University of Sri Jayewardenepura

Impact of Clear Cutting and Replanting on Runoff Patterns and Sedimentation Dynamics: A Case Study In Naturalized Nature Pine Plantation In Tropical Lowland Sri Lanka.

STA 474 2.0 Statistical Consultancy

Submitted By

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Table of Contents

List of Figures

List of Tables

1 Introduction

The impact of forestry practices on environmental dynamics is a critical area of study, particularly in the context of tropical lowland regions. This research focuses on a case study conducted in a naturalized mature Pine plantation in Sri Lanka, examining the effects of clear cutting and replanting on runoff patterns and sedimentation dynamics. The significance of this study lies in its investigation of the hydrological and soil erosion processes, which are pivotal in understanding the ecological consequences of forest management strategies.

Mature plantations, such as those of Pine, are often subjected to felling, which can lead to substantial environmental impacts. Among these, alterations in the hydrological regime and sediment transport processes are of particular concern. These changes have the potential to increase both the magnitude and frequency of surface runoff and soil erosion, thereby posing risks to the ecosystem's stability and health.

In this study, three runoff plots were constructed within the Pine plantation to represent the vegetation accurately. These plots differ in slope angle, canopy cover percentage, litter thickness, and the number of trees, which are factors that influence runoff and sediment generation.

The primary goal was to analyze these data to address the study's objectives. It is important to note that the client, given their domain knowledge in forestry, will be directly assessing species diversity, forest density, and the structure of the naturalized mature Pine forests. Additionally, the client will handle the quantification of pre- and post-harvesting sedimentation to assess changes in inter-plot sedimentation variations, as the sedimentation data was not provided to us.

Our specific objectives in this research were:

1. To quantify pre- and post-harvesting runoff to assess changes in inter-plot runoff variations.
2. To identify the factors that have a major impact on runoff variation among the three plots.

These insights will contribute to the broader knowledge of forest hydrology and inform sustainable forestry practices in tropical lowland regions.

2. Methodology

2.1 Research Design

This study utilized a case study design to investigate the impact of clear cutting and replanting on runoff patterns and sedimentation dynamics in a naturalized mature pine plantation in tropical lowland in Sri Lanka. The analysis was conducted using primary in data collected by undergraduate student, Sithumi Lakshani Balahewa from the University of Sri Jayewardenepura B.Sc. Honors in Environmental Management and Forestry department.

2.2 Data Collection

Data were collected in three phases:

1. Before Felling
2. After Felling
3. After Replanting

The dataset included variables as follows:

Variable Name	Type	Description
Runoff	Quantitative	Response Variable
Rainfall	Quantitative	Uncontrollable Explanatory Variable
Litter Thickness (LT)	Quantitative	Explanatory Variable
Ground Cover Vegetation Percentage (GCVP)	Quantitative	Explanatory Variable
Basel Area	Quantitative	Explanatory Variable
Phase	Qualitative	Before Felling (BF) After Felling (AF) After Replanting (AR)
Plot No	Qualitative	Plot 1 Plot 2 Plot 3

Table 1: Study Variables and Type

2.3 Data Cleaning

The initial dataset, consisting of 234 observations, was first transformed into a Tibble format using R software to facilitate data management and analysis, subsequently, data cleaning procedure were implemented. Given that rainfall is an uncontrollable variable, outliers were identified and removed using box plots specially for rainfall in each of the three phases (before felling, after felling, after replanting). Six outliers were detected and removed based on the box plots. After outlier removal, the dataset was refined to 228 observations; maintain the Tibble format for future analysis.

2.4 Data Analysis

2.4.1 Descriptive Analysis

To address the first objective, which is to assess species diversity, forest density, and structure of the naturalized mature pine forests, descriptive statistics were conducted. Measures such as mean, median, mode, standard deviation and frequency distribution were calculated to summarize the key characteristics of the data set.

2.4.2 Inferential statistics

2.4.2.1 Analysis of Covariance

To quantify pre and post harvesting runoff and assess changes in inter-plot runoff variation, an Analysis of Covariance (ANCOVA) was performed. In this analysis, all quantitative variables including litter thickness, ground percentage, basal area, and rainfall were chosen as covariates. This approach allows for controlling the effects of these variables while examining the differences in runoff across the three phases of data collection (before felling, after felling, after replanting).

2.4.2.2 Regression Analysis

To identify the factors that have a major impact on runoff variations among the three plots, multiple regression analysis was conducted. The response variable was runoff, and the predictor variables included litter thickness, ground percentage, Basel area, slope, and the rainfall. This analysis helped determine the relative influence of each factor on runoff patterns.

2.5 Limitations

Measurement Accuracy: Variability in measurements accuracy may be present due to the nature of data collection procedure.

Unequal Sample Sizes: The inability to control rainfall results in unequal sample sizes across the three phases of data collection. For instance, before felling phase, rainfall measurements vary between 1 to 18 units. In contrast, other phases exhibit larger sample sizes due to substantial rainfall events.

Outlier Removal: The removal outliers based on rainfall may affect the generalizability of the results to all potential rainfall conditions.

2.6 Ethical Consideration

As this study utilized pre-existing data collected by Sithumi Lakshani Balahewa for her undergraduate research and did not involve direct interaction with human subjects, the primary ethical considerations focused on ensuring the accuracy, validity, and appropriate use of the secondary data. Measures were taken ensure that the data were accurately recorded and appropriately utilized for research purposes.

3 Explanatory Data Analysis

3.1 Composition of the Sample

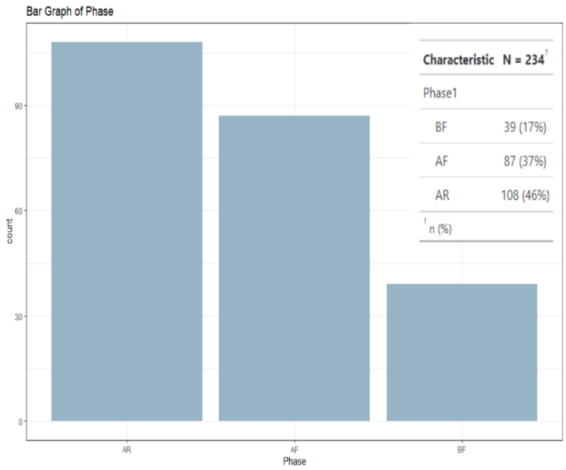


Figure 1: Bar graph of phase

According to the figure 1,

- Phase is not uniformly distributed in the sample.

3.2 Data Description of the Sample

3.2.1 One variable at a time

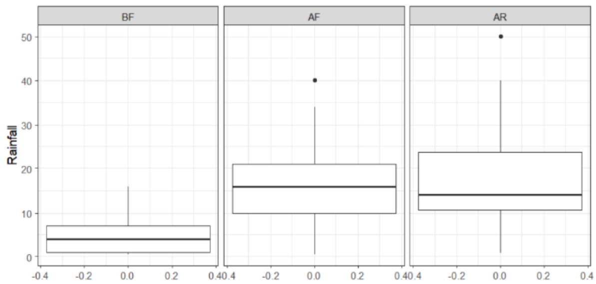


Figure 2: Box plot of Rainfall with outliers

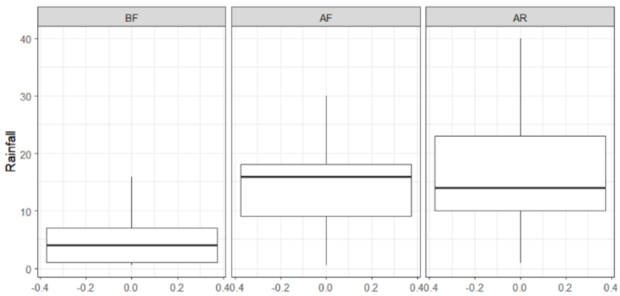


Figure 3: Box plot of rainfall without outliers

According to the figure 2 and figure 3,

- Although "Rainfall was considered as an uncontrollable variable, outliers in this variable were removed.

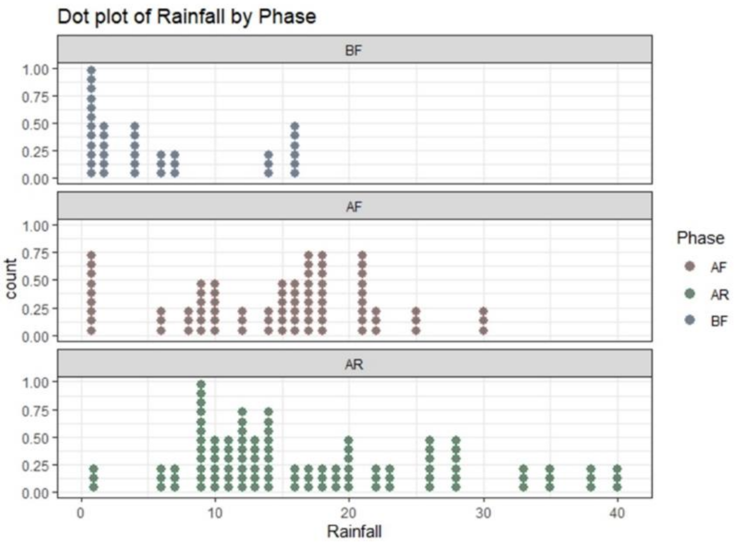


Figure 4: Dot plot of rainfall by phase

According to the figure 4,

- Approximately similar distribution in rainfall was observed in both After Felling (AF) & After Replanting (AR) Phases.
- However, there was a clear difference in Before Felling (BF) phase compared to other two phases.
- The distribution of rainfall in After Replanting and After Felling were approximately normal distributed, while the distribution of Before Felling was positively skewed.

Phase1	min	median	max	sd	IQR	mean
<fct>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>
BF	0.5	4	16	5.75	6	5.65
AF	0.5	16	30	7.22	9	14.3
AR	1	14	40	9.42	13	17.3

Table 2: Summary statistics of figure 4

According to the Table 2,

- Half of the rainfall data in BF phase have a value around 4 and middle 50% of rainfall data have a spread of 6 in that phase.
- However, in After Felling phase, average rainfall is 14.3 with a spread of 7.22.
- In After Replanting phase, the average rainfall is 17.3 with a spread of 9.42.
- The range considered for rainfall in After Replanting phase is higher compared to other phases.

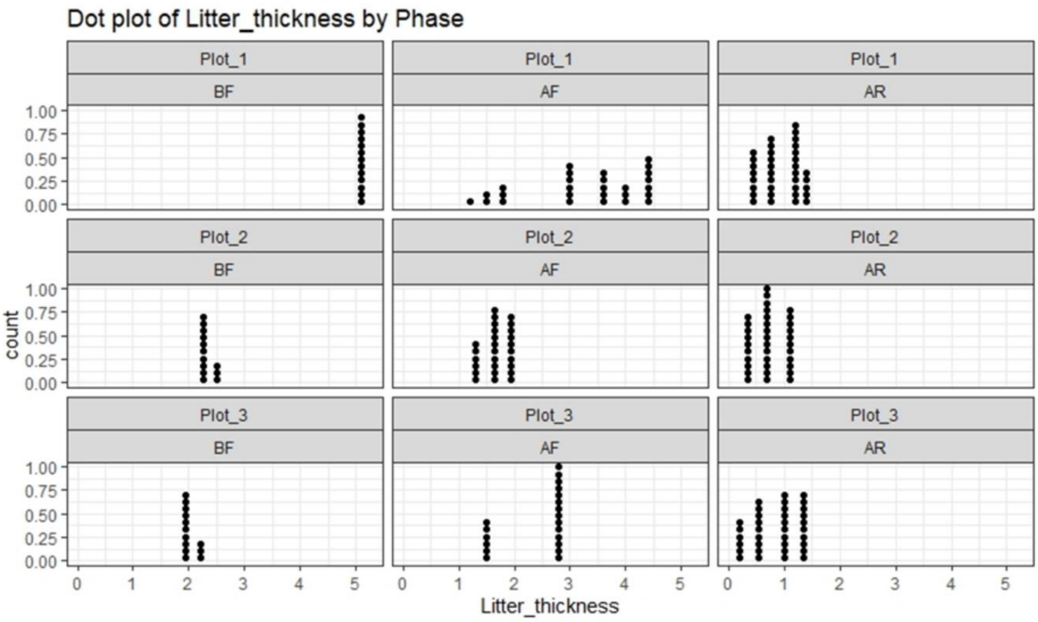


Figure 5: Dot plot of litter thickness by phase

According to the Figure 5,

- Litter thickness is differently distributed with respect to Phase and Plot number.
- Before Felling, Plot 1 Litter Thickness is higher compared with Before Felling other two plots.
- After Replanting Litter Thickness is low compared with other phases.

Phase1	Plot_No	min	median	max	sd	IQR	mean
<fct>	<chr>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>
BF	Plot_1	5	5.1	5.2	0.0801	0.100	5.08
BF	Plot_2	2.2	2.3	2.5	0.119	0.100	2.31
BF	Plot_3	1.9	2	2.2	0.114	0.100	2.02
AF	Plot_1	1.2	3.5	4.5	1.05	1.25	3.27
AF	Plot_2	1.3	1.7	2	0.248	0.300	1.69
AF	Plot_3	1.4	2.8	2.9	0.544	0.150	2.52
AR	Plot_1	0.4	0.8	1.4	0.352	0.6	0.929
AR	Plot_2	0.3	0.7	1.2	0.299	0.6	0.731
AR	Plot_3	0.2	0.9	1.4	0.418	0.8	0.829

Table 3: Summary Statistics of figure 5

According to Table 3,

- In After Replanting phase litter thickness shows approximately same distribution with a sample mean in between 0.8 and 0.9 and a SD in between 0.3 and 0.42.

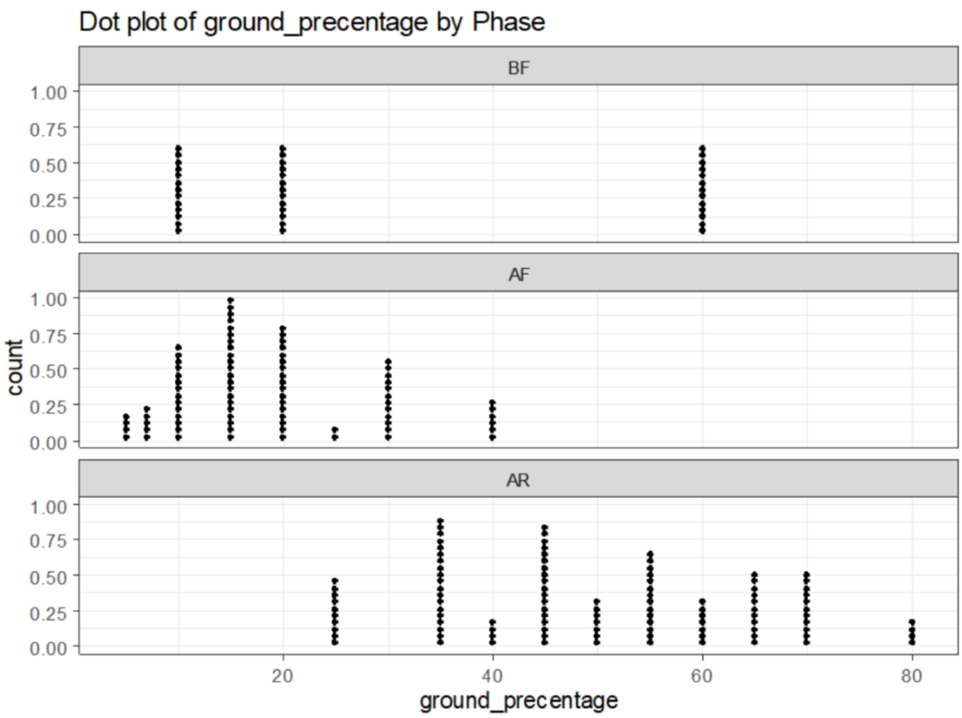


Figure 6: Dot plot of ground percentage by phase

According to the Figure 6,

- Ground Percentage in After Replanting phase is higher compared to the other two Phases.
- Ground percentage is approximately symmetrically distributed in both After Felling and After Replanting phases.

Phase1	min	median	max	sd	IQR	mean
<fct>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>
BF	10	20	60	21.9	50	30
AF	5	15	40	9.45	10	18.5
AR	25	50	80	14.8	25	49.8

Table 4: Summary statistics of figure 6

According to Table 4,

- In After Replanting phase, Ground Percentage has an average of 49.8 and SD 14.8
- In After Felling phase, Ground Percentage has an average of 18.5 and SD 9.45.

3.2.2 Two variable at a time

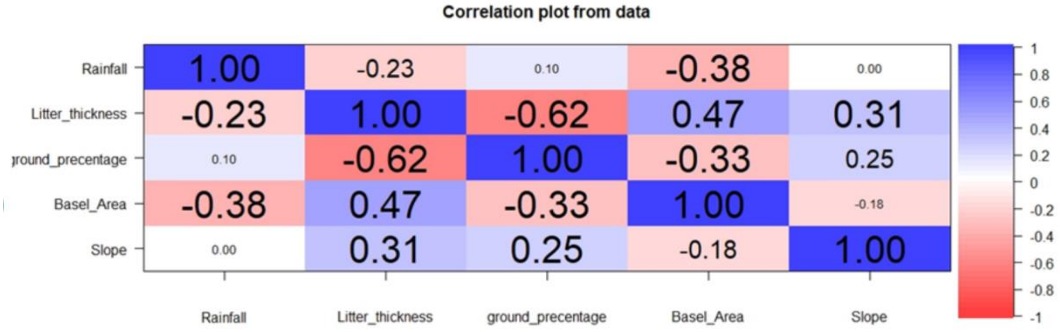


Figure 7: Correlation plot of Explanatory variables

According to the Figure 7,

- None of the predictors were strongly correlated.
- However, moderately negative correlations were observed between two variables (litter thickness and GCVP) while some other variables showed either weak positive or negative correlations.

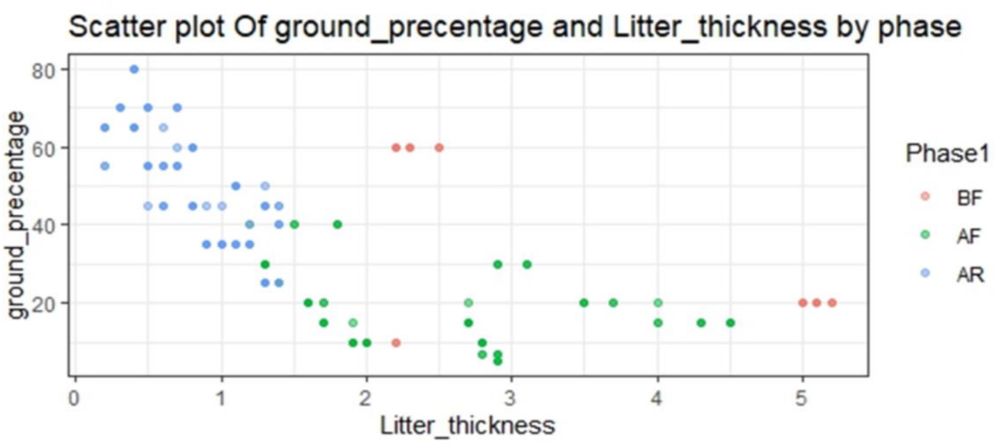


Figure 8: Scatter plot of Ground percentage and Litter thickness

According to the figure 8,

- Ground cover vegetation percentage and litter thickness showed approximately negative correlation when compared phase-wise.

3.2.3 Response Variable

Figure 9: Correlation plot between Runoff and Explanatory variables

According to the Figure 9,

- Rainfall and runoff show a strong positive correlation.
- Basel area shows a moderately negative relationship with runoff.
- Other explanatory variables display weak correlations (near zero) with runoff.

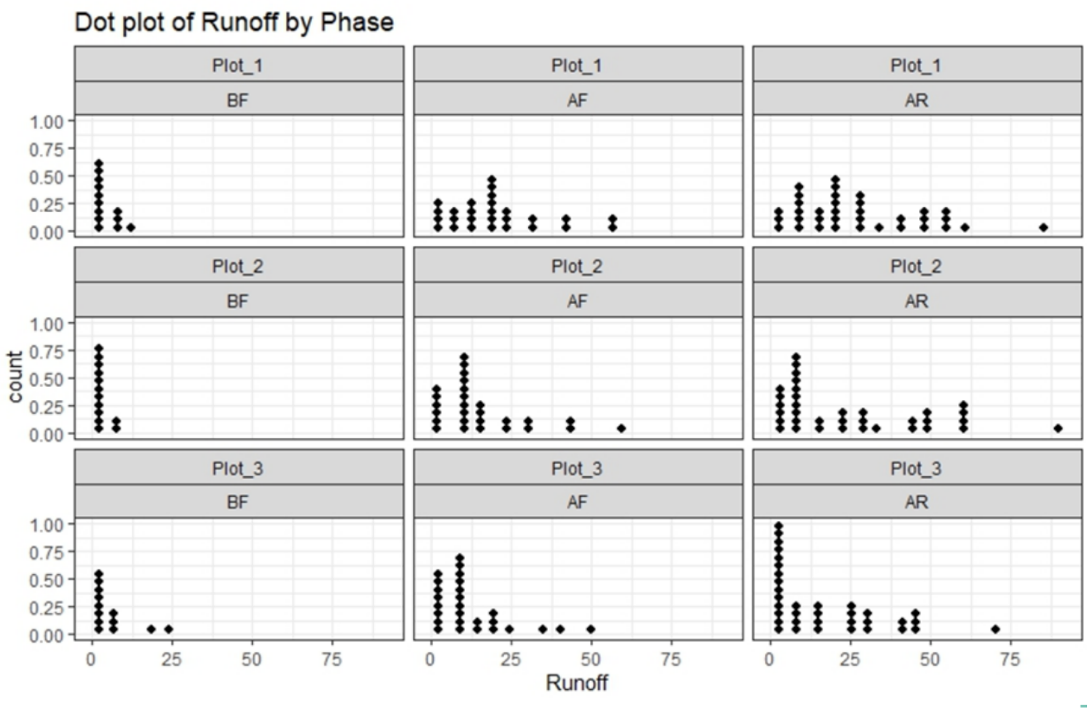


Figure 10: Dot plot of Runoff by Phase

According to the Figure 10,

- Within each plot, runoff distribution is approximately the same with respective to phase.
- In before felling phase, runoff is much lower compared to other two phases.

Phase1	Plot_No	min	median	max	sd	IQR	mean
<fct>	<chr>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>
BF	Plot_1	0	3.2	12.1	4.19	5.86	3.75
BF	Plot_2	0	1.57	8.1	2.80	4.13	2.36
BF	Plot_3	0	3.9	24.1	7.66	6.4	5.60
AF	Plot_1	0	18.4	58	15.5	14.2	19.9
AF	Plot_2	0	11.6	59.3	14.6	11.1	15.8
AF	Plot_3	0	8.7	50	12.6	12.7	12.5
AR	Plot_1	0.42	22	85.2	19.5	29.2	27.7
AR	Plot_2	0.5	16.0	90	22.9	38.2	25.2
AR	Plot_3	0.3	10.3	70.2	17.5	25.0	17.3

Table 5: Summary statistics for Figure 10

According to the Table 5,

- Between plots in same phase Runoff distributions are approximately same.
- Before Felling phase, Runoff distribution is lower compared with other two phases in each plot.

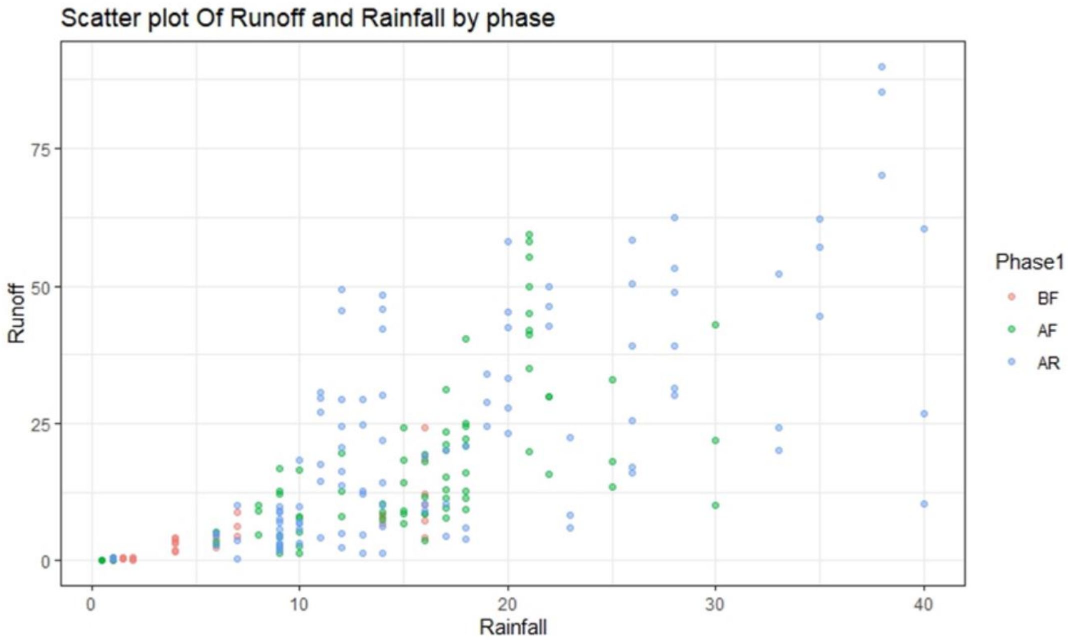


Figure 11: Scatter plot of Runoff vs Rainfall

According to the figure 11,

- There is a positive linear relationship between runoff and rainfall.

4. Results

4.1 R Packages Used

```
library(readxl)     # Import data from excel file
library(tidyverse)  # For data manipulation and visualization
library(broom)      # To print tidy summaries of statistical tests as data frames
library(rstatix)    # For easy pipe-friendly statistical analyses
library(car)        # To assess homogeneity of error variances & multicollinearity
library(lindia)     # Influential Outliers
```

Figure 12: R Packages Used

4.2 Data Pre-processing

```
names <- c(1,2,8)
data[,names] <- lapply(data[,names], factor)
data$Slope <- relevel(data$Slope, ref = '23')
data$Phase <- relevel(data$Phase, ref = 'BF')
str(data)


## tibble [228 × 10] (S3: tbl_df/tbl/data.frame)
##  $ Plot No     : Factor w/ 3 levels "1","2","3": 1 1 1 1 1 1 1 1 1 1 ...
##  $ Phase       : Factor w/ 3 levels "BF","AF","AR": 1 1 1 1 1 1 1 1 1 1 ...
##  $ Rainfall    : num [1:228] 6 16 1.5 0.5 7 14 0.5 1 1 2 ...
##  $ Runoff      : num [1:228] 4.11 12.11 0.3 0 6.16 ...
##  $ LT          : num [1:228] 5.2 5.2 5.2 5.1 5.1 5.1 5.1 5.1 5 5 ...
##  $ GCVP        : num [1:228] 20 20 20 20 20 20 20 20 20 20 ...
##  $ Basel Area  : num [1:228] 0.42 0.42 0.42 0.42 0.42 0.42 0.42 0.42 0.42 0.42 ...
##  $ Slope       : Factor w/ 3 levels "23","26","31": 3 3 3 3 3 3 3 3 3 3 ...
##  $ Runoff_sqrt : num [1:228] 2.027 3.48 0.548 0 2.482 ...
##  $ Log_Runoff+1: num [1:228] 1.631 2.573 0.262 0 1.969 ...
```

Figure 13: R Code and Output of Pre-processed Data

4.3 Model Building

4.3.1 Procedure

Seven ANCOVA models which met the required model assumptions were built. However, since the “Slope” measurements were same for each plot number, this made the two variables (Slope and ‘Plot No’) highly correlated. Therefore, slope was dropped when building the ANCOVA model.

4.4 Model Selection

4.4.1 Procedure

Two models were identified to meet the following research objectives:

1. To quantify pre- and post-harvesting runoff and assess changes in inter-plot runoff variations - **Analysis of Covariance (ANCOVA) Model**
2. To identify the factors that have a major impact on runoff variation among the three plots - **Multiple Linear Regression (MLR) Model**

4.4.2 ANCOVA Model

This model was built on 180 observations after addressing for multicollinearity and by eliminating influential outliers using Cook's Distance. Refer Appendix A for model diagnostics.

```
model_7 <- lm(`Log_Runoff+1` ~ Rainfall + Phase + `Plot No` + GCVP, data = df6)
summary(model_7)
##
## Call:
## lm(formula = `Log_Runoff+1` ~ Rainfall + Phase + `Plot No` +
##     GCVP, data = df6)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -0.91749 -0.28019 -0.06101  0.31446  1.04388
##
## Coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept)  1.227618   0.137427   8.933 6.01e-16 ***
## Rainfall     0.100219   0.004629  21.650  < 2e-16 ***
## PhaseAF      0.421923   0.110986   3.802 0.000199 ***
## PhaseAR      0.832759   0.115597   7.204 1.73e-11 ***
## `Plot No`2  -0.324758   0.077893  -4.169 4.82e-05 ***
## `Plot No`3  -0.992549   0.085360 -11.628  < 2e-16 ***
## GCVP        -0.011931   0.002499  -4.775 3.81e-06 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.4299 on 173 degrees of freedom
## Multiple R-squared:  0.8539, Adjusted R-squared:  0.8488
## F-statistic: 168.5 on 6 and 173 DF,  p-value: < 2.2e-16
```

Figure 14: ANCOVA Model Output

4.4.3 Multiple Linear Regression Model

This model was built on 228 observations after eliminating potential outliers in Exploratory Data Analysis (EDA), excluding the variable "Basel Area" to address issues with multicollinearity. Refer Appendix B for model diagnostics.

```
model_B <- lm(`Log_Runoff+1` ~ Rainfall + Phase + Slope + GCVP + LT, data = data)
summary(model_B)
##
## Call:
## lm(formula = `Log_Runoff+1` ~ Rainfall + Phase + Slope + GCVP +
##     LT, data = data)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -1.72087 -0.46651 -0.01162  0.40852  1.73973
##
## Coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept)  1.020327   0.298183   3.422 0.000742 ***
## Rainfall     0.090429   0.005198  17.396  < 2e-16 ***
## PhaseAF      0.199763   0.158713   1.259 0.209494
## PhaseAR      0.759423   0.203947   3.724 0.000250 ***
## Slope26      0.492243   0.116756   4.216 3.63e-05 ***
## Slope31      0.833547   0.147818   5.639 5.22e-08 ***
## GCVP        -0.018962   0.003985  -4.758 3.54e-06 ***
## LT          -0.093525   0.074608  -1.254 0.211335
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.6472 on 220 degrees of freedom
## Multiple R-squared:  0.7155, Adjusted R-squared:  0.7065
## F-statistic: 79.06 on 7 and 220 DF,  p-value: < 2.2e-16
```

Figure 15: Multiple Linear Regression (MLR) Model Output

5. Discussion

In this study, there were three main objectives and one sub-objective. The primary objective was to assess species diversity, forest density, and the structure of naturalized mature Pine forests. It is important to note that the client, given their domain knowledge in forestry, will be directly assessing species diversity, forest density, and the structure of the naturalized mature Pine forests.

Initially, an exploratory data analysis (EDA) was conducted to read about the data set and get an idea about it. As the results of that, it was found that the sample composition is unbalanced according to the phase. Accordingly, this can be underlined as a factor that could possibly affect the accuracy of the results provided by this study.

Overall, the provided EDA offers a comprehensive view of forest density and structure, with indirect insights into species diversity. Further detailed species-specific data would be necessary for a more accurate assessment of biodiversity.

Moreover, rainfall was an uncontrollable variable in this study. As noted by the client, there was less rainfall than expected during the before felling phase, whereas relatively more rainfall was received in the subsequent phases. Therefore, the effect of rainfall was considered when analyzing the impact of the phases on runoff.

Besides since no strong correlations were observed among variables, all the variables were included in model building initially. However, in model building, the log transformation of runoff values was used as the response variable. This transformation was necessary because using the original runoff values resulted in violations of the normality and constant variance assumptions in both models. One unit was added to each runoff value before applying the log transformation, as there were zero values in some runoff measurements, which prevented direct log transformation.

Moving towards the analysis, the second objective was to quantify pre- and post-harvesting runoff to assess changes in inter-plot runoff variations. The quantitative variable rainfall, which has a strong correlation with runoff, and several other quantitative variables were considered as covariates, while phase and plot number were taken as treatments. Consequently, there was 2 grouping variables and 5 covariates. So, for this study two-way ANCOVA (Factorial ANCOVA) was the most suitable statistical technique which is used to evaluate simultaneously the effect of two independent grouping variables on an outcome variable, after adjusting for one or more continuous variables, called covariates. However, since the slope measurements were the same for each plot number, slope and plot number became highly correlated. Therefore, slope was dropped when building the ANCOVA model.

The first step was to fit an ANCOVA model. After fitting the initial model, multicollinearity between basal area and litter thickness was identified based on the Generalized Variance Inflation Factor (GVIF). Consequently, these two variables were dropped from the model one by one, and a new model was fitted each time. GVIF was used instead of VIF due to the presence of two categorical variables.

In the next couple of models, influential outliers were identified and deleted based on Cook's distance, reducing the dataset to 180 observations. Model assumptions were also tested, including homogeneity of regression slopes, linearity of covariates, presence of outliers, normality of error terms and heteroscedasticity.

Since all the model satisfied the model assumptions, Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) was considered when selecting the best model.

Accordingly, based on the smallest AIC and BIC values, the seventh model was selected as the best model. An ANCOVA table was then obtained for this model.

The final ANCOVA model provided insights into the effects of the phases and plot numbers on runoff. The analysis revealed significant changes in runoff associated with different phases and plot numbers.

Phases:

- **PhaseAF (After Felling phase)**: Compared to the "Before Felling phase," runoff on average was approximately **52.5%** higher in the "After Felling phase" after controlling for other variables. This increase indicated that tree felling significantly impacts runoff, possibly due to reduced vegetation and increased surface water flow.
- **PhaseAR (After Replanting phase)**: Compared to the "Before Felling phase," runoff on average was approximately **130%** higher in the "After Replanting phase" after controlling for other variables. The substantial increase in runoff suggested that even after replanting, the landscape does not immediately return to its pre-felling hydrological state, likely due to immature vegetation not yet providing sufficient ground cover or root stabilization.

Plot Numbers:

- **Plot No 2**: Compared to Plot No 1, runoff on average was approximately **27.7%** lower in Plot No 2, after controlling for other variables. This reduction could be due to differences in soil composition, micro-topography, or other site-specific characteristics that affect water absorption and runoff.

- **Plot No 3**: Compared to Plot No 1, runoff on average was approximately **63.0%** lower in Plot No 3, after controlling for other variables. The significant decrease in runoff for Plot No 3 suggested even more pronounced site-specific factors influencing hydrological responses, potentially including better water retention properties or different vegetation types.

These findings underscore the importance of considering both the temporal phases of land use (pre- and post-harvesting) and spatial variations between plots when assessing runoff dynamics. The results highlight the necessity of targeted management practices to mitigate increased runoff in post-harvesting phases and account for plot-specific characteristics in water management strategies.

The third objective was to quantify pre- and post-harvesting sedimentation to assess changes in inter-plot sedimentation variation. However, the necessary data for this objective was not received, so data analysis related to this objective was not performed. If the dataset had been available, a multivariate analysis of variance (MANOVA) would have been conducted using runoff and sedimentation as response variables. This approach would have addressed the last two objectives simultaneously

Moreover, the client also wanted to identify the factors that have a major impact on runoff variation among the three plots which was regarded as a sub-objective in this study. To address this, a multiple regression (MLR) model was fitted using litter thickness, basal area, slope, GVCP, and phase as independent variables. Moreover, the plot number was used as replicates. The initial model indicated issues with multicollinearity involving the basal area. As a remedial measure, the basal area was dropped from the model, and a new model was fitted.

The new model satisfied all assumptions and did not indicate multicollinearity. Additionally, the adjusted R-squared value was approximately 70%, suggesting a good fit. This analysis revealed that rainfall, phases (especially After Replanting phase), and slope gradients (26 and 31 degrees) are the major factors impacting runoff variation among the three plots. Specifically:

- **Rainfall**: Each unit increase in rainfall results in an approximately 9.46% increase in runoff on average after controlling for other variables.
- **Phase AR (After Replanting phase)**: Compared to the Before Felling phase, runoff on average is approximately 113.6% higher in the After Replanting phase after controlling for other variables.
- **Slope**: Runoff on average is approximately 63.6% higher for a slope of 26 degrees and 130.1% higher for a slope of 31 degrees compared to the reference slope of 23 degrees after controlling for other variables.
- **GCVP**: Each unit increase in GCVP is associated with a 1.88% decrease in runoff on average after controlling for other variables.

These findings suggest that increased rainfall, after replanting conditions, and steeper slopes significantly contribute to higher runoff, while GCVP has a moderate negative impact on runoff after controlling for other variables. Adjustments in management practices considering these factors could help mitigate runoff variations and improve water management strategies in the plots.

6. Conclusion

In this study, we examined the impact of clear-cutting and replanting on runoff patterns and sedimentation dynamics within a naturalized Pine plantation in tropical lowland Sri Lanka. By collecting and analyzing data across three distinct phases; before felling, after felling, and after replanting, we aimed to provide a comprehensive understanding of how forestry practices influence hydrological processes and soil erosion.

Our findings highlighted several key points:

- Clear-cutting significantly altered the runoff patterns within the plantation. The removal of trees and subsequent exposure of the soil surface led to an increase in runoff volume. This was particularly evident immediately after the felling phase, where the lack of vegetation covers reduced water infiltration and increased surface runoff.

- Through multiple linear regression analysis, we identified key factors influencing runoff variation. Variables such as litter thickness, ground percentage, and slope were significant predictors of runoff, underscoring the importance of maintaining ground cover and soil structure in managing hydrological responses.

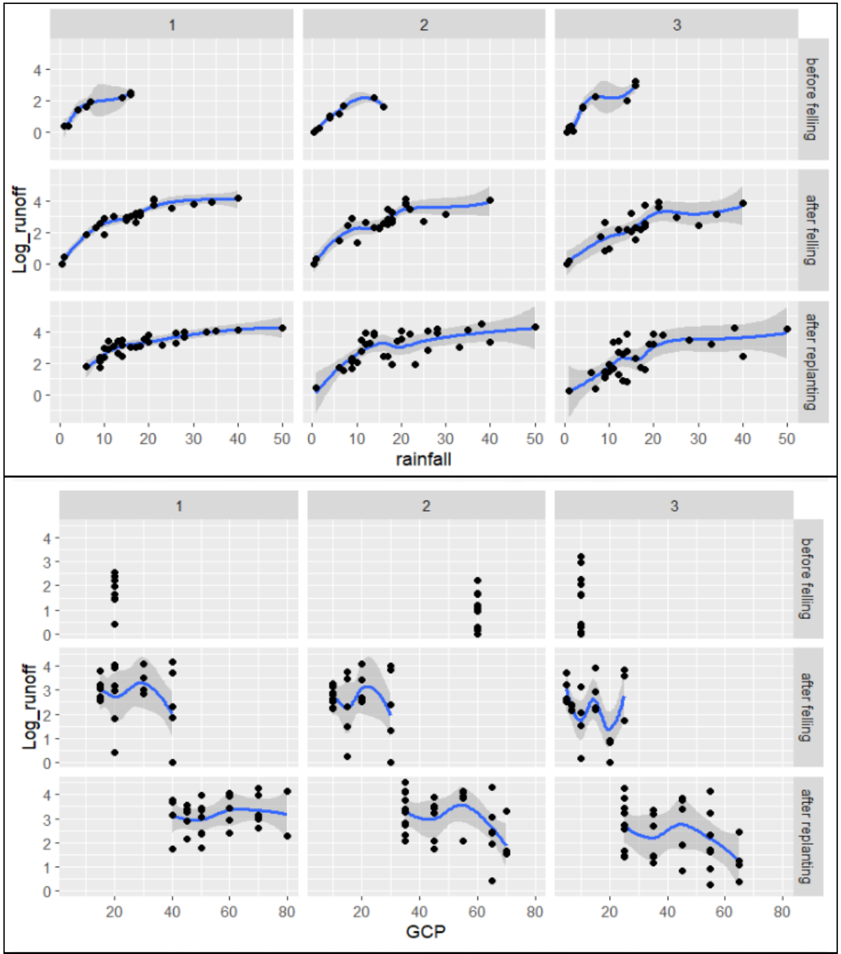
Our study underscores the critical need for sustainable forest management practices. Clear-cutting, while sometimes necessary, should be carefully planned and executed with considerations for its hydrological impacts. Replanting efforts must prioritize species that can quickly establish ground cover and enhance soil stability to mitigate adverse environmental effects.

Future studies should long-term monitoring beyond the initial replanting phase would offer valuable insights into the full recovery trajectory of runoff and sedimentation dynamics.

Overall, this research contributes to the growing body of knowledge on forest hydrology and highlights the importance of integrating environmental considerations into forest management practices.

4 Appendix A

Figure A.1 – Assessing Model Assumptions



ANOVA Table (type II tests)

	Effect	DFn	DFd	F	p	p<.05	ges
1	rainfall	1	168	306.581	9.95e-40	*	0.646
2	group	8	168	11.235	1.12e-12	*	0.349
3	GCP	1	168	32.148	6.11e-08	*	0.161
4	rainfall:group	8	168	1.634	1.19e-01		0.072
5	group:GCP	5	168	1.199	3.12e-01		0.034
6	rainfall:GCP	1	168	0.290	5.91e-01		0.002
7	rainfall:group:GCP	5	168	1.074	3.77e-01		0.031

Anova Table (Type II tests)

Response: Log_runoff+1

	Sum Sq	Df	F value	Pr(>F)	
rainfall	121.557	1	289.500	< 2.2e-16	***
Phases	19.319	2	23.005	1.169e-09	***
`plot number`	20.627	2	24.563	3.375e-10	***
GCP	15.277	1	36.385	8.494e-09	***
Phases:`plot number`	3.003	4	1.788	0.133	
Residuals	78.519	187			

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Figure A.2 - ANCOVA Model Diagnostics

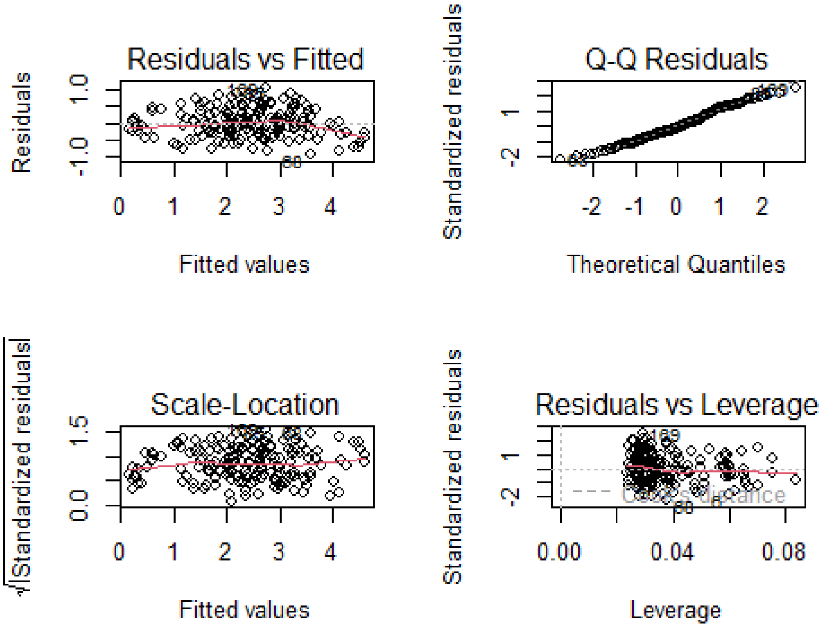


Figure A.3 - Normality of Residuals

```
##   variable                  statistic p.value
##   <chr>                         <dbl>   <dbl>
## 1 model.metrics7$.resid         0.986  0.0750
```

Figure A.4 - Homogeneity of Error Variances

```
## Non-constant Variance Score Test
## Variance formula: ~ fitted.values
## Chisquare = 1.540016, Df = 1, p = 0.21462
```

Figure A.5 – Multicollinearity

```
##                GVIF Df GVIF^(1/(2*Df))
## Rainfall   1.303861  1        1.141867
## Phase      2.922136  2        1.307450
## `Plot No`  1.271503  2        1.061890
## GCVP       2.491280  1        1.578379
```

Figure A.6 – Adjusted R squared, AIC and BIC values of the fitted ANCOVA models

```
##   model    adj.r.squared   AIC   BIC
##   <chr>            <dbl> <dbl> <dbl>
## 1 Model 1          0.706  458.  486.
## 2 Model 2          0.739  422.  449.
## 3 Model 3          0.769  386.  413.
## 4 Model 4          0.793  338.  364.
## 5 Model 5          0.825  284.  310.
## 6 Model 6          0.835  261.  287.
## 7 Model 7          0.849  216.  241.
```

5 Appendix B

Figure B.1 - Multiple Linear Regression Model Diagnostics

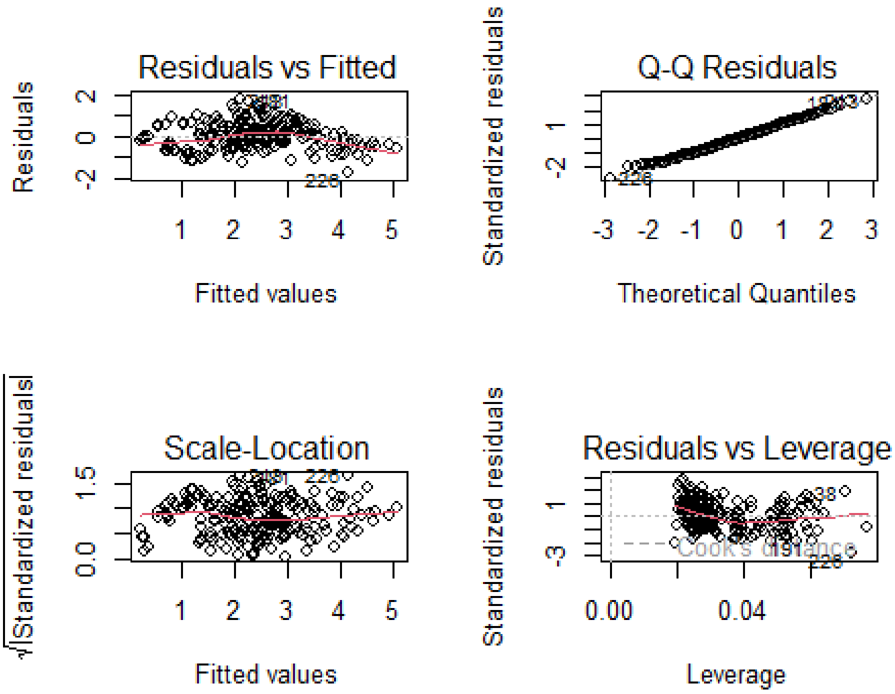


Figure B.2 - Normality of Residuals

```
##   variable                 statistic p.value
##   <chr>                        <dbl>   <dbl>
## 1 model.metricsB$.resid        0.995   0.599
```

Figure B.3 - Homogeneity of Error Variances

```
## Non-constant Variance Score Test
## Variance formula: ~ fitted.values
## Chisquare = 0.1666556, Df = 1, p = 0.6831
```

Figure B.4 – Multicollinearity

```
##              GVIF Df GVIF^(1/(2*Df))
## Rainfall 1.267875  1        1.126000
## Phase    5.015430  2        1.496501
## Slope    2.432701  2        1.248884
## GCVP     3.620823  1        1.902846
## LT       4.953543  1        2.225656
```

Figure B.5 - Adjusted R squared, AIC and BIC values

```
##   model    adj.r.squared   AIC   BIC
##   <chr>            <dbl> <dbl> <dbl>
## 1 Model A          0.714  453.  488.
## 2 Model B          0.706  458.  489.
```