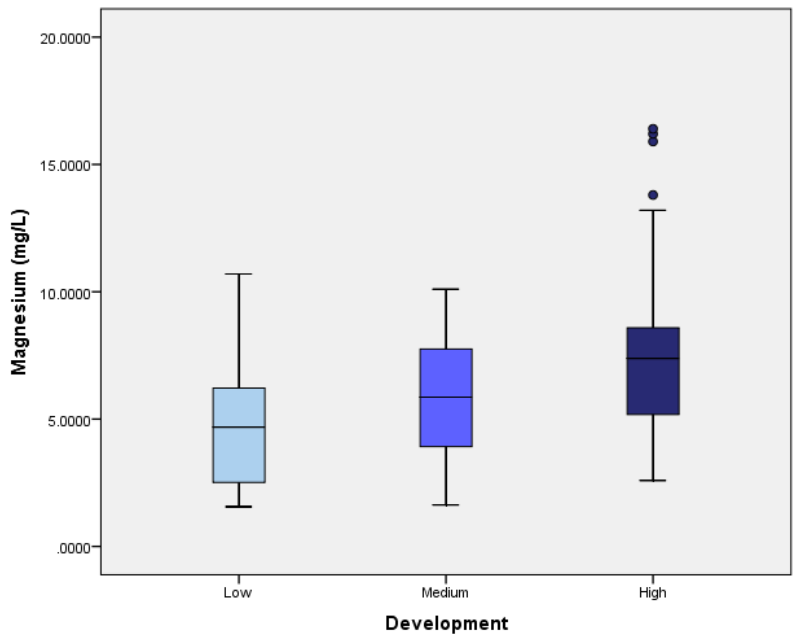

Figure 17: Box plot showing ranges of magnesium concentrations in areas with low, medium, and high development levels with no GI present in the dry season

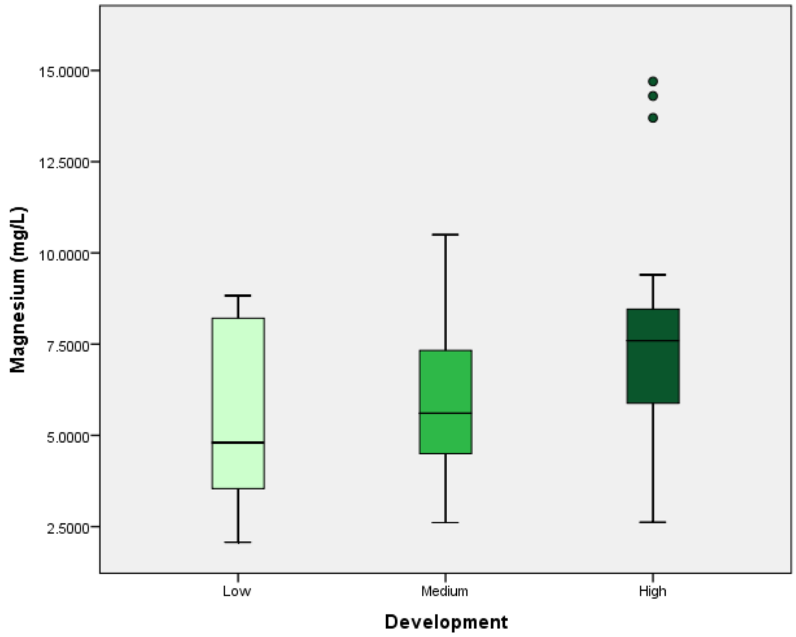

Figure 18: Box plot showing ranges of magnesium concentrations in areas with low, medium, and high development levels with GI in the dry season

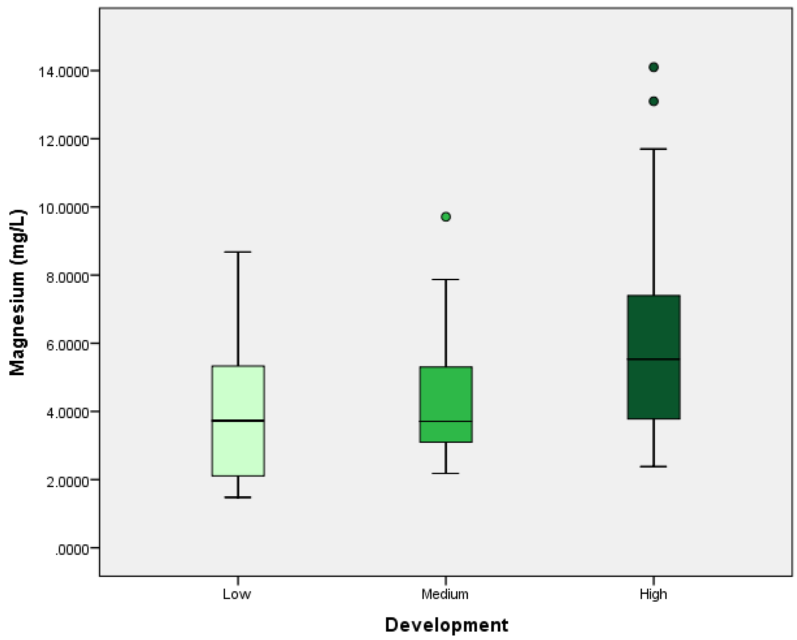

Figure 19: Box plot showing ranges of magnesium concentrations in areas with low, medium, and high development levels with GI in the wet season

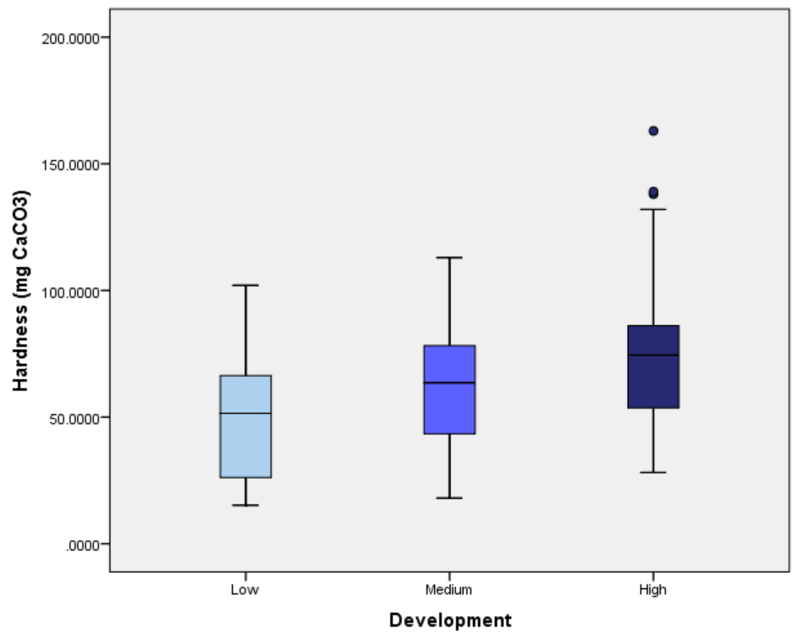

Figure 20: Box plot showing ranges of water hardness in areas with low, medium, and high development levels with no GI present in the dry season

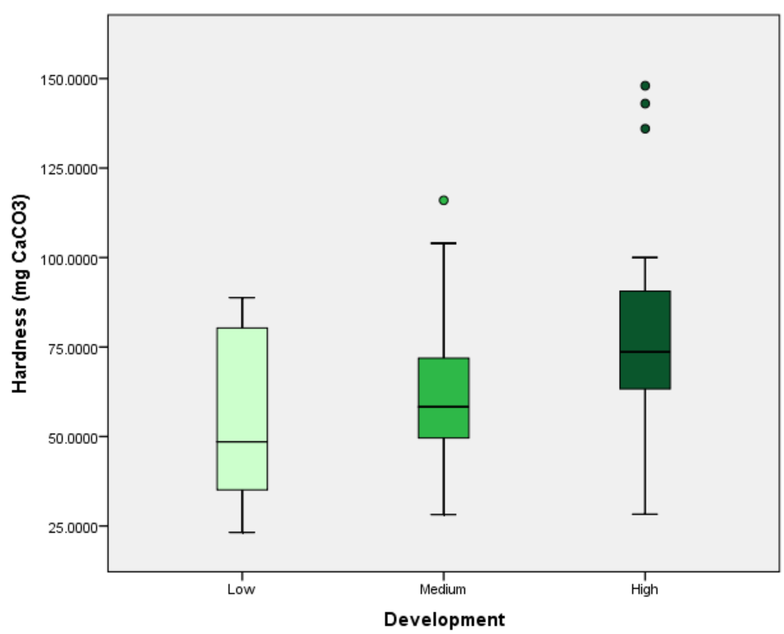

Figure 21: Box plot showing ranges of water hardness in areas with low, medium, and high development levels with GI in the dry season

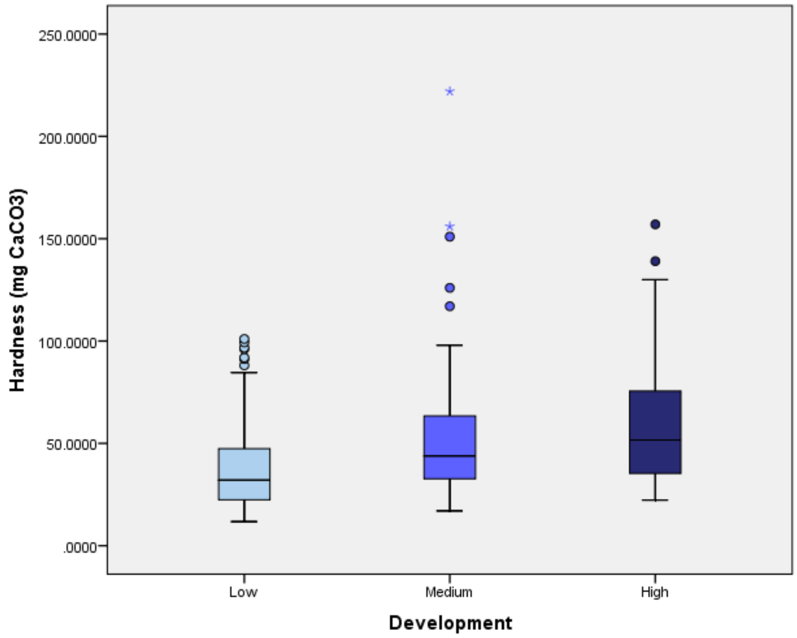

Figure 22: Box plot showing ranges of water hardness in areas with low, medium, and high development levels with no GI present in the wet season

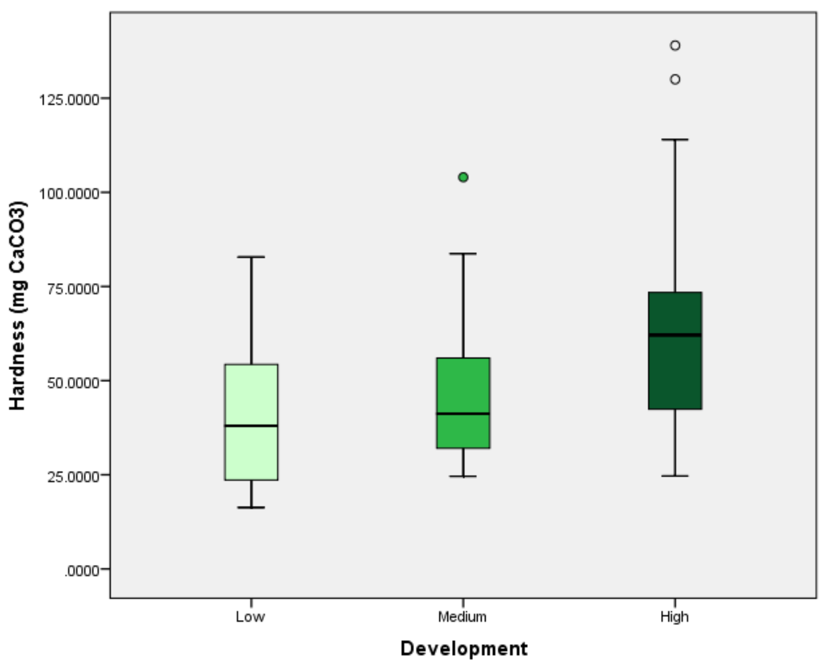

Figure 23: Box plot showing ranges of water hardness in areas with low, medium, and high development levels with GI in the wet season

Table 6: Results from independent samples t-test with grouping by GI

	Land Use	Mean		Levene's test for equality of variances	Independent Samples test

Element Analyte	Development Level	Season	GI absent	GI present	unit	p-value	p-value
Calcium	High	dry	17.07	18.27	mg/L	0.729	0.265
		wet	13.93	14.88		0.519	0.268
	Medium	dry	15.18	14.70		0.271	0.702
		wet	12.75	10.99		0.002	0.054
	low	dry	12.06	13.28		0.728	0.487
		wet	9.05	9.80		0.462	0.466
Copper	High	dry	1.754	1.090	ug/L	0.001	0.006
		wet	2.846	1.834		0.021	0.091
	Medium	dry	1.668	1.545		0.933	0.607
		wet	2.406	2.271		0.931	0.7
	low	dry	1.631	4.139		<0.001	0.049
		wet	1.7	2.1		0.38	0.222
Dissolved Copper	High	dry	1.127	0.655	ug/L	0.015	0.004
		wet	1.310	0.975		0.011	0.029
	Medium	dry	0.937	1.003		0.942	0.575
		wet	1.147	1.047		0.213	0.358
	low	dry	0.739	2.705		<0.001	0.01
		wet	0.738	1.223		<0.001	<0.001
Hardness	High	dry	72.5	76.0	mg CaCO3	0.302	0.44
		wet	57.8	61.3		0.319	0.34
	Medium	dry	62.0	60.8		0.406	0.809
		wet	51.3	45.2		0.005	0.1
	low	dry	49.5	56.0		0.519	0.364
		wet	37.5	40.8		0.457	0.439
Lead	High	dry	0.491	0.323	ug/L	0.01	0.127
		wet	1.203	0.749		0.001	0.09
	Medium	dry	0.723	0.377		0.164	0.201
		wet	1.141	0.894		0.332	0.304
	low	dry	0.744	0.375		0.297	0.381
		wet	0.798	0.758		0.373	0.893
Dissolved Lead	High	dry	0.118	0.100	ug/L	0.003	0.111
		wet	0.158	0.120		0.001	0.058
	Medium	dry	0.123	0.107		0.063	0.341
		wet	0.167	0.124		<0.001	0.034
	low	dry	0.122	0.137		0.212	0.307
		wet	0.140	0.173		0.034	0.088
Magnesium	High	dry	7.25	7.38	mg/L	0.112	0.782
		wet	5.60	5.87		0.178	0.492
	Medium	dry	5.86	5.86		0.631	0.992
		wet	4.71	4.30		0.015	0.246
	low	dry	4.70	5.55		0.356	0.225
		wet	3.61	3.95		0.514	0.412
Mercury	High	dry	0.00221	0.00173	ug/L	0.049	0.07
		wet	0.00396	0.00341		0.007	0.31
	Medium	dry	0.00299	0.00245		0.421	0.319
		wet	0.00458	0.00428		0.701	0.664
	low	dry	0.00420	0.00317		0.356	0.61
		wet	0.00466	0.00964		<0.001	0.012
Zinc	High	dry	7.66	4.52	ug/L	0.053	0.088
		wet	18.03	12.73		0.232	0.305
	Medium	dry	7.66	5.05		0.175	0.281
		wet	11.72	19.17		0.029	0.154
	low	dry	4.98	5.66		0.256	0.77
		wet	5.63	5.44		0.526	0.927
Dissolved Zinc	High	dry	4.31	2.34	ug/L	0.124	0.177
		wet	8.91	7.84		0.919	0.711

	Medium	dry	3.79	2.34		0.154	0.443
		wet	4.83	12.37		0.006	0.107
	low	dry	1.52	3.54		0.001	0.05
		wet	1.79	2.24		0.549	0.583

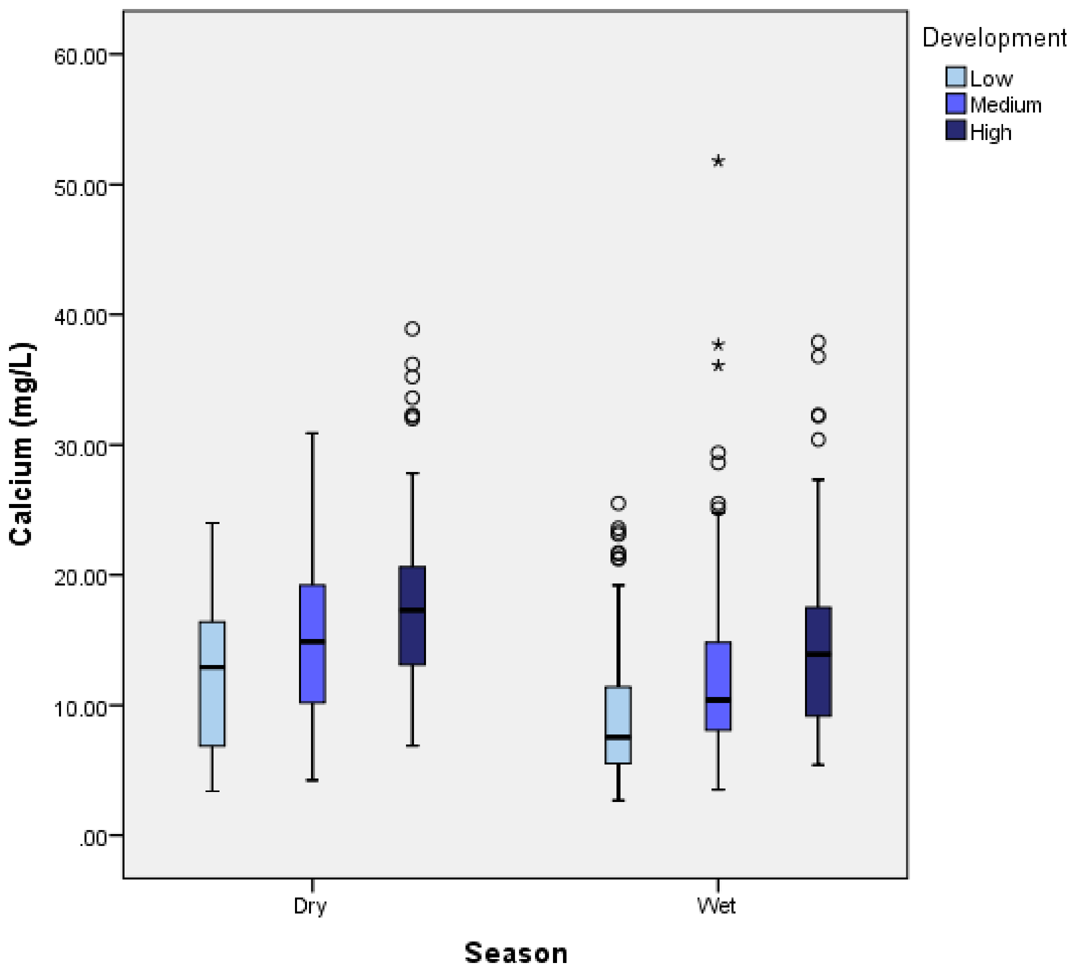

Figure 24: Box plot showing concentration of calcium across all locations, grouped by season, clustered by development

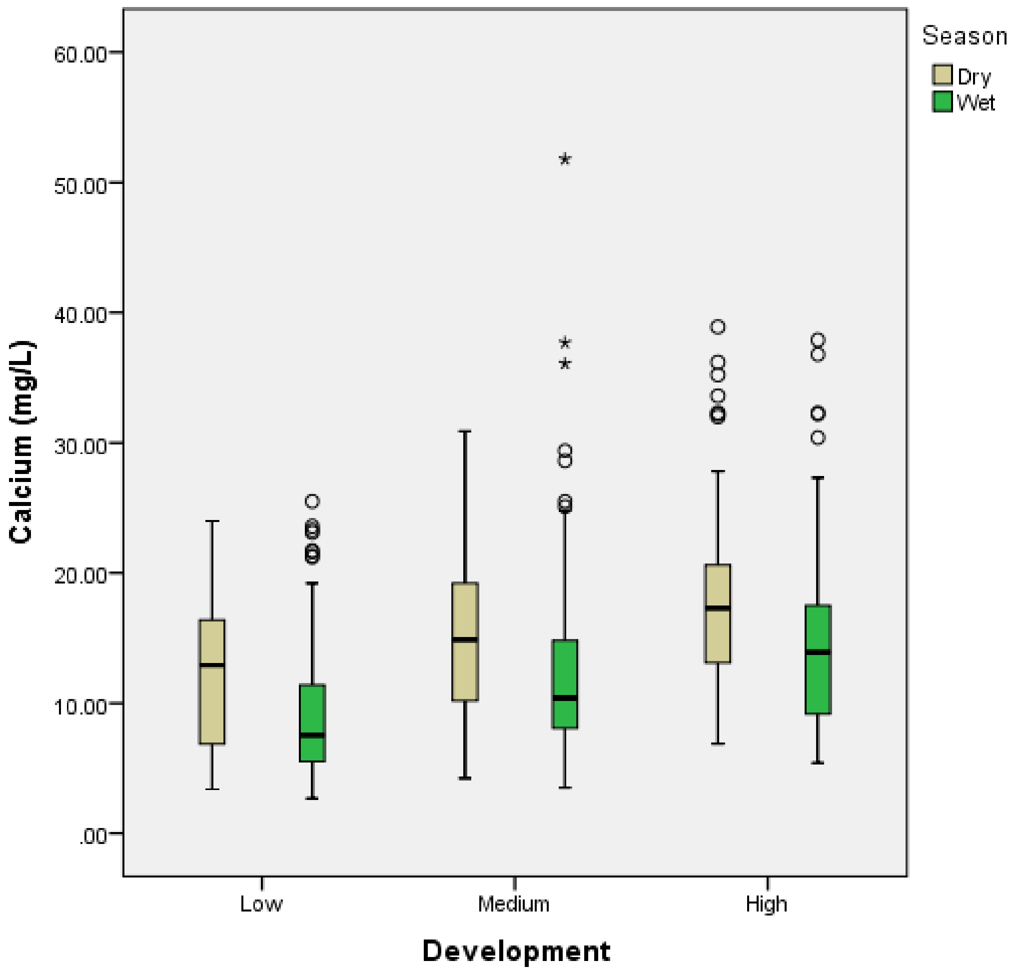

Figure 25: Box plot showing concentrations of calcium across all locations, grouped by development and clustered by season

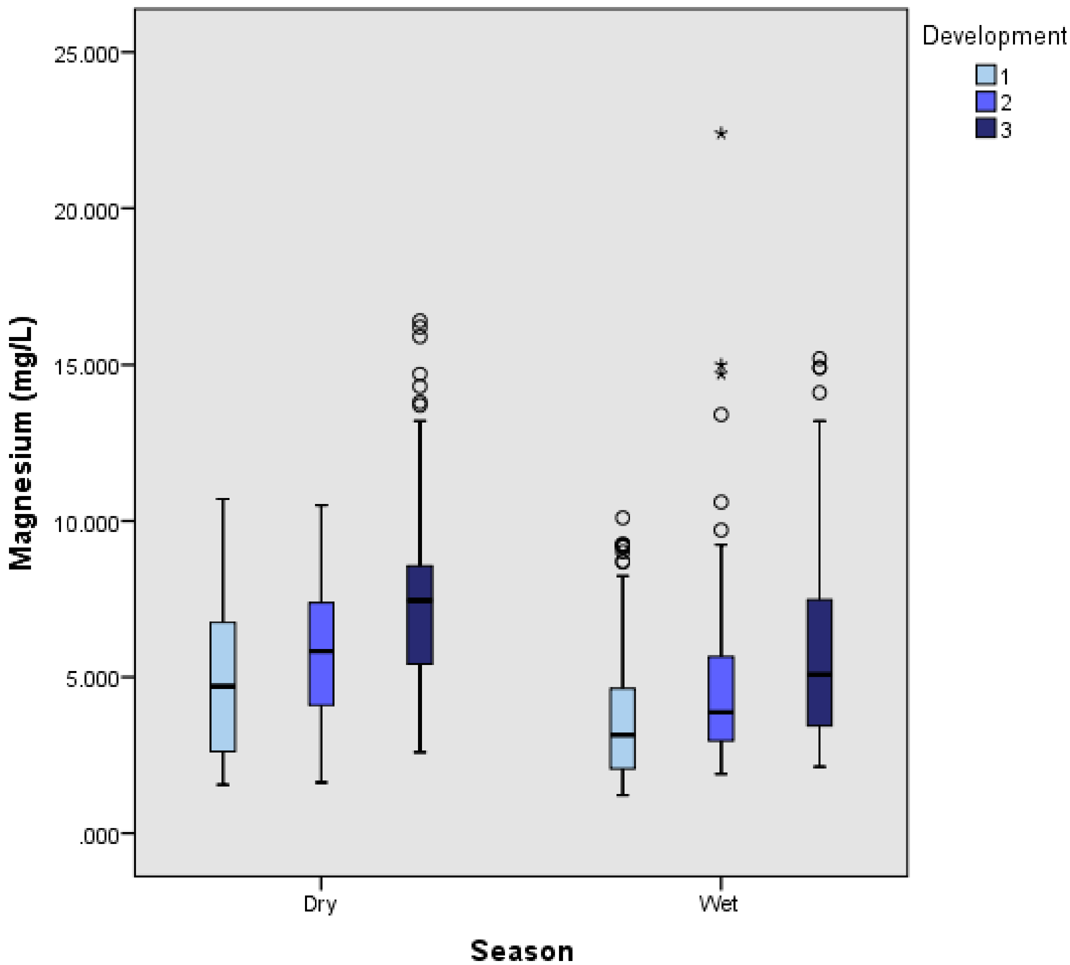

Figure 26: Box plot showing concentrations of magnesium across all locations, grouped by season and clustered by development

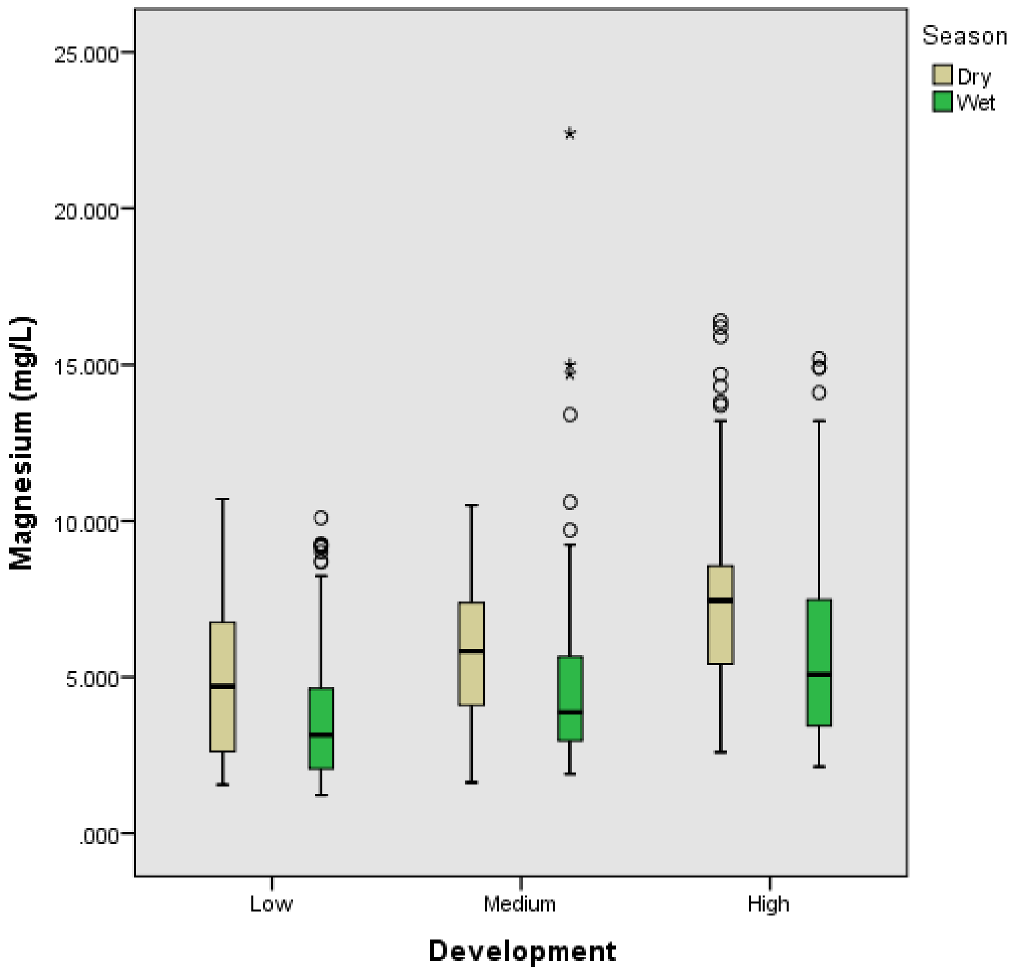

Figure 27:Box plot showing concentrations of magnesium across all locations, grouped by development and clustered by season

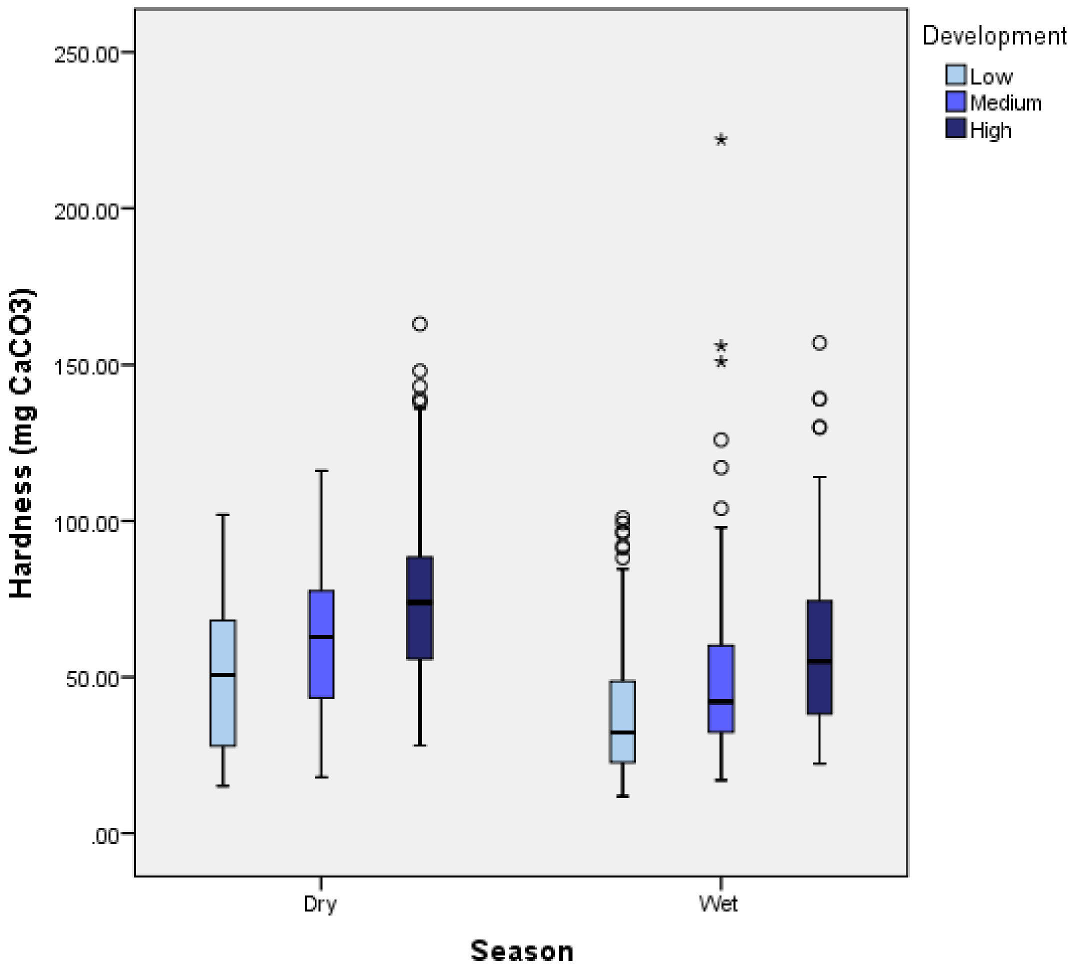

Figure 28: Box plot showing water hardness across all locations, grouped by season and clustered by development

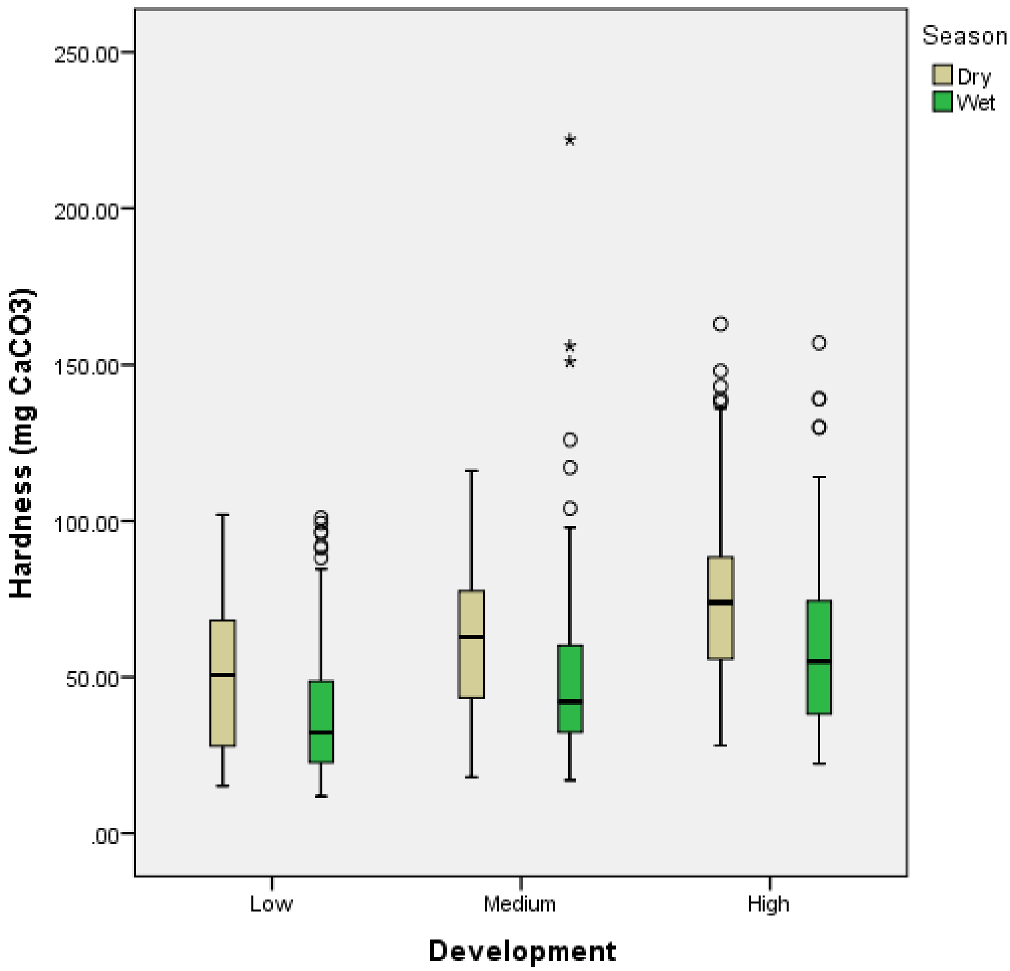

Figure 29: Box plot showing water hardness across all locations, grouped by development and clustered by season

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