Cool water effects on shallow surface water

In partial fulfilment of the requirements for the degree of Master of Science in Water Management at Delft University of Technology

Master Thesis Civil Engineering

by Cara van Megchelen

Deltares

TU Delft

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Cara van Megchelen

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Student number: 4412206

Supervisor: Dr ir Frans H. M. van de Ven   TU Delft / Deltares

Thesis committee:

- Chair: Prof. dr ir Nick C. van de Giesen   TU Delft
- Dr ir Thom Bogaard   TU Delft
- Dr ir Marie-Claire ten Veldhuis   TU Delft
- Ir Pascal Boderie   Deltares
- Dr ir Ivo Pothof   Deltares

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I am glad to have embarked on this multidisciplinary topic and for the opportunity to develop skills with python and modelling of water temperature, water quality and ecology. I appreciate the opportunity to take part in a study that may benefit towards the expansion of a renewable energy.

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ABSTRACT

The research project advanced the understanding of effects of cold water discharge pollution in the Netherlands. The effects of cooling surface water were investigated based on an ATES pilot site to proactively assess effects, prior to issuing a licence to discharge cooler water. The issues addressed were:

a) Research and investigation of current and relevant guidelines and requirements
b) Defining the cool water discharge regime
c) Impact of cool water on receiving water body temperature
d) Impact of cold water discharge on the aquatic environment
e) Impact of cold water discharge on water quality

Research and analysis has been built combining theoretical literature and collected data, by a targeted case study site, literature study and the development of a theoretical model, summarised below.

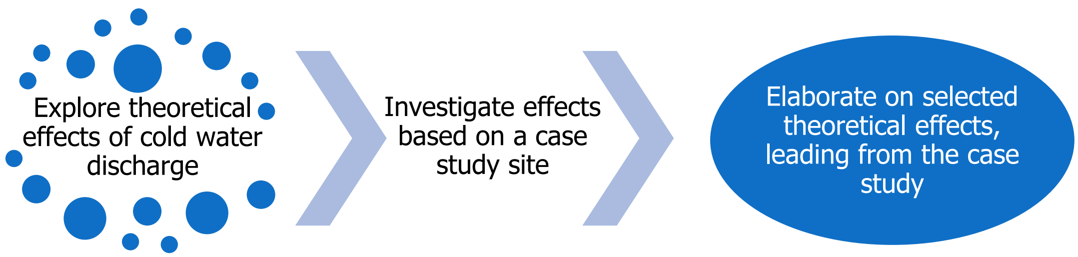


Figure 0.1 Study approach

Seasonal and diurnal variations affect water quality, water plant growth increase during biological spring, establish during summer then decompose in autumn, so that in winter plant biomass is minimal. When plants grow their photosynthesis increases oxygen available in the water, creating an ecological environment conducive to growth of plants and organisms. Toward the end of autumn, plant decomposition consumes a significant amount of available oxygen and too much consumption may decline health and numbers of desirable species.

The magnitude of effects from artificial cooling is dependent on timing. Cooling during biological spring, 1 March to 1 June, can impede the establishment of aquatic plants and impact fish and other organisms during sensitive breeding stages. The case study timing was considered to be optimum in terms of minimising impact on the aquatic ecosystem, operating outside of the most temperature sensitive periods of the year. Study of the ramifications of cooler water discharge, such as 10 °C temperature difference during biological spring may provide further insights into effects on water quality and aquatic ecosystems.

Water quality was found to be greatly influenced by seasonal and diurnal variation as well as location or locations along the waterway of operational cool water discharge. Cool water discharge effects on water quality were most strongly associated with the parameters influenced by respiration and photosynthesis. Flow associated with the cool water discharge was found to weakly influence the water quality parameters that are influenced by system retention time. It was interesting that while the cool water discharge temperature difference was actually relatively low, minor changes in water quality along the channel could still be observed. Overall, the natural variation in water quality and the aquatic ecosystem was found to have a much more significant influence on the waterway studied than the operational cool water discharge.

DEFINITION OF TERMS

Table 0.1 Definition of terms

Topic	Term	Description
General	TES	Thermal energy storage
	WSRL	Rivierenland Waterboard (Waterboard)
	STOWA	Stichting Toegepast Onderzoek Waterbeheer
	EWFD	European Water Framework Directive
	BwB	Bureau Waardenburg
Thermal stratification	Epilimnion	Highest layer in profile, closest to surface
	Metalimnion / thermocline	Middle layer in profile, location of highest change in temperature
	Hypolimnion	Furthest from surface, closest to base
	De-stratification	Mixing and/or dissipation of thermal stratification
Water quality	T	Water temperature
	v	Velocity
	Cl	Chloride
	SO_3^-	Sulphide
	SO_4	Sulphate
	DO	Dissolved oxygen
	O%	Oxygen saturation
	DOC	Dissolved organic carbon
	TOC	Total organic carbon
	SS	Suspended solids
	Turb	Turbidity
	SD	Secchi depth
	TP	Total phosphorus
	PO4	Orthophosphate
	TN	Total nitrogen
	NH_4^+	Ammonium
	N-TKN	Total kjeldahl nitrogen
	NO_3^-	Nitrate
	NO_2^-	Nitrite
	Chl-*a*	Chlorophyll-a
	Pheo-a	Pheophytin-a
	EC	Electrical conductivity
	pH	Acidity
	CO_3	Carbonate (pH)
	$HCO^-{}_3$	Bicarbonate (pH)
	Fe	Iron
	Br	Bromide
Ecology	Tansely scale	Ecology survey method that reports observations based on letter categories. For Tansley scale conversion, see: Tabel 11.3 STOWA-schaal met vertaling naar de Tansley- en Braun-Blanquet-schaal (STOWA, 2010)
	Aquatic macrophytes	Aquatic vascular plants with internal structures which transport water and nutrients throughout the organism, typically have

Topic	Term	Description
		roots (Lamberti & Richard Hauer, 2007, p. 381)
	Flab	Floating algal beds
Modelling terms	EM	Emerged macrophyte (floating on water surface)
	SM	Submerged macrophyte (grows from substrate vertical to water column)

TABLE OF CONTENTS

ABSTRACT VII

DEFINITION OF TERMS IX

FIGURES INDEX XIII

TABLES INDEX XIX

1. INTRODUCTION 1

1.1 BACKGROUND AND SETTING 1

1.2 STATEMENT OF PROBLEM 2

1.3 STUDY OBJECTIVES 3

1.3.1 RESEARCH METHOLODY 3

2 COLD WATER POLLUTION DESCRIPTION 5

2.1 POTENTIAL EFFECTS OF COLD WATER POLLUTION 6

2.1.1 SEVERITY OF COLD WATER POLLUTION 7

2.1.2 TIMING – FREQUENCY AND DURATION OF COLD WATER POLLUTION 8

2.1.3 METABOLIC RATE AND PHOTOSYNTHESIS PRODUCTION 8

2.1.4 WATER QUALITY 9

2.1.5 SUMMARY 11

2.2 EXISTING GUIDELINES AND REQUIREMENTS FOR COLD WATER POLLUTION 11

2.2.1 GUIDELINES AND REGULATION RELEVENT TO THE NETHERLANDS 12

2.2.2 GUIDELINES RELEVENT FOR COLD WATER POLLUTION 17

2.2.3 DISCUSSION 19

2.3 SUMMARY 21

3 COOL WATER EFFECTS ON SHALLOW SURFACE WATER – A CASE STUDY 23

3.1 SITE DESCRIPTION 23

3.1.1 FIELD VISIT 25

3.2 CONCEPT AND METHODOLOGY TO ASSESS COOL WATER EFFECTS 27

3.3 CASE STUDY DATA 28

3.3.1 DATA COLLECTION METHODOLOGY 28

3.3.2 TEMPERATURE OBSERVATIONS 31

3.3.3 ECOLOGICAL SURVEY DATA 32

3.3.4 WATER QUALITY MEASUREMENTS 32

3.3.5 SUMMARY 35

3.4 STUDY SITE INDICATOR METRICS 35

3.5 RESULTS 38
3.5.1 TEMPERATURE 38
3.5.2 ECOLOGY 43
3.5.3 WATER QUALITY 44
3.5.4 OVERVIEW OF STATUS BASED ON STOWA INDICATORS 55
3.6 DISCUSSION 58
3.6.1 WATERWAY STATUS EFFECTS 59
3.6.2 TEMPERATURE EFFECTS 59
3.6.3 EFFECTS ON ECOLOGY 61
3.6.4 EFFECTS ON WATER QUALITY 63
4 THEORETICAL EFFECTS OF COOL WATER ON AQUATIC ECOSYSTEM 67
4.1 FISH 67
4.1.1 FISH SPECIES LIKELY PRESENT ATCASE STUDY 67
4.1.2 STOWA METRICS FOR FISH 68
4.1.3 DISCUSSION 69
4.2 MODELLING TWO AQUATIC PLANTS 70
4.2.1 THEORETICAL GROWTH DESCRIPTION FOR TWO MACROPHYTES 71
4.2.2 MODEL DESCRIPTION 76
4.2.3 MODEL RESULTS 83
4.2.4 DISCUSSION 89
5 DISCUSSION 91
6 CONCLUSION 93
6.1 RECOMMENDATIONS 96
BIBILIOGRAPHY 97
7 APPENDICIES 1
APPENDIX I – SIT LOCATION AND LAYOUT MAP 2
APPENDIX II – SITE VISIT OBSERVATIONS 3
APPENDIX III – AIR TEMPRATURE 9
APPENDIX IV – ECOLOGY OBSERVATION DATA 12
APPENDIX V – WATER QUALITY DATA OVERVIEW 19
APPENDIX VI - TROPHIC STATE INDEX 65
APPENDIX VII – THEORETICAL EFFECTS DATA 70

FIGURES INDEX

Figure 0.1 Study approach vii

Chapter 1

Figure 1.1 Schematic of ATES for heating and cooling buildings, heat from water surface transferred into the substrate to balance the heat and effectively cooling the water (Boderie & van Geest, 2014) 2

Chapter 2

Figure 2.1 Thermal pollution schematic 5
Figure 2.2 Schematic of potential impacts from temperature change (Fondriest Environmental, Inc., 2014) 6
Figure 2.3 Oxygen and carbon dioxide processes schematic (RIVERWATCH, 2013) 9
Figure 2.4 Typical DO, pH and temperature cycles in a control tube of a 2.6m deep freshwater lake in England, from 17:14 h on 12 June 1996, measured at a depth of 10 cm (Ansa-Asare, Marr, & Cresser, 2000) 10
Figure 2.5 Seasonal DO - Mean daily DO concentration and water temperature, Passaic River below Prompton River at two bridges, N.J. January –December (USGS, 2017) 10
Figure 2.6 Schematic of European and The Netherlands guidelines 12
Figure 2.7 Schematic of European Union Water Framework Implementation within The Netherlands guidelines 13
Figure 2.8 Classification of ecological status 15
Figure 2.9 Thermal discharge criteria to protect freshwater aquatic environment based on Dutch guidelines (CIW) (Baptist & Uijttewaal, 2005, p. 4) 16
Figure 2.10 Types of physical and chemical stressors 18
Figure 2.11 Schematic of guidelines relevant to a modification in freshwater thermal regime 20
Figure 2.12 Schematic of necessary considerations for assessing cool water effects 21

Chapter 3

Figure 3.1 Top right; location of study site (yellow dot) (International Students in The Netherlands, 2016) and bottom left; view of landscape in vicinity (AD, 2016) of new residential area, Hoog Dalem 23
Figure 3.2 Site layout and observation locations 24
Figure 3.3 Evolution of the temperature of the surface water in summer (de Boer, et al., 2015) 24
Figure 3.4 View of field sheet taken to site to assist recognising aquatic plants 25
Figure 3.5 View of intake structure (intake circled) 27
Figure 3.6 Case study potential effects investigated 27
Figure 3.7 Methodology for assessing effects 28
Figure 3.8 Heirachy for assessing effects 28
Figure 3.9 Data collection summary 29
Figure 3.10 Summary of companies involved in data collection 29
Figure 3.11 Location of watercourses in new residential area, Hoog Dalem 31
Figure 3.12 The natural shoreline has four components, beginning underwater and extending upland - the aquatic zone, the shoreline, the riparian zone, and the upland zone. The riparian zone is the section of land closest to the shoreline - buffer between the water and the land. (Riparian Zone and Regulations, 2016) 32

Figure 3.13 Macrophyte illustration within the littoral zone (closest to the shore where light reaches all the way to the bottom). (Aquatic and Wetland Plants in Florida) 32
Figure 3.14 Field campaign mesured water quality observations 33
Figure 3.15 Yearly bi-monthly mesured water quality observation parameters (Part 1 of 2) 34
Figure 3.16 Yearly bi-monthly mesured water quality observation parameters (Part 2 of 2) 34
Figure 3.17 Operational cold water discharge -ΔT°C 40
Figure 3.18 Operational cold water discharge – Q 40
Figure 3.19 Cold water discharge– intake and discharge temperature – 2013 41
Figure 3.20 Cold water discharge– intake and discharge temperature – 2015 41
Figure 3.21 Cold water discharge– intake and discharge temperature – 2016 41
Figure 3.22 Water temperature –2015 – 60cm 42
Figure 3.23 Water temperature –2015 – 100cm 42
Figure 3.24 Water temperature – 2016 – shallow (50cm from surface) 43
Figure 3.25 Water temperature –2015 – deeper (70cm from surface for MP1 and 100cm from surface for other points) 43
Figure 3.26 Scatter matric for -ΔT°C ON / OFF –for Chl-a (ug/l), pH, DO (mg/), water temperature (°C) 45
Figure 3.27 Closer view of water plants, north of BNL0504, likely *Callitriche platycarpa* (based on advice from Gerben van Geest, 23/08/2016) 56
Figure 3.28 BNL0505 measuring point, high coverage of algae on water surface and emerged macrophytes near the banks 57
Figure 3.29 Closer view of algae / flab floating on channel surface between BENL0505 and intake ... 57
Figure 3.30 Case study data observations compared to theoretical expected effects 58

Chapter 4

Figure 4.1 Fish egg/larvae [referred water temperature range with potential effect based on 2015 68
Figure 4.2 Lemna minor global abundance map 71
Figure 4.3 Lemna minor image 71
Figure 4.4 *Lemna minuta* global abundance map 72
Figure 4.5 *Lemna minuta* images 72
Figure 4.6 Lemna trisulca global abundance map 72
Figure 4.7 *Lemna trisulca* images 72
Figure 4.8 *Lemna* minor intrinsic growth rate in dependence of phosphorus concentration; the bars represent the maximum error deduced from the nitrogen and phosphorus mass balances. (Lasfar, et al., 2007) 73
Figure 4.9 *Lemna* minor intrinsic growth rate in dependence of nitrogen concentration; the bars represent the maximum error deduced from the nitrogen and phosphorus mass balances. (Lasfar, et al., 2007) 73
Figure 4.10 *Lemna minor* intrinsic growth rate in dependence of temperature, the bars represent the maximum error deduced from the nitrogen and phosphorus mass balances. (Lasfar, et al., 2007) 75
Figure 4.11 *Elodea nuttallii* species global abundance map (Image source: http://wilde-planten.nl/gewoon%20sterrenkroos.htm, accessed 18/08/2016.) 76
Figure 4.12 Photo of *Elodea nuttallii* observed at Hoog Dalem (dark green) 76
Figure 4.13 Overview model configuration 77

Figure 4.14 Channel schematic, model point locations and naming (sometimes Outlet is stated as Uitstroom and Intake is Inname) 78
Figure 4.15 Heat transfer mechanisms at the water surface (Medrano, 2008) 79
Figure 4.16 Interactions between the nutrient cycles and the life cycle of macrophytes (Deltares, 2017) 81
Figure 4.17 Macrophyte modelling summary of inputs 83
Figure 4.18 Modelled ambient water temperature –ΔT °C OFF during a very warm day – upper layer (1) 4-Jul-2015 14:00 84
Figure 4.19 Modelled ambient water temperature –ΔT °C ON during a very warm day – upper layer (1) 4-Jul-2015 14:00 84
Figure 4.20 *Elodea Nuttallii mass (g) - without -ΔT°C* 85
Figure 4.21 *Duckweed mass (g) - without -ΔT°C* 85
Figure 4.22 *Water temperature (°C) without -ΔT°C* 85
Figure 4.23 *Oxygen (mg/l) without -ΔT°C* 85
Figure 4.24 *Elodea Nuttallii mass (g) - without -ΔT°C and no Q* 86
Figure 4.25 *Duckweed mass (g) - without -ΔT°C and no Q* 86
Figure 4.26 *Water temperature (°C) without -ΔT°C and no Q* 86
Figure 4.27 *Oxygen (mg/l) without -ΔT°C and no Q* 86
Figure 4.28 *Elodea Nuttallii mass (g) - realised -ΔT°C* 87
Figure 4.29 *Duckweed mass (g) - realised -ΔT°C* 87
Figure 4.30 *Water temperature (°C) realised -ΔT°C* 87
Figure 4.31 *Oxygen (mg/l) realised -ΔT°C* 87
Figure 4.32 *Elodea Nuttallii mass (g) - with -10 ΔT°C* 88
Figure 4.33 *Duckweed mass (g) - with -10 ΔT°C* 88
Figure 4.34 *Water temperature (°C) with - 10ΔT°C* 88
Figure 4.35 *Oxygen (mg/l) with -10 ΔT°C* 88

Appendix

Figure 7.1 Hoog Dalem site location and layout 2
Figure 7.2 Box Plot - Average Monthly Temperature 1906 – 2015 10
Figure 7.3 Hoog Dalem measurement year temperature deviation from median of monthly average (1906-2015) 11
Figure 7.4 Ecology – BwB – macrophyte observations – 28 May 2012 12
Figure 7.5 Ecology – BwB – macrophyte observations – 11 July 2012 12
Figure 7.6 Ecology – BwB – macrophyte observations – 3 June 2013 13
Figure 7.7 Ecology – WSRL – macrophyte observations – 8 August 2013....13
Figure 7.8 Ecology – BwB – macrophyte observations – 15 July 2013 14
Figure 7.9 Ecology – BwB – macrophyte observations – 27 May 2015 14
Figure 7.10 Ecology – BwB – macrophyte observations – 7 July 2015 15
Figure 7.11 Ecology – WSRL – macrophyte observations – 10 July 2015 15
Figure 7.12 Ecology – BwB – macrophyte observations – 26 May 2016 16
Figure 7.13 Ecology – BwB – macrophyte observations – 13 July 2016 16
Figure 7.14 Ecology – macrofauna observations – 15 July 2015 (part a) 17
Figure 7.15 Ecology – macrofauna observations – 15 July 2015 (part b) 17
Figure 7.16 Operational water temperature during field campaign A 20

Figure 7.17 Operational water temperature during field campaign B 20
Figure 7.18 Operational water temperature during field campaign C 21
Figure 7.19 Scatter matrix with correlation coefficient – field observations for all measuring points for depths 0.1m, 0.3m and 0.7m 22
Figure 7.20 Scatter matrix – BENL0502 for depth 0.1m 23
Figure 7.21 Scatter matrix – BENL0502 for depth 0.3m 24
Figure 7.22 Scatter matrix – BENL0502 for depth 0.7m 24
Figure 7.23 Scatter matrix – BENL0505 for depths 0.1m....25
Figure 7.24 Scatter matrix – BENL0505 for depths 0.3m....26
Figure 7.25 Scatter matrix – BENL0505 for depths 0.7m....26
Figure 7.26 Box plot – field data – water temperature....27
Figure 7.27 Box plot – field data – oxygen....28
Figure 7.28 Time series – field data – DO diurnal variation BENL0502 28
Figure 7.29 Time series – field data – DO diurnal variation BENL0505 29
Figure 7.30 Box plot – field data – turbidity 29
Figure 7.31 Turbidity Vs. location – 2015 field campaign – 0.1m from surface 30
Figure 7.32 Turbidity Vs. location – 2015 field campaign – 0.3m from surface 30
Figure 7.33 Turbidity Vs. location – 2015 field campaign – 0.7m from surface 30
Figure 7.34 Box plot – field data – EC 31
Figure 7.35 EC Vs. location – 2015 field campaign – 0.1m from surface 31
Figure 7.36 EC Vs. location – 2015 field campaign – 0.3m from surface 32
Figure 7.37 EC Vs. location – 2015 field campaign – 0.7m from surface 32
Figure 7.38 Box plot – field data – pH 32
Figure 7.39 pH Vs. location – spatial variation – field data....33
Figure 7.40 Scatter matrix – laboratory data along x-axis (water temperature, oxygen, pH, TOC and SS) 34
Figure 7.41 Scatter matrix – BENL0502 35
Figure 7.42 Scatter matrix – BENL0505 36
Figure 7.43 Combined effects – 2013 - BENL0502 37
Figure 7.44 Combined effects – 2013 - BENL0505 37
Figure 7.45 Combined effects – 2015 - BENL0502 38
Figure 7.46 Combined effects – 2015 - BENL0505 38
Figure 7.47 Combined effects – 2016 - BENL0502 39
Figure 7.48 Combined effects – 2016 - BENL0505 39
Figure 7.49 Box plot – ON / OFF – laboratory data – water temperature 40
Figure 7.50 Box plot – each year ON / OFF – laboratory data – water temperature 40
Figure 7.51 Time series plot – laboratory data – water temperature....41
Figure 7.52 Box plot – laboratory data – velocity 42
Figure 7.53 Time series plot – laboratory data – velocity 42
Figure 7.54 Box plot – laboratory data – sulphate 43
Figure 7.55 Time series plot – laboratory data – sulphate....43
Figure 7.56 Box plot – laboratory data – oxygen 44
Figure 7.57 Time series plot – laboratory data – oxygen....44
Figure 7.58 Box plot – laboratory data – oxygen (%) 45
Figure 7.59 Time series plot – laboratory data – oxygen (%)....45
Figure 7.60 Box plot – laboratory data – DOC....46

Figure 7.61 Time series plot – laboratory data – DOC....46
Figure 7.62 Box plot – laboratory data – TOC....47
Figure 7.63 Time series plot – laboratory data – TOC....47
Figure 7.64 Box plot – laboratory data – SS....48
Figure 7.65 Time series plot – laboratory data – SS....48
Figure 7.66 Box plot – laboratory data – turbidity....49
Figure 7.67 Time series plot – laboratory data – turbidity....49
Figure 7.68 Box plot – laboratory data – SD....50
Figure 7.69 Time series plot – laboratory data – SD....50
Figure 7.70 Box plot – laboratory data – TP....51
Figure 7.71 Time series plot – laboratory data – TP....51
Figure 7.72 Box plot – laboratory data – orthophosphate....52
Figure 7.73 Time series plot – laboratory data – orthophosphate....52
Figure 7.74 Box plot – laboratory data – TN....53
Figure 7.75 Time series plot – laboratory data – TN....53
Figure 7.76 Box plot – laboratory data – ammonium....54
Figure 7.77 Time series plot – laboratory data – ammonium....54
Figure 7.78 Box plot – laboratory data – TKN....55
Figure 7.79 Time series plot – laboratory data - TKN....55
Figure 7.80 Box plot – laboratory data – nitrate....56
Figure 7.81 Time series plot – laboratory data – nitrate....56
Figure 7.82 Box plot – laboratory data – nitrite....57
Figure 7.83 Time series plot – laboratory data – nitrite....57
Figure 7.84 Box plot – laboratory data – Chl-a....58
Figure 7.85 Time series plot – laboratory data – Chl-a....58
Figure 7.86 Box plot – laboratory data – Pheo-a....59
Figure 7.87 Time series plot – laboratory data – Pheo-a....59
Figure 7.88 Box plot – laboratory data – EC....60
Figure 7.89 Time series plot – laboratory data – EC....60
Figure 7.90 Box plot – laboratory data – chloride....61
Figure 7.91 Time series plot – laboratory data – chloride....61
Figure 7.92 Box plot – laboratory data – pH....62
Figure 7.93 Time series plot – laboratory data – pH....62
Figure 7.94 Box plot – laboratory data – bicarbonate....63
Figure 7.95 Time series plot – laboratory data – bicarbonate....63
Figure 7.96 Box plot – laboratory data – iron....64
Figure 7.97 Time series plot – laboratory data – iron....64
Figure 7.98 Time series plot – laboratory data – trophic state index....66
Figure 7.99 Box plot for each measuring point per year – laboratory data – trophic state index – Summer – Chl-a....66
Figure 7.100 Box plot for each measuring point per year – laboratory data – trophic state index – Summer – TP and SD....67
Figure 7.101 Time series plot - 2015 – laboratory data – trophic state index – BENL0502....68
Figure 7.102 Time series plot - 2013 – laboratory data – trophic state index – BENL0502....68
Figure 7.103 Time series plot - 2012 – laboratory data – trophic state index – BENL0502....68
Figure 7.104 Time series plot - 2015 – laboratory data – trophic state index – BENL0503....69

Figure 7.105 Time series plot - 2015 – laboratory data – trophic state index – BENL0504 69
Figure 7.106 Time series plot - 2015 – laboratory data – trophic state index – BENL0505 69
Figure 7.107 *Elodea nuttallii* abundance at Hoog Dalem (note the method of ecological survey is different for BwB and WSRL)..70
Figure 7.108 *Lemna* abundance at Hoog Dalem 70
Figure 7.109 *Lemna minuta* abundance at Hoog Dalem...71
Figure 7.110 *Lemna minor* abundance at Hoog Dalem...71
Figure 7.111 *Lemna trisulca* abundance at Hoog Dalem 72

TABLES INDEX

Table 0.1 Definition of terms ix

Chapter 2

Table 2.1 Factors to be considered when determining whether a modification in a thermal regime will adversely affect aquatic ecosystems (ANZECC, 2000, pp. 8.2-20): 18

Chapter 3

Table 3.1 Site visit photos of each measuring point 25
Table 3.2 Data available at study site (Boderie & van Geest, 2014, p. 5) 29
Table 3.3 Summary data collection for each month, year, type of observation and number of observations 30
Table 3.4 Summary measured water temperature 31
Table 3.5 Macrophytes survey frequency 32
Table 3.6 Water temperature metric M1A waterway 35
Table 3.7 STOWA recommended plant coverage (%) for GEP (STOWA, 2012-34, p. 106) 36
Table 3.8 Macrofauna metrics for WFD type M1A (STOWA, 2012-34, p. 114) 36
Table 3.9 Macrofauna score description (STOWA, 2012-34, p. 114) 37
Table 3.10 STOWA M1A water quality metrics 37
Table 3.11 Cold water discharge – total monthly flow (m^3) 39
Table 3.12 Cold water discharge – total monthly energy (million MJ) 39
Table 3.13 Summary water quality observations - physical 46
Table 3.14 Summary water quality observations – non-metallic inorganics 46
Table 3.15 Summary water quality observations – dissolved oxygen and organic matter 47
Table 3.16 Summary water quality observations – optical properties 49
Table 3.17 Summary water quality observations – nutrients 50
Table 3.18 Summary water quality observations – biomass 52
Table 3.19 Summary water quality observations – salinity 53
Table 3.20 Summary water quality observations – acidity 53
Table 3.21 Summary water quality observations – bromide 54
Table 3.22 Compare results to STOWA M1A water quality metrics 55
Table 3.23 STOWA macrophyte metrics 56

Chapter 4

Table 4.1 Fish species found for WFD type M1A (STOWA, 2012-34, p. 135) 67
Table 4.2 STOWA M1A fish metrics (STOWA, 2012-34, p. 135) 68
Table 4.3 Duckweed preferred habitat (Floran, 2016) 71
Table 4.4 Water temperature and flow model description 80
Table 4.5 Overview of included processes working on the state variables (Deltares, 2016, p. 282) 82

Appendix

Table 7.1 Air temperature (°C) Hoog Dalem measurement year (2012, 2013, 2015) 10
Table 7.2 Air temperature (°C) warmest cool water discharge (May., Jun., Jul., Aug., Sept.) 11

Table 7.3 M1A type fish species preferred water temperature range for life stages (Buijse, 2016) 18
Table 7.4 Air temperature during field campaigns (KNMI, station 356 Herwijnen) 27
Table 7.5 Trophic status 65
Table 7.6 Summary of macrophyte inputs for model 74

1. INTRODUCTION

Exploration of renewable energy is globally motivated by a need to decrease dependence on carbon emitting fossil fuels. The expansion and modernisation of renewable energy systems comes with a need to study their potential environment effects.

Aquifer Thermal Energy Storage (ATES) is a type of renewable energy, a study from 2008 confirmed it can successfully be utilised as an energy source (de Graaf, et al., 2008). ATES has the potential to contribute up to half of the residential heating and cooling demand within a kilometre of studied waterways in The Netherlands (de Boer, et al., 2015). Supplying energy needs with ATES is beneficial to reducing demand on fossil fuels. The Netherlands has set objectives for reducing carbon emissions. Given the efficiency of ATES technology in The Netherlands, expansion of this type of renewable energy is anticipated.

Cooling surface water is a consequence of ATES. Warmer water is extracted from an open water source, heat from the water is absorbed into the substrate and then the cooler water is discharged back to the open water. The open water sources that are likely coupled with ATES systems are typically relatively shallow. The consequence of extracting heat from an open water source is an effective cool water discharge. This study sought to identify effects of discharging cooler water to a relatively shallow water body, based on a case study site in The Netherlands. The topic of the thesis is:

> *Cool water effects on shallow surface water*

1.1 BACKGROUND AND SETTING

During winter, warmer groundwater is used for heating homes and in summer cooler groundwater is used to cool homes. In The Netherlands, the majority of the residential demand for energy is due to heating in winter (World Energy Council, 2016). Greater need for heating than for cooling is the consequence of an annual heating and cooling imbalance in The Netherlands. When heating and cooling needs are exclusively supplied by an ATES system, this could result in a thermal imbalance in the substrate, more heat than cool is extracted.

Measures to balance the heat flux in the substrate are necessary to mitigate thermal imbalance (de Graaf, et al., 2008). To achieve annual thermal equilibrium in the substrate, heat is supplied to the substrate (de Graaf, et al., 2008). The heat, for this case, is sourced from an open water body when the water is warm enough for heat to be extracted, typically May to September. An ATES system is illustrated Figure 1.1.

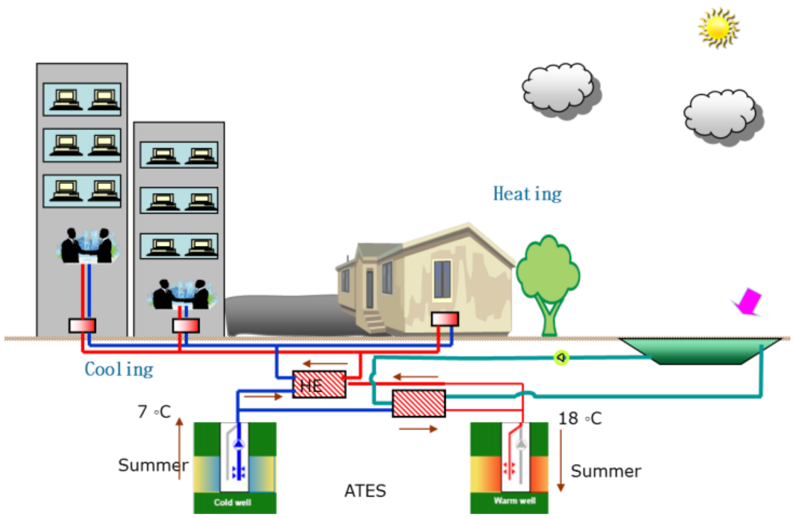


Figure 1.1 Schematic of ATES for heating and cooling buildings, heat from water surface transferred into the substrate to balance the heat and effectively cooling the water (Boderie & van Geest, 2014)

1.2 STATEMENT OF PROBLEM

Thermal pollution is the artificial change of a water body's temperature and can be an increase or a decrease. It is most commonly associated with warm water pollution, the artificial heating of a water body. Cold water pollution is defined by the artificial temperature reduction of a body of water. Cold water pollution is an anthropogenic change to a water body which has the potential to negatively impact water quality and aquatic ecosystems. Studies on cold water pollution have predominantly been initiated due to changes in ecology downstream of large-scale river modifications such as dams (Lugg & Copeland, 2014).

In regard to water quality, temperature is classified as a physical component (ANZECC, 2000, pp. 3.1–1) that has potential direct toxic effects on organisms and animals (ANZECC, 2000, pp. 2-9). Water quality has a significant influence on the ecosystem, such as the type and range of flora and fauna present (ANZECC, 2000, pp. 3.1–1). The potential consequences of artificially modified water temperature vary greatly. Further, temperature has additional indirect effects by having influence on or modifying other stressors, for example temperature can influence physiological rates and biological diversity.

This is the first study on the effect of artificial cold water discharge to a freshwater body within The Netherlands. Within The Netherlands, guidelines and regulation specifically for cold water discharge are not available (de Boer, et al., 2015). Research on the consequences from ATES cooling surface water was identified as necessary to gain insight into the consequences.

The engineering problem addressed was the potential environmental effects of artificially modifying the temperature of a shallow body of surface water, particularly during May to September. The secondary problem addressed, the investigation was structured in an investigation methodology relevant to existing and suitable water temperature guidance, to contribute to future development of guidelines and regulation for cold water discharge.

1.3 STUDY OBJECTIVES

The objective of the study was to investigate the environmental effects of cooling shallow surface water based on literature and a case study site in The Netherlands. Conclusions on the magnitude of the effect were made with an outlook of assisting future forming of guidelines or regulation for cool water discharge.

1.3.1 RESEARCH METHOLODY

The methodology procedure was a combination of an experimental and theoretical approach. The study incorporated data from a study site, results were analysed, relationships investigated and a model developed to simulate and predict effects was developed. To investigate the effects of cooling surface water, the main phases of the study included:

1. Literature study
    a. Cold water pollution
    b. Guidelines and regulation
    c. Water quality
    d. Aquatic ecosystems
    e. Modelling in Delft-3D
        i. Delft3D-Flow
        ii. Delwaq
2. Describe cold water pollution
    a. Elaborate on theoretical effects
    b. Outline existing guideline requirements
3. Analyse a case study site and assess effects, based on:
    a. Dutch guideline metrics (STOWA)
    b. Temperature data
        i. ATES operational cold water discharge
        ii. In stream temperature measurements
    c. Ecology surveys
    d. Water quality measurements
4. Elaborate on theoretical effects, leading from the case study
    a. Theoretical effects on fish
    b. Theoretical effects on two water plants
5. Draw conclusions

The following sub-questions were answered:

1. What relevant guidelines and frameworks are currently available?
2. What does the case study data available indicate?
    a. Is there a strong relationship between water quality observations and-ΔTºC?
    b. Is there a strong relationship between ecological surveys and ΔTºC?
3. Can a model demonstrate a realistic relationship between -ΔTºC and DO and macrophytes?
4. Can a model be developed to predict spatial temperature distribution and associated effect on macrophytes with higher -ΔTºC?

2 COLD WATER POLLUTION DESCRIPTION

Chapter 2 defines Cold water pollution, discusses potential effects, provides two examples of effects for context and summarises relevant guidelines and regulations. Chapter 2 provides context to The Netherlands, the country of focus for this study and is otherwise purposefully generic regarding the water body type.

Thermal pollution is the artificial change of a water body's temperature and can be an increase or a decrease, see Figure 2.1. The natural temperature for a water body is not always clear for all water body's since most water body's across the world have experienced severe modifications, which may directly affect the temperature, e.g. different vegetation types in the riparian zone may directly alter the water temperature due to shading. Alternatively, modified flow regimes and global warming can have the indirect effect of changing the water temperature. Therefore, the natural water temperature for water body's in developed areas is typically different from the actual natural status. For very large water body's, the water temperature desired is typically a compromise between ecological and water quality aspirations together with limitations of implementation and financial aspects.

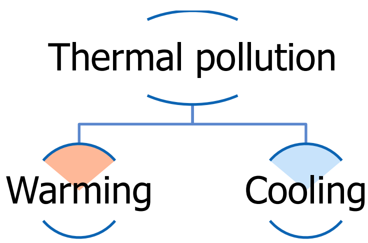


Figure 2.1 Thermal pollution schematic

Thermal pollution is most commonly associated with warm water pollution, the artificial heating of a water body. This common association is largely to the prevalence of historically known issues associated with warm water pollution, such as large scale warm water discharges from power stations. In Europe and in The Netherlands, information about the environmental effects of warm water discharge is available, such as the Rhine River case (Rutten, 2006). Warm water pollution can have significant impacts on waterways including long-term severely changed ecology, such as the lack of salmon in the Rhine River and fish kill events during thermal dumps, with few cases where there has been a benefit observed.

Cold water pollution is defined by the artificial temperature reduction of a body of water. Cold water pollution is a type of thermal pollution, as is warm water pollution. Cold water and warm water pollution share similarities in the type of potential effects, with opposing and mirroring effects. For example, water becomes more viscous as the water temperature increases and less viscous for cooler water. From this example it can be understood that warming or cooling water share that they both have an effect on viscosity, the effect of one contrasts the other. Potential cold water pollution effects are discussed further within the next section.

Research on cold water pollution has received increasing attention since the 1980's, (Walker, 1980) and (Cowx, et al., 1987). Studies on cold water pollution have predominantly been initiated due to observed changes in ecology downstream of large-scale river modifications, such as dams, which effect river flow regimes and associated thermal regimes (Lugg & Copeland, 2014). Research on the impact of cold water pollution in Australia, England and America has been undertaken and it is understood that Brazil also experiences issues with cold water pollution (from discussion with ecologist Gerben van Geest, 6 June 2016). The range of countries contributing to research on cold water pollution demonstrates that it is a global issue.

2.1 POTENTIAL EFFECTS OF COLD WATER POLLUTION

Thermal pollution and the potential consequences of artificially modified water temperature vary greatly and are influenced by:

1. Severity of temperature difference (quantity and ΔTºC)
2. Frequency of change (frequency)
3. Duration of change (time)

Thermal pollution, altering the temperature of a water body, has potential physical, chemical and biological effects (ANZECC, 2000). The potential effects are ranging and often complex since thermal changes can have direct and indirect effects on the biological and chemical relationships of a water body. Potential impacts from modifying water temperature are summarised within the next schematic, ordered based on the relevance to cold water pollution.

Metabolic rate & photosynthesis production	•Theory: rates drecrease for decreasing temperature
Dissolved oxygen	•Theory: solubility increases with decreasing temperature
pH	•Theory: cooling water increases ionic concentration, decreasing pH
Conductivity & salinity	•Theory: most salt solubilty decreases for decreasing temperature
Oxidation reduction potential	•Theory: decreases with decreasing temperature
Water density	•Theory: density decreases with increasing temperature •Denser for cooler water
Compound toxicity	•Theory: compound solubility and potential toxicity increases for increasing temperature

Figure 2.2 Schematic of potential impacts from temperature change (Fondriest Environmental, Inc., 2014)

The potential, direct, effects from cold water pollution are generally reverse from the effect of warm water pollution. For example, significant warming of water leads to an increase in photosynthesis production and in contrast cooling water leads to a decrease in photosynthesis production. Both cold and warm water pollution are types of thermal pollution and therefore have the potential to impact on a water body’s biological and water quality status.

2.1.1 SEVERITY OF COLD WATER POLLUTION

Effects of cold water pollution are predominantly associated with large dams and weirs. Theory of how temperature affects water quality is based on known scientific theories, summarised in Figure 2.1, which are primarily based on pure water in laboratory conditions. How the theory of modifying water temperature translates into observable, measurable effects in a natural waterway varies for each site, influenced by the cause of cold water pollution and climatic, geographic and environmental aspects. For example, the impact of cold water pollution from large dams is combined with several other important water quality influencing aspects, including geographic location and climatic conditions, severely modified flow regimes and lowered DO concentrations. Two examples shall be discussed here to provide insight into the type of effects from previously investigated cold water pollution studies, the examples are the Colorado River in America and the Murray-Darling Basin (MDB) in Australia.

The MDB case concerns the effect on downstream rivers due to large water storages. In the MDB, thermal stratification, difference in temperature between epilimnetic and hypolimnetic layers, exceeds 13°C in most of the large storages. The extreme differences were found to occur from the first month of summer to the first month of autumn. These storages discharge water from fixed level offtakes that typically draw water from the cool layer of the storage (hypolimnion). This discharge causes a suppression of water temperature downstream, compared to what would naturally occur in the absence of the storage. The cold water pollution was found to threaten the condition of riverine fish assemblages, the impacts on the biology and life-cycles of fish observed in the MDB are summarised into key components, below. (Murray-Darling Basin Authority, 2009)

1. Redistribution of species
2. Timing and success of reproduction
3. Growth and metabolism
4. Recruitment

For the Colorado River, a study on the consequence for a specific native fish species from altering the thermal regime was undertaken, the main question to be answered was, is highest impact from water temperature or trout. The study found that when the temperature is below 12°C, the dominant effect is due to the cooled water temperature. Further, it was concluded for water temperatures higher than 12°C, the effects on the native fish are due to a combination of temperature and trout. The study found that for every 1°C increase in water temperature, the predation vulnerability of the native fish was decreased by 5% approximately. In addition, the study found that while cold water discharge can be detrimental to the native fish, it has the potential to conserve them as well, for this specific case studied. (Ward, 2013)

Both of the examples discussed are for large scale, severe thermal modifications and were focussed on fish. Fish are a major indicator of overall waterway health and therefore the focus for most thermal pollution studies. While thermal dumps may be directly toxic to fish, cold water pollution effects are less severe, nonetheless significant, such as modified behaviour and reduced size (Astles, et al., 2003).

The differing nature of effects caused by cold water pollution, in contrast to warm water pollution, is fundamental to this study.

2.1.2 TIMING – FREQUENCY AND DURATION OF COLD WATER POLLUTION

Water bodies experience natural variations in water temperature. Two dominant reasons for natural water temperature changes are diurnal variation and seasonality. Likewise, ecosystems and water chemistry vary seasonally and diurnally. Therefore, timing and frequency of cold water pollution is an important aspect when considering its potential effect on water chemistry and aquatic ecosystems (Lugg, 1999).

Occurrence of cold water pollution could be very severe and occur once per year, this would have a very significant effect at the time, with a longer period of time between the events enabling opportunity for the ecosystem to work towards restoring. Alternatively, cold water pollution could occur at reduced magnitude throughout a whole year, which would have less severe initial effects, the consistent nature of the thermal change would preclude the system from restoring and the effects would be gradual. Over time, the ecosystem impacted by continuous cold water pollution would be modified from the system previous to cold water pollution. The next three descriptions summarise timing aspects and terminology relevant to cold water pollution (Lugg, 1999).

1. Summer suppression – reduction in temperature compared to natural conditions that typically occur between mid-spring to late summer and reaches a maximum in summer
2. Seasonal displacement – the timing delay of natural temperature peaks, troughs, rises and falls, e.g. delayed biological spring
3. Annual amplitude reduction – the reduction in the natural difference between annual maximum and minimum temperatures.[1]

2.1.3 METABOLIC RATE AND PHOTOSYNTHESIS PRODUCTION

A study confirming ecosystem respiration rate[2] and to a lesser extent gross primary productivity[3] increase with warmer temperatures, based on a natural stream, highlight the importance of water temperature (Demars, et al., 2011). Further, the increase or decrease in rate for individual species is dependent on their respective growth curve characteristics, species with temperature dependency experience a peak in growth at a certain temperature, followed by a decline in growth rate.

The growth dynamics of aquatic plants involves more than temperature dependency. Dominant aspects of plant growth that are considered in this study are temperature, nutrients and radiation. Photosynthesis rate increases with increasing temperature. Photosynthesis occurs during the day and ceases at night due to the absence of radiation. Aquatic plant dependence on temperature and radiation is demonstrated by seasonal changes, such as growth in spring and decomposition from autumn. An observable example for the Netherlands is algal growth on canals during summer, compared to winter where algae blooms are rarely observed.

In terms of the temperature dependency for growth of aquatic plants, higher temperatures than normal can cause excessive growth of undesirable species, such as algae. This excessive growth of algae is not

[1] (Murray-Darling Basin Authority, 2009)
[2] Ecosystem respiration: respiration sum of all living organisms in the respective ecosystem
[3] Gross primary productivity: rate at which photosynthesis or chemosynthesis occurs

sustainable and is often followed by severe decomposition; the excessive growth and decomposition cause water quality issues and have an impact on desirable water plants.

Native aquatic plants, such as macrophytes, improve water quality and overall aquatic ecosystem health (Rutherford, et al., 2009). Where macrophytes are in high quantities, they may have a significant impact on function and structure of the waterway, such as modifying sediment and current conditions (Lamberti & Richard Hauer, 2007, p. 381). Aquatic plants provide habitat for fish and invertebrates. Therefore aquatic plants are an important indicator of a water body's health (Rutherford, et al., 2009).

The strong aquatic plant and temperature relationship discussed above demonstrates that delayed or lower spring and summer water temperature has potential to influence plant growth and distribution (Rutherford, et al., 2009). Potential impacts on macrophytes due to reduced water temperatures include (Rutherford, et al., 2009):

1. Shortened growth periods caused by 'delayed spring and summer' effects
2. Reduced growth rates caused by 'summer suppression' effects
3. Shift in species caused by 'annual amplitude reduction' effects

Artificially cooling the water has the potential to interrupt lifecycle development, reduce growth rates and reduce competition potential for aquatic plants, invertebrate and fish. Impacts on these organisms have the potential to affect the aquatic ecosystem and a water body's chemical and physical status. (Rutherford, et al., 2009)

Aquatic ecosystem growth and interactions is a science that this study will not endeavour to comprehensively explore. The strong relationship between plant growth and temperature demonstrates that aquatic plants are an important consideration for understanding potential effects from modifying a thermal regime.

2.1.4 WATER QUALITY

Water quality is influenced by diurnal and seasonal fluctuations, dissolved oxygen (DO) shall be discussed as an example. The next schematic illustrates the dominant processes of DO and carbon dioxide in water.

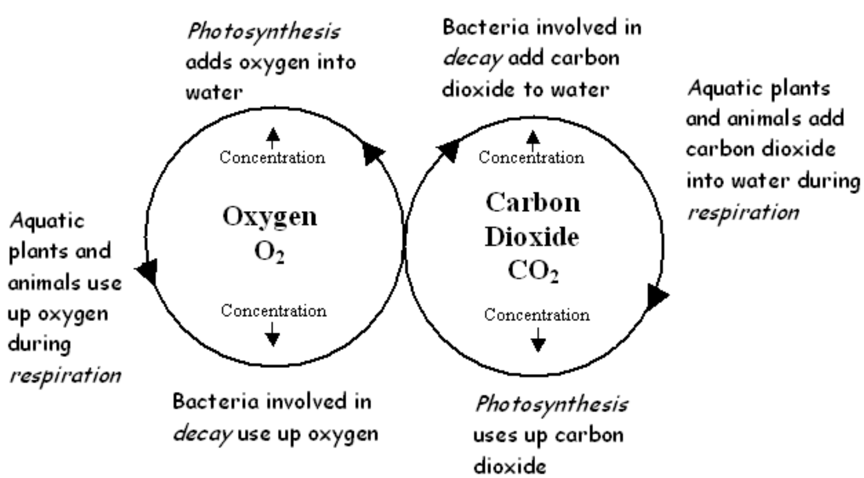


Figure 2.3 Oxygen and carbon dioxide processes schematic (RIVERWATCH, 2013)

Studies on DO have found that concentration fluctuations are dependent on the reaeration rate (TOC dependent), photosynthetic rate, light intensity, algal density, temperature and respiration rate (Ansa-Asare, et al., 2000). During day light hours, DO concentrations increase due to photosynthesis, which requires radiation, the next figure illustrates DO increasing as temperature increases, which coincides with day light hours. The reaeration and photosynthetic rates increase with higher temperatures and radiation, the next figures shows the oxygen dynamics during three days and clearly demonstrates the diurnal variation, (Ansa-Asare, et al., 2000). During the night, in the absence of radiation, DO concentrations decrease due to the demand for DO from the decomposition of organic matter and respiration (Butcher & Pentelow , 1927).

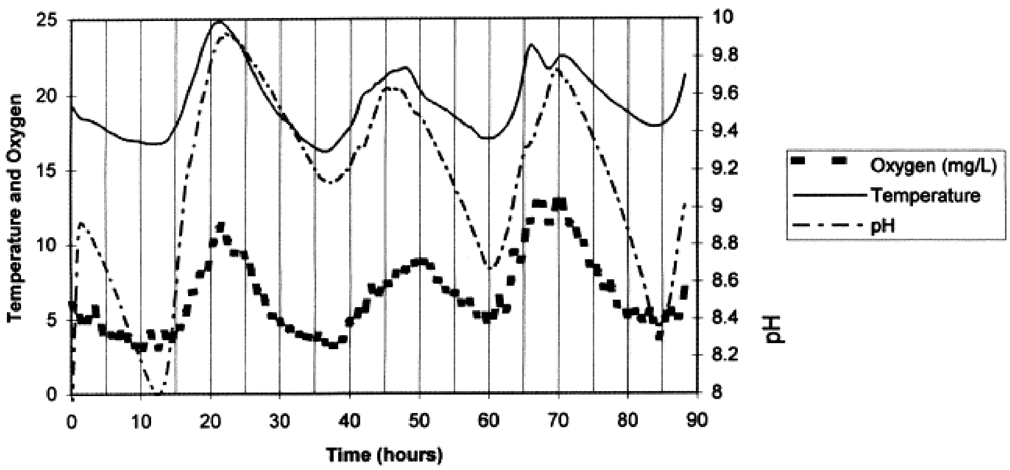


Figure 2.4 Typical DO, pH and temperature cycles in a control tube of a 2.6m deep freshwater lake in England, from 17:14 h on 12 June 1996, measured at a depth of 10 cm (Ansa-Asare, Marr, & Cresser, 2000)

In addition to diurnal fluctuations, DO experiences seasonal fluctuations, as presented in the next figure. The seasonal change of DO is observed in the decrease in water quality during autumn, spring and summer compared to winter (Enrique, et al., 2007).

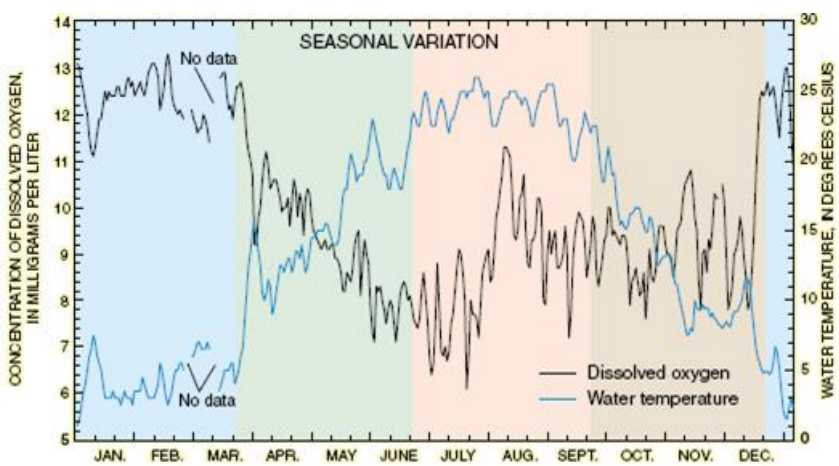


Figure 2.5 Seasonal DO - Mean daily DO concentration and water temperature, Passaic River below Prompton River at two bridges, N.J. January –December (USGS, 2017)

The above described seasonal and diurnal variation of a water bodies biological and water quality status highlights the importance of timing and frequency of cold water pollution. Timing of cold water pollution is another fundamental consideration in order to understand its effect.

2.1.5 SUMMARY

Based on literature reviewed and the examples discussed throughout this section it can be concluded that the potential effects from cold water discharge are highly variable and dependent not only on the direct cold water discharge, magnitude of temperature change, frequency and timing, but also dependent on the climate and type of water body discharge to. Further, the magnitude of the effect is variable for each case and sometimes it is not clear what is driving the observed or measured effects. The Colorado River case differentiated two scenarios based on when a direct link to cold water pollution could be found and when a direct link could not be found. On the other hand, the MDB case found there is a clear link between cold water pollution and effects on the ecosystem and water quality (Lugg, 1999).

In order to understand the effect of cold water discharge, the following fundamental aspects of cold water pollution shall be focussed on:

1. Severity of temperature difference (quantity and ΔT°C)
2. Frequency of change (frequency)
3. Duration of change (time)
4. Indicators for:
    a. Metabolic rate & photosynthesis production
    b. Water quality

2.2 EXISTING GUIDELINES AND REQUIREMENTS FOR COLD WATER POLLUTION

Cold water pollution is an anthropogenic change which has the potential to negatively impact a water body's quality and aquatic ecosystems. In developed countries, artificial changes to a water body that may negatively affect water quality are typically addressed in legal frameworks or guidelines. Water quality guidelines typical present concepts and metrics, determined as relevant and often critical for the health of the water body(s) they were developed to address. Guidelines are often an important aspect for understanding the level of impact and relative acceptability of an anthropogenic influence on a water body when they are developed for the type of water body.

Guidelines relevant to a modification in the thermal regime of a freshwater waterway, within The Netherlands and other international guidelines, have been reviewed and incorporated into this research. Specific cold water discharge guidelines were not found during the study, which is likely due to the high variability in source and impact, as discussed in Section 2.1. It was found that previous studies on cold water pollution in The Netherlands were not available and that cold water pollution is not formally address in the Dutch specific thermal discharge guidelines (Rijkswaterstaat, 2004).

Although guidelines / legal requirements explicitly about cold water discharge are not available, it was found that implicit requirements exist. Implicit requirements are water quality and ecological indicators, selected since they represented the overall status of the water body for which they are developed, further elaborated throughout this section.

Research approach undertaken to determine which guidelines and requirements exist that are relevant for cold water pollution:

1. Review existing and relevant guidelines / regulations
   I. European Water Framework Directive (EWFD), European Union (EU)
   II. Stichting Toegepast Onderzoek Waterbeheer[4] (STOWA), The Netherlands
   III. Seek international reference information
2. Review and compare with current guidelines on warm water discharge
   I. Dutch guidelines compare with cold water pollution
      - Rijkswaterstaat. (2004). CIW beoordelingssystematiek warmtelozingen. Rijkswaterstaat

2.2.1 GUIDELINES AND REGULATION RELEVENT TO THE NETHERLANDS

Historical evidence and information on the effects of warm water discharge has been incorporated into the development of guidelines and regulation for warm water discharge to surface water in The Netherlands (Baptist & Uijttewaal, 2005). Given this study is focussing on The Netherlands, legal requirements and guidelines on cold water pollution was sought to understand if limitations or legal requirements existed, since they exist for warm water discharge (Baptist & Uijttewaal, 2005).

2.2.1.1 EUROPEAN WATER FRAMEWORK DIRECTIVE

Within this section, water quality requirements for water bodies within The Netherlands are further discussed, the next schematic illustrates the relationship between EU and Dutch guidelines that are further elaborated on within this section.

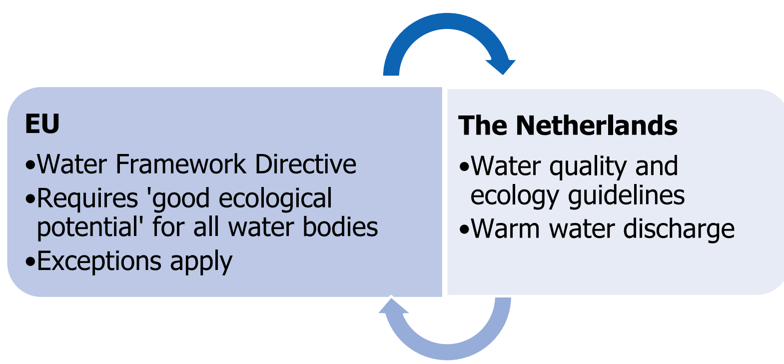


Figure 2.6 Schematic of European and The Netherlands guidelines

The EWFD is relevant to this study since the case study site is located within The Netherlands, which is one of 28 member states of the EU. The EWFD states that the member state (The Netherlands) was to set the water quality criteria for all waterways / water bodies and to define the reference waterway, EWFD Annex V No. 1.2.5, (European Commission, 2003). The EWFD aims to include the protection and improvement of aquatic ecosystems and outlines goals, water quality monitoring and actions.

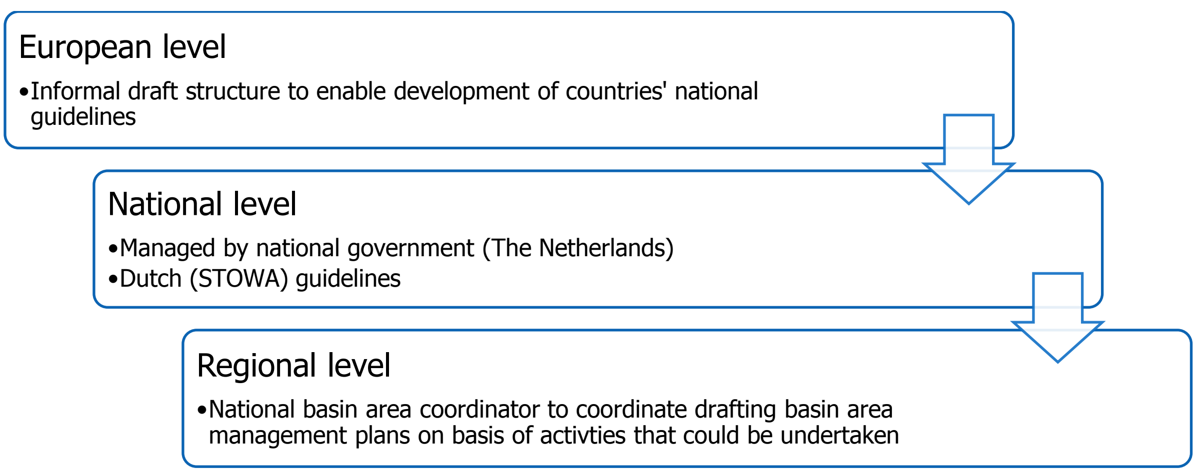
[4] Dutch Foundation for Applied Water Research

The measures to be taken are dictated by the results relating to the goals and monitoring. The technical specifications to be met, by the characterisation of the river basin, are provided within Annexes II and III of the EWFD. In summary, it states that surface water bodies shall be named and defined. Surface water bodies must be defined in classes and types, with ecological reference conditions for each type determined.

In early 2005 the reference of natural global surface water types were reported to the European Commission. A reference describes a substantially undisturbed natural water type and is distinctively dissimilar to an environmental standard or policy. Two types of objective status are described by the EWFD; Maximum Ecological Potential (MEP), which is based on the 'natural' condition of a waterway and a less stringent alternative, Good Ecological Potential (GEP), see below for elaboration. For natural water body types, the standard at the lower limit is classed as GEP. Since water types occur in multiple regions, the objectives for natural waters are nationwide.

> *[Good Ecological Potential is defined as the state where] "the values of the relevant biological quality elements reflect, as far as possible, those associated with the closest comparable surface water body type, given the physical conditions which result from the artificial or heavily modified characteristics of the water body."*

Overall, the target was to achieve "good status" (GEP) for all surface waters. GEP status is divided into a good water quality and ecological condition, clear objectives for each type of water body are required. The ecological state is divided into good biological state and requirements for hydro morphology, general water quality and other discharged pollutants. The responsibility is with Rijkswaterstaat, regional water authorities of the municipalities and regional water managers. The below schematic illustrates the general organisation for implementing the EWFD within The Netherlands:



[5]

Figure 2.7 Schematic of European Union Water Framework Implementation within The Netherlands guidelines

[5] Regional level: activities that could be undertaken were determined by the Waterboards and regional branches of the state water management agency / Rijswaterstraat (from conversation with Erik Mostert January 2017)

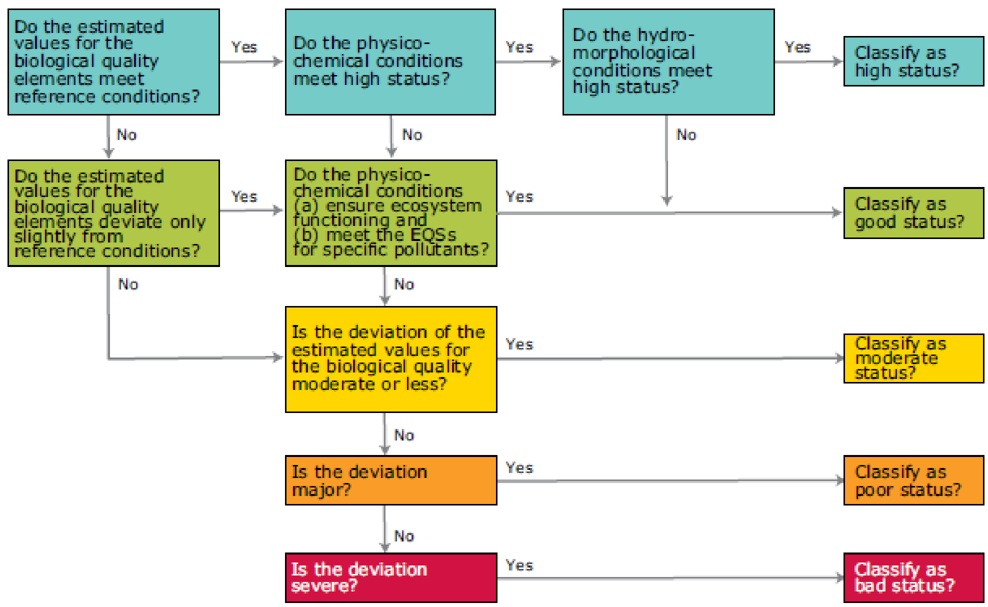
Waterways within The Netherlands have been modified for hundreds of years and this lends to a complication when attempting to define the natural state of a water body. Definition of the 'natural' status of artificial waterways, such as ditches and canals, is especially challenging given these are not natural types of waterways. In addition to this aspect, to be considered is the practicality of achieving a natural state for all waterways in a country that has been developed and has heavily modified water bodies for such an extended period of time. (STOWA, 2012-34)

The Netherlands has specified for all water bodies a reference status and associated ecological indicators, which includes artificial water bodies with an alternative status objective than for more 'natural' waterways. This is since the vast majority of water bodies within The Netherlands are not natural, therefore most are categorised as heavily modified or artificial. The principal of achieving MEP applies, with an alternative to 'natural' as the basis. This standard is derived from the most similar natural water type and is due to a type of exemption outlined in Article 4.4 and 4.5 of the WFD, (STOWA, 2012-34).

The Dutch STOWA guidelines define each type of Dutch water body and associated ecological metric, in accordance with the requirements of the EWFD, (STOWA, 2012-34). For example, based on the STOWA guidelines, the status for each type of water body can be assessed. The indicator information, such as ecological information, for each type of water body is used to estimate the Ecological Quality Ratio. The objective was to reach 'good EQR', which corresponds to a metric of 0.6. In summary, scores are based on the EQR and associated with the following:

1. Dutch water bodies defined in classes
2. Each class has metrics determined for selected water quality and ecological indicators
3. Prague method – decision framework not to always reach 0.6
    a. Consider all potential measures
        i. Omit measures that are prohibitive due to constraints (e.g. agriculture or flood management)
        ii. Omit measures that are low benefit / high cost
    b. Assess potential EQR based on potential measures

For the Waterboard (WVL) region studied, minor waterways were not categorised as waterways significant enough to determine individual EQR status for, by WVL. WVL reports on approximately 30 "higher" (larger) waterways that are required for reporting and assumes the "lower" (smaller) waterways are represented by the status of the "higher" waterways. The following schematic illustrates the process required to calculate the EQR for a waterway. In general, to estimate a waterway EQR score, 5-6 locations are measured, the EQR of each location determined and averaged to obtain the overall for the area assessed.



Source: EC, 2005.

Figure 2.8 Classification of ecological status

2.2.1.1.1 SUMMARY

To conclude the outcome of investigating guidelines and regulations relevant to water body's within The Netherlands, it was found that The Netherlands has defined each type of water body and developed metrics for each water body type in accordance with EWFD requirements. Further, it was found that metrics for selected indicators, developed for each type of water body, is published in the STOWA Guidelines. Indicator metrics for each type of water body, within The Netherlands, have been developed in accordance with the EWFD. The Netherlands has specified, for all water bodies, a reference status and associated water quality and ecological indicators. The principal of achieving MEP applies, with an alternative to 'natural' as the basis. The metrics outlined for each type of water body were derived from the most similar natural water type, based on an exemption outlined in the WFD, (STOWA, 2012-34).

2.2.1.2 DUTCH WARM WATER POLLUTION GUIDELINES

Cold water and warm water pollution are both types of thermal pollution, with often opposing effects in similar categories of effect, as discussed in Section 2.2. To understand the current requirements and the aspects requiring consideration for an anthropogenic warming on Dutch waterways, the Dutch thermal pollution guidelines were indirectly reviewed. Dutch specific warm water discharge guidelines were prepared by the Commissie Integraal Waterbeheer, (beoordelingssystematiek warmtelozingen, 2004). Additional relevent warm water discharge guidelines (Cooling Water Discharge Guidelines in The Netherlands, p413) are described, below:

1. Integrated Pollution Prevention and Control guideline (IPPC) (EC 1996)
    - Including the European IPPC Reference Document on the application of Best Available Techniques to Industrial Cooling Systems 2001
2. Water Framework Directive (WFD) (EC 2000)

The Dutch thermal discharge guidelines outline subtraction criterion, mixing zone criteria and heating criteria, these are elaborated on in Figure 2.9, (Baptist & Uijttewaal, 2005, p. 4). The Dutch heat discharge guidelines have been indirectly reviewed (Baptist & Uijttewaal, 2005) to gain insight into the tolerances that were used.

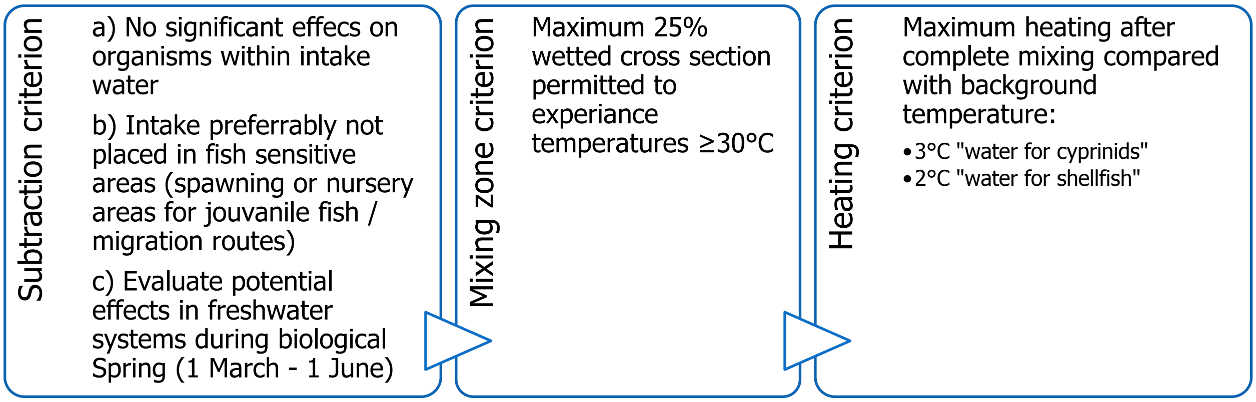


Figure 2.9 Thermal discharge criteria to protect freshwater aquatic environment based on Dutch guidelines (CIW) (Baptist & Uijttewaal, 2005, p. 4)

Based on the criteria summarised in Figure 2.9, metrics for warm water pollution are unlikely to be exceeded by cold water pollution. Subtraction criteria is typically an issue for large power stations that extract flows at a very high rate, compared with this case study. Mixing zone criteria is based on exceeding 30°C, cold water pollution does not contribute to exceeding this. Heating criteria is based on waterways containing two different aquatic fauna, with a metric assigned of 2 and 3 °C, which the cold pollution would not be a contributing factor for exceeding. The CIW guidelines require the following information to assess the impact and justify permits for thermal heating (Boderie & van Geest, 2014):

1. Design conditions of the cooling water system (for power stations, not cool water discharge)
2. Bathymetry and flow of receiving water body
3. Variability of flow conditions
4. Design of water intake and outlet, location, dimension, discharge, velocities
5. Meteorological conditions

Requirements:

1. Adequate instruments to assess and control emissions and surface water quality
2. 2D cooling water models shall support the conceptual set-up for each industry

2.2.1.2.1 SUMMARY

The review of existing Dutch warm water pollution guidelines found the criteria for artificially increasing the thermal regime was based on three main criteria, which are; subtraction, mixing zone and heating. These guidelines have generally been developed for large power stations that extract high volumes of water and discharge the water with significant increases in temperature.

The CIW guidelines outline the information required in order to assess the impacts and effects and to justify permits for an artificial increase in thermal regime. The CIW guidelines benefit this study on cold water discharge in The Netherlands by providing insight on previously defined criteria for an artificial thermal change to a water body and the information required to assess the thermal modifications effects.

2.2.2 GUIDELINES RELEVENT FOR COLD WATER POLLUTION

Cold water pollution is less well known than warm water pollution due to the higher profile and prevalence of warm water pollution problems. Australia has significant cold water pollution issues (Lugg, 1999) and due to this, a study of Australian guidelines was undertaken to enhance understanding on how cold water pollution metrics could be developed. While the ecology and climatic conditions between Australia and Europe differ, the strategy and methodology of previous studies on the impact of cold water pollution benefits this study. The National Water Quality Management Strategy (NWQMS) Guidelines (also known as 'ANZECC Guidelines') provide criteria for developing temperature guidance and trigger values in Australia and New Zealand:

- National Water Quality Management Strategy. (2000). Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Environment and Conservation Council (ANZECC). Artarom NSW 2064: Environment Australia.

The NWQMS Guidelines are separated into the following volumes:
- Volume 1 - The guidelines (chapters 1 - 7) (314 pages)
- Volume 2 - Aquatic ecosystems - rationale and background information (chapter 8) (678 pages)
- Volume 3 - Primary industries - rationale and background information (chapter 9)

Volume 1 and 2 are the volumes most relevant to this study. The NWQMS Guidelines are based on a risk-based[6] approach, with the intention to improve the application of the guidelines to all Australian and New Zealand aquatic environments. Decision frameworks are used, especially for the protection of aquatic ecosystems that assist users to tailor water quality guidelines to local environmental conditions. Based on this revised approach, previous 'single number' guidelines are now referred to as *guideline trigger values*.

Guideline trigger values can be derived for regional, local or site specific guidelines and take into consideration aspects such as variability of the respective ecosystem or environment, soil type, rainfall and level of exposure to contaminants. The concept of the decision frameworks was to produce values that are more appropriate to the particular water resource, they are not mandatory to use.

Due to high variability in climatic, physical, geographic and biological factors that can influence an aquatic ecosystem in Australia and New Zealand, the NWQMS Guidelines incorporate site specific information with generalised scientific information relating to ecosystem changes. The general basis of the NWQMS Guidelines is the use of decision frameworks to tailor water quality guidelines to local conditions. (ANZECC, 2000, pp. 3.1-7)

Trigger value approach, information required to develop trigger values (recommendation is data frequency of collection; monthly over 2 year duration):

1. Biological data

[6] The term 'risk-based' does not imply the need for a full quantitative risk assessment. For example, the aquatic ecosystem guidelines trigger values for toxicants are risk-based in the sense that they are calculated to protect a predetermined percentage of species with a specified level of confidence, the frameworks simply provide an estimate of whether a low or high risk exists.

2. Ecological effects data
3. Reference system
4. Predictive modelling

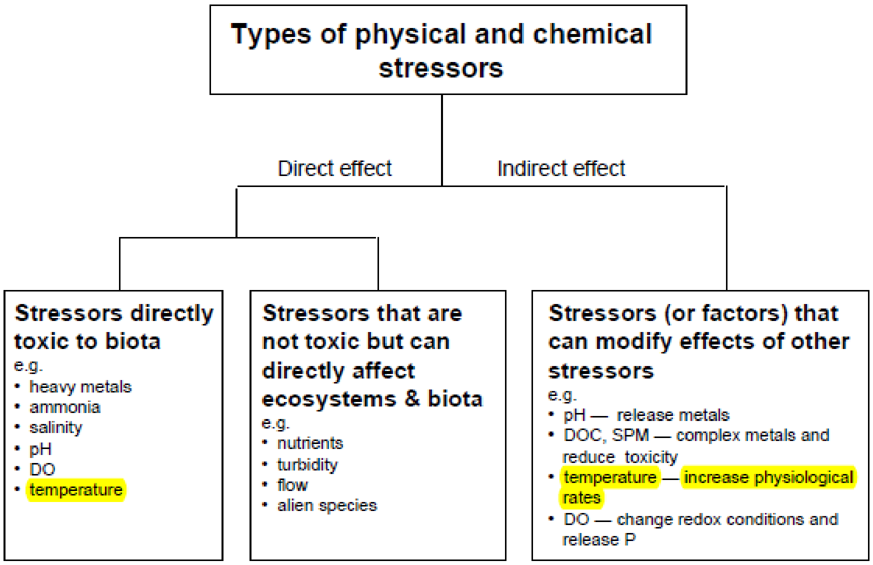


Figure 2.10 Types of physical and chemical stressors

Factors to be considered when determining whether a modification in a thermal regime will adversely affect aquatic ecosystem are summarised in the next table.

Table 2.1 Factors to be considered when determining whether a modification in a thermal regime will adversely affect aquatic ecosystems (ANZECC, 2000, pp. 8.2-20):

Potential effect	Description
1. Lethal tolerance range (including length of exposure)	All stages of the lifecycle of the endemic populations
2. Influence on primary rate of production in the system	Typically nuisance plant growth increases with increasing temperatures This is important because studies have demonstrated greater sensitivity of plant growth to temperature increases than to nutrient increases, which can lead to nuisance growths
3. Influence on the secondary rate of production of key species within the system	Such as increase / decrease in production of desirable / undesirable species Thermal changes can lead to increased production of undesirable species and decreases in the production of desirable species e.g. bacteria out competing algae for nutrients
4. Tolerances of the various life stages of the species that occur within the affected area	Not all life stages of a given species are equally sensitive, and reproductive stages are often the most sensitive to thermal disruption, such as reproductive stages are typically most sensitive to thermal disruption
5. Likely impact on species richness and natural community composition in the affected area	

Potential effect	Description	
6. Influence on enzyme-dependent microbial process, including	1. Photosynthesis 2. N_2 fixation 3. Denitrification	4. Respiration 5. Methanogenesis

To determine maximum temperature for long term exposure (for thermal discharges) USEPA (1986b) recommends using information for at least nine species, with the value adopted being based on the most sensitive of the species, comprised of:

1. Three fish
2. Three invertebrates
3. Three plants

Approaches could include using the sum of average daily water temperatures as the threshold required for normal development. Another approach includes a two stage process for evaluating the effects, first is an experimental quantification of the consequences of their temperature increase for DO and organic pollution. The second is a multivariate evaluation of the laboratory results based on a decision support system.

2.2.2.1.1 SUMMARY

The review of ANZECC guidelines provided insight into several methods and approaches for determining effects from artificially modifying a thermal regime and subsequently, methods for determining metrics. The variability in methods and approaches outlined in the ANZECC guidelines confirms the conclusion made in Section 2.2; it is not possible to assess the effect of an artificial thermal change on water body based on one single water quality or ecological indicator. While the ANZECC guidelines confirm the complexity of determining the effects caused by thermal changes to a water body, the guidelines benefit this study by outlining methods previously developed and applied.

2.2.3 DISCUSSION

What relevant guidelines and frameworks are currently available?

To conclude the outcome of investigating guidelines and regulations relevant to water body's within The Netherlands, it was found that The Netherlands has defined each type of water body and developed metrics for each water body type in accordance with EWFD requirements. Further, it was found that metrics for selected indicators, developed for each type of water body, is published in the STOWA Guidelines. Indicator metrics for each type of water body, within The Netherlands, have been developed in accordance with the EWFD. The Netherlands has specified, for all water bodies, a reference status and associated water quality and ecological indicators. The principal of achieving MEP applies, with an alternative to 'natural' as the basis. The metrics outlined for each type of water body were derived from the most similar natural water type, based on an exemption outlined in the WFD, (STOWA, 2012-34).

The metrics have been developed for similar waterway types within each category and therefore the metrics reflect realised or in-situ water quality and ecological status. In order to understand the effect of cold water pollution to a water body, the water quality and ecological metrics can be used in an implicit approach to improve understanding if the anthropogenic change in thermal regime could prevent the waterway from achieving GEP.

For the site studied, the water quality and ecological observations shall be compared to the STOWA indicator metrics, for the relevant water body type. The individual STOWA metric indicators are incorporated in order to give context to the observations and relative state of the waterway. Based on the information presented in this section, existing suitable Dutch guidelines are available and these have been utilised to assist assessing cool water effects.

The overall ecological status of the case site studied is not available and therefore it is not possible to state if the site studied is currently at GEP, in regard to the waterways type.

The initial approach proposed was to research the case study site in agreement with the ANZECC Guidelines. After further investigation and consideration of the guidelines relevant to The Netherlands, it was considered beneficial to prioritise these guidelines over the ANZECC since implicit metrics can be incorporated into assessing the effect of artificially cooling a water body in The Netherlands. Further, STOWA guidelines cover an extensive amount of information on waterways similar to the case study site that is beneficial for the study. Therefore, it is proposed to incorporate current Dutch guidelines (STOWA, 2003) into the study by using metrics for assessing waterway condition and to find what is binding with this status.

The dominant requirement, based on EWFD, was to achieve a GEP. Therefore, it is necessary to determine if the artificial cooling of the surface water inhibits the potential of the waterway to achieve a GEP, based on the STOWA definition of GEP. The proposed methodology for incorporation of guidelines into the study is outlined, below.

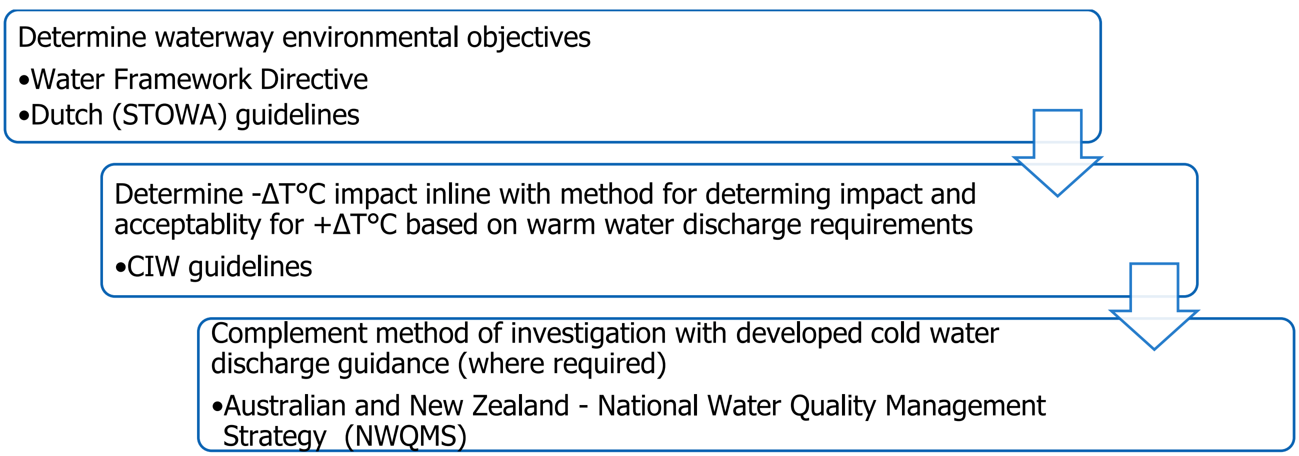


Figure 2.11 Schematic of guidelines relevant to a modification in freshwater thermal regime

2.3 SUMMARY

Throughout Chapter 2, cold water pollution was defined, potential effects discussed, two examples of effects outlined for context and relevant guidelines and regulations summarised. This section endeavoured to broadly outline cold water pollution and the associated dynamic and interchangeable potential effects from cold water discharge.

In summary, cold water pollution can influence water chemistry and aquatic ecosystems. Potential effects are dependent on the magnitude of the cold water discharge, water quality indicators and aquatic ecosystem groups that are most likely to be influenced by an artificial reduction in water are summarised in the next schematic. Potential effects from temperature modifications to the receiving water body are also summarised in the next schematic.

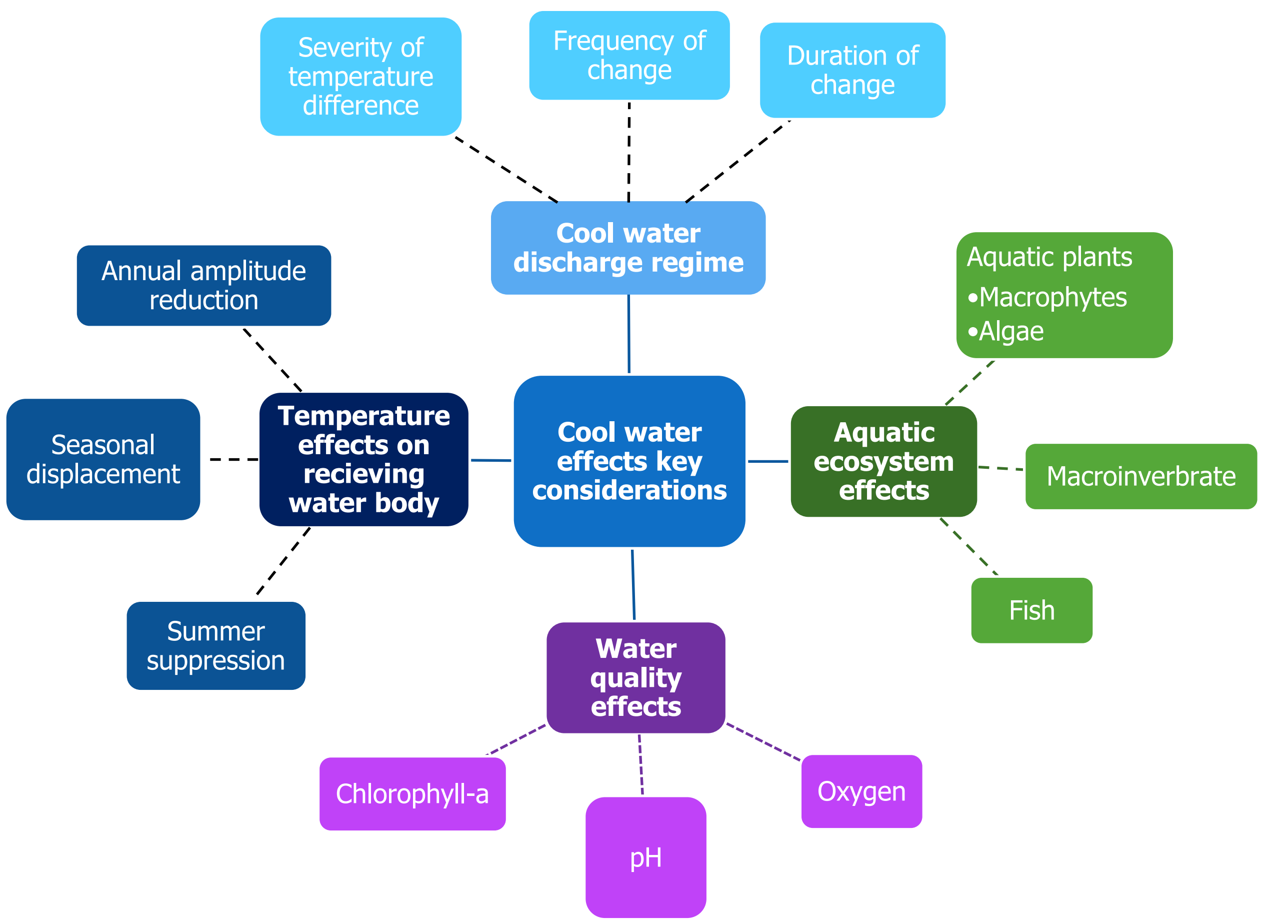


Figure 2.12 Schematic of necessary considerations for assessing cool water effects

3 COOL WATER EFFECTS ON SHALLOW SURFACE WATER – A CASE STUDY

Chapter 3 incorporates the principals outlined in Chapter 2 and applies them to a specific type of water body within The Netherlands, the case study

3.1 SITE DESCRIPTION

In 2012 an ATES pilot plant was constructed to deliver energy within a new housing development area named Hoog Dalem, near Gorinchem in South Holland, as shown in Figure 3.1. Hoog Dalem consists of 1400 homes (Hoog Dalem) and has been designed to be independent from the traditional electricity network; ATES is one of the alternative energy sources. The ATES system at Hoog Dalem utilises energy from a channel that forms part of the residential area.

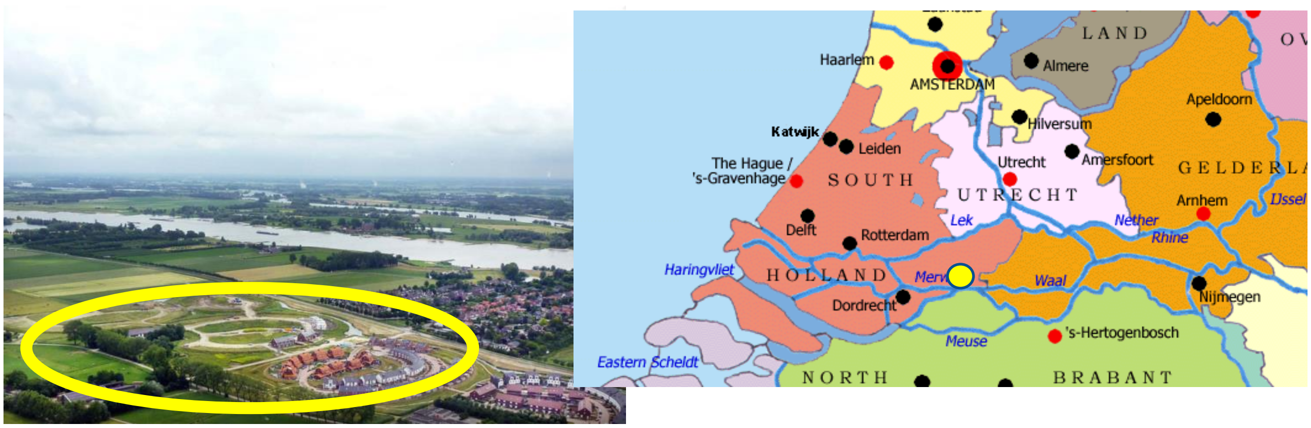


Figure 3.1 Top right; location of study site (yellow dot) (International Students in The Netherlands, 2016) and bottom left; view of landscape in vicinity (AD, 2016) of new residential area, Hoog Dalem

The channel[7] used for the pilot ATES project is approximately 1.5km long, 2.5 – 10 m wide and ranges in depth from 1-1.5 m, see Figure 3.2. The width varies along the channel, approximately 2-2.5 m wide at BENL0502 and BENL0503, 3-3.5 m wide at BENL0504, 7-7.5m wide at BENL0505 and 10-25 m wide near the intake (located in a bend). The channel has vegetated side slopes consisting of riparian grasses and reeds and is classified as an artificial water body (European Comission, 2012, p. 38).

Main system components include an ATES system, 1.5km long channel and a lock system that circulates water

Water within the low turbulence channel is re-circulated via a newly constructed lock system with a rate of 200m^3/h (4,800m^3/day or 0.06m^3/s) and has a total volume of (very approximately) 6,000-7,000m^3 (Boderie & van Geest, 2014, p. 2). The residence time in the channel ranges from 30 to 45 hrs or 1.5 to 2

[7] The channel may be referred to as "ditch", this is since the direct translation of the Dutch name assigned to this type of waterway is "ditch". Given that in English "ditch" would refer to a much smaller waterway and the term "canal" refers to a waterway with water traffic, it has been considered appropriate to refer to the waterway as a channel throughout the study.

days. An aerial view of the channel, illustrating observation points and the flow direction of cold water discharge (-ΔT°C) is shown in Figure 3.2.

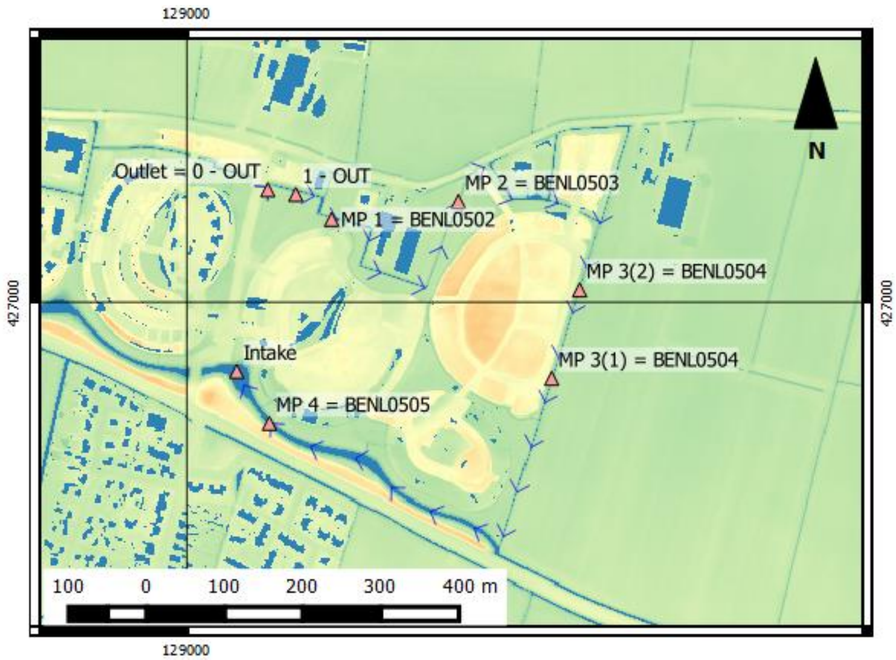


Figure 3.2 Site layout and observation locations

The heat demand of the substrate is based on the annual difference between heating and cooling demand (de Graaf, et al., 2008). The preferred heat extraction for ATES systems is based on balancing the annual thermal equilibrium in the substrate and system efficiency considerations. The potential timing and magnitude of heat extraction for a generic ATES system in The Netherlands is presented in Figure 3.3 (de Boer, et al., 2015).

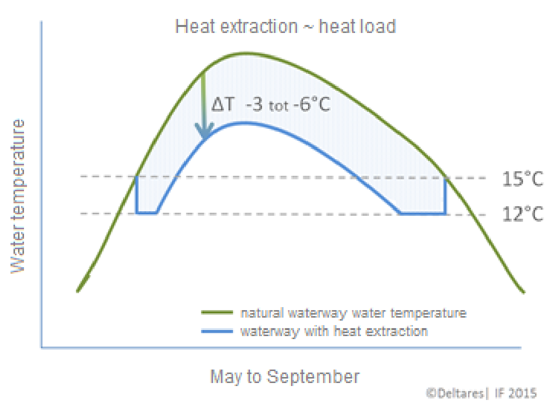
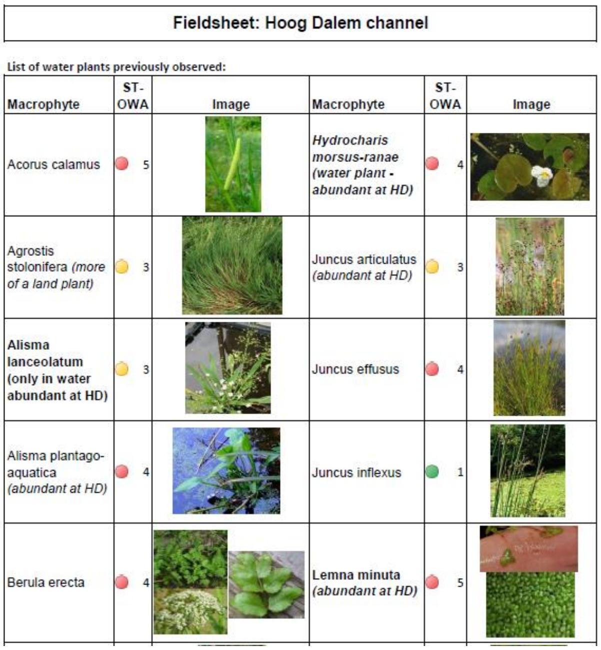


Figure 3.3 Evolution of the temperature of the surface water in summer (de Boer, et al., 2015)

During May to September, at periods when water temperature in the channel exceeded 18ºC, water within the channel experiences an equivalent "cold water discharge" of a maximum intended difference of 5ºC to the "natural" temperature, (Boderie & van Geest, 2014, p. 2). The favoured water temperature difference to "discharge" is 7ºC, however the permit from the Waterboard was 5ºC, this permit ceased end of 2016.

3.1.1 FIELD VISIT

A field trip to the site was undertaken on 18 August 2016, Appendix II contains a description and photographs taken at each of the measuring points. To recognise the water plants at the site, a comprehensive field sheet with names, pictures and desirable or undesirable category was made to assist identifying the species present, see Figure 3.4.



Fieldsheet: Hoog Dalem channel

List of water plants previously observed:

Macrophyte	ST-OWA		Image	Macrophyte	ST-OWA		Image
Acorus calamus	●	5		*Hydrocharis morsus-ranae (water plant - abundant at HD)*	●	4	
Agrostis stolonifera *(more of a land plant)*	●	3		Juncus articulatus *(abundant at HD)*	●	3	
Alisma lanceolatum (only in water abundant at HD)	●	3		Juncus effusus	●	4	
Alisma plantago-aquatica *(abundant at HD)*	●	4		Juncus inflexus	●	1	
Berula erecta	●	4		**Lemna minuta** *(abundant at HD)*	●	5	

Figure 3.4 Example view of field sheet taken to site to assist recognising aquatic plants

Photos from the site visit for each measuring point is provided in Table 3.1. As can be observed in these photographs, during the site visit higher amounts of algae and flab were present near the intake to BENL0504. From BENL0502 to the cold water discharge there were minimal floating algae or flab present, with some floating and submerged macrophytes such as *Elodea nuttallii*.

Table 3.1 Site visit photos of each measuring point

Outlet

View of cold water discharge area (discharge headwall location indicated by circle, flow direction of cold water indicated by arrow)

View of water plants near cold water discharge, likely species are *Elodea nuttallii* (undesirable) and *Callitriche obtusangula* (desirable) (based on advice from Gerben van Geest, 23/08/2016)

BENL0502

View of BNL0502 measuring point area, device indicated by circle, looking towards the north-west, much less algae present than between BENL0504 and Intake. Likely an undesirable plant species, *Elodea nuttallii* (based on advice from Gerben van Geest, 23/08/2016) (indicated by circle).

BENL0503

View of BNL0503 measuring point area, device indicated by circle, looking towards the south-west, much less algae present than between BENL0504 and Intake

BENL0504

View of BNL0504 measuring point area, device indicated by circle

View between BENL0505 and BENL0504, observing high coverage of algae

BENL0505

View of BNL0505 measuring point, high coverage of algae can be observed

Near intake

View of channel from bridge near intake, facing east

Intake

View of channel from bridge near intake, facing north-east

Figure 3.5 View of intake structure (intake circled)

3.2 CONCEPT AND METHODOLOGY TO ASSESS COOL WATER EFFECTS

Water quality and flora and fauna conditions were assessed in order to investigate the effect of the cold water discharge to the channel (European Comission, 2012) and (ANZECC, 2000). Trends in data while cooling surface water were sought to find if there was a strong relationship between measured water quality and -ΔTºC and / or a strong relationship between ecological studies and -ΔTºC. It was investigated to find if cold water discharge prevents or benefits the waterway from achieving a GEP, as discussed in Chapter 2, with current guidelines.

From Chapter 2, the main issues associated with artificially cooling water discharged to a water body were identified. The case study site was assessed based on the key issues identified in Chapter 2, areas of potential effects, summarised below, were investigated for the case study.

1. Temperature effects

- **a. Define cool water discharge**
  - Severity of temperature difference
  - Frequency of change
  - Duration of change
- **b. Asess effect on recieving water temperature**
  - Summer suppression
  - Seasonal displacement
  - Annual amplitude reduction

2. Effects on aquatic ecosystem

- **Fish**
- **Macroinvertebrate**
- **Aqautic plants** (macrophytes and algae)

3. Effects on water quality

- **a. Detailed study on indicators**
  - Oxygen
  - pH
  - Chlorophyll-a
- **b. Higher level study on all water quality parameters measured at site**

Figure 3.6 Case study potential effects investigated

To find if cold water discharge prevents the waterway from achieving GEP, the metrics of individual indicators are considered in a more general sense for reference to similar waterways, it is not intended to calculate the EQR for the waterway. Therefore, each indicator metric relevant to Hoog Dalem was assessed to inform on the general quality status of the waterway. The methodology to understand the quality status of the waterway and if cold water discharge prevents the waterway from achieving GEP is outlined in the next schematic.

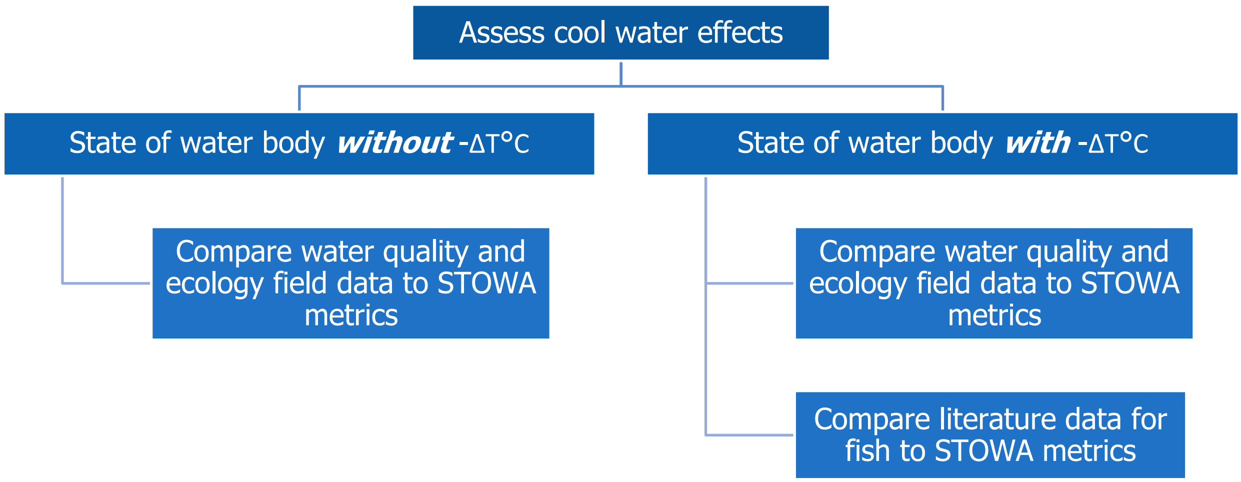


Figure 3.7 Methodology for assessing effects

For the case study, data was available for the operational cool water discharge, water quality, aquatic plants and a lesser amount of data for macroinvertebrate. Where case study data is not available for important indicators, such as fish, theoretical literature based data is incorporated into the study, see Chapter 4. This approach is in line with recommendations for guidelines and shall be approached in a method as shown in the next schematic.

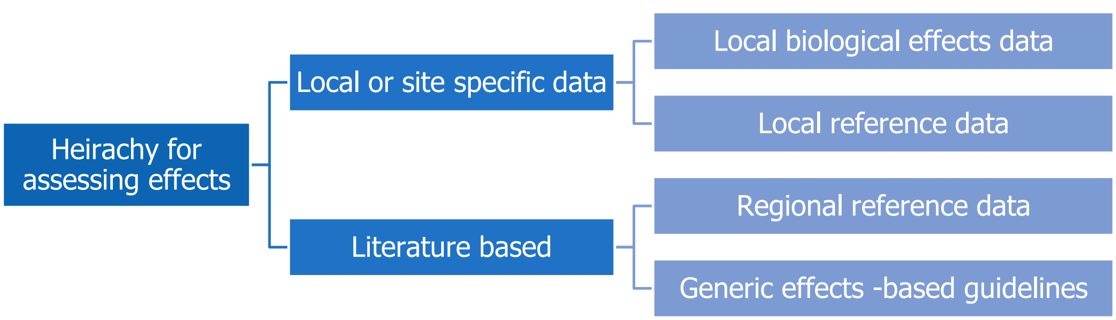


Figure 3.8 Heirachy for assessing effects

3.3 CASE STUDY DATA

3.3.1 DATA COLLECTION METHODOLOGY

Data collection at the channel and adjacent riparian area was undertaken during 2012, 2013, 2015 and 2016. 2012 is the 'base case' year since there was no cool water discharge. Field measurement locations for the channel study site are illustrated in Figure 3.5 and Figure 3.11, a comprehensive map is provided in Appendix I. *Outlet* is the cool water discharge location, at locations 1, 2, 3 and 4 the effect of the remaining cooled water is monitored in the indicated flow direction. Location *Intake* is the location where water is extracted (offtake) for heat recovery. As illustrated, BENL0504 was moved location once to location 3(2) in 2015. (Boderie & van Geest, 2014)

The next schematic outlines the data that was collected at the study site.

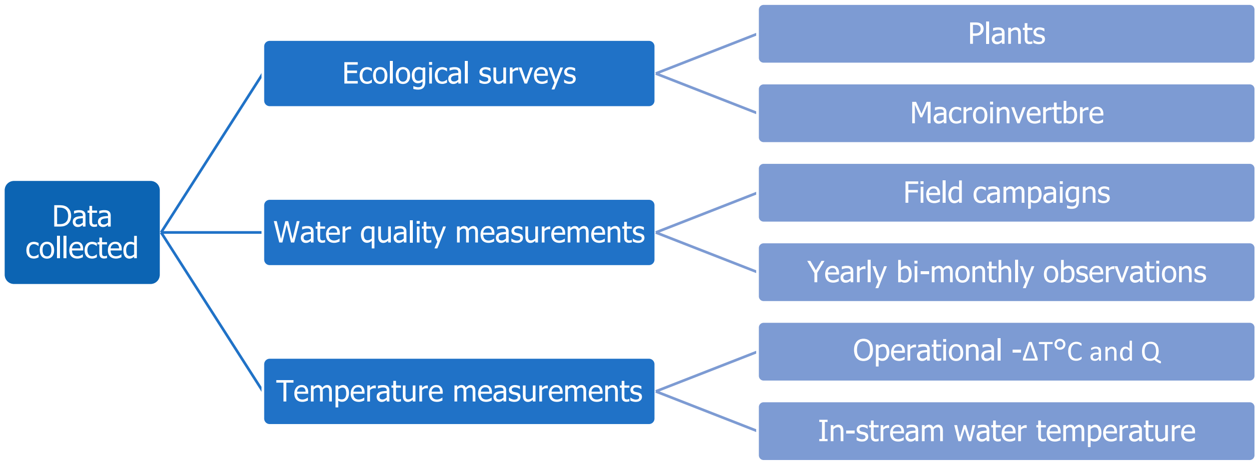


Figure 3.9 Data collection summary

The four companies involved in the data collection are described in the next schematic.

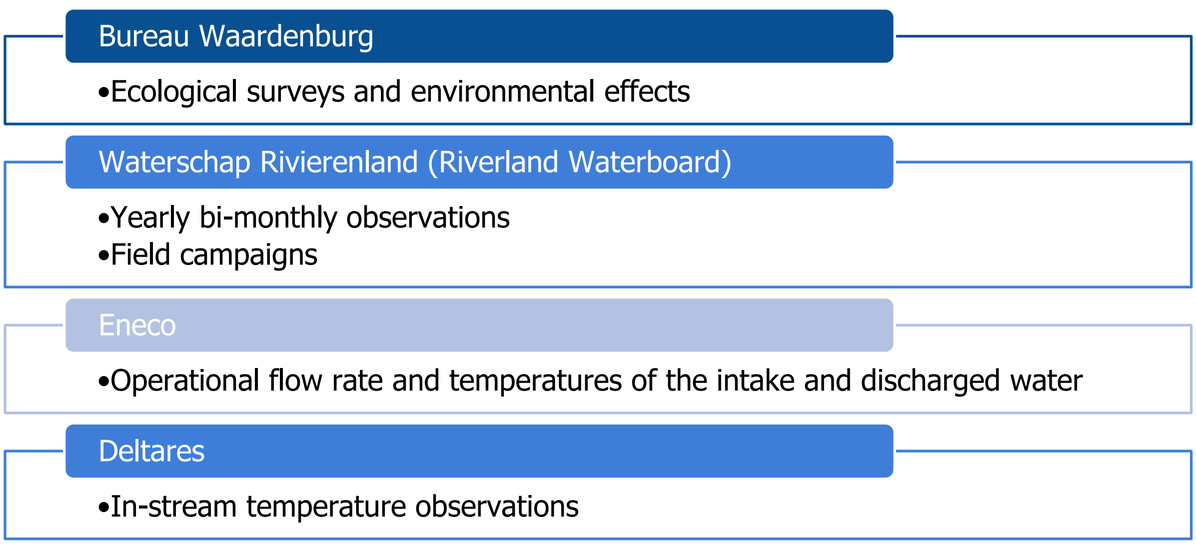


Figure 3.10 Summary of companies involved in data collection

The next table summarises the data collection, type and location of observation.

Table 3.2 Data available at study site (Boderie & van Geest, 2014, p. 5)

No.	Type	Description	Location measured (see Figure 3.2)
1	Field campaigns	3 separate days T,O_2, pH, EC, Turb	Outlet, 1,2,3,4 varying depths
2	Bi-monthly observations	1-2 observations a month Extensive range of water quality parameters	1,2,3,4 one depth
3	In-stream water temperature (T)	Hourly interval when in place	1,2,3,4 at varying depths

No.	Type	Description	Location measured (see Figure 3.2)
4	Operational water temperature (-ΔT) and flow (Q)	Every 8 to 16 minute interval when in operation	"Inlet" (in supply pipe) and "Outlet" (return line)
5	Air temperature and global radiation	Hourly	Herwijnen (~9km east of site) atmosphere

The next table summarises monthly timing and frequency of data collected at Hoog Dalem during cold water discharge. Water quality data, from laboratory observations, was also carried out during months where there was no cold water discharge.

Table 3.3 Summary data collection for each month, year, type of observation and number of observations

M	Mar				Apr				May				Jun				Jul				Aug				Sep			
Y	**'12**	**'13**	**'15**	**'16**	**'12**	**'13**	**'15**	**'16**	**'12**	**'13**	**'15**	**'16**	**'12**	**'13**	**'15**	**'16**	**'12**	**'13**	**'15**	**'16**	**'12**	**'13**	**'15**	**'16**	**'12**	**'13**	**'15**	**'16**
C							✓	·	·	·	✓	✓	·	✓	✓	✓	·	✓	✓	✓	·	✓	✓	✓	·	✓	·	·
T							·	·	✓	✓	·	·	✓	✓	✓	·	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
L			1	1			1	1	2	3	2	1	2	2	2	2	2	3	2	3	2	2	2	2	2	2	2	2
E									1		1	1		1			1	1	2	1		1						
F														1					1			1						
M																			1			1						

Note: **C)** Cold water discharge operational **T)** In-stream water temperature monitoring **L)** Laboratory data **E)** Macrophyte ecological surveys **F)** Feld campaigns **M)** Macrofauna quick scans

3.3.2 TEMPERATURE OBSERVATIONS

3.3.2.1 COLD WATER DISCHARGE – OPERATIONAL DATA

The temperature of the water at the intake (T-in) and discharge point (T-return) was recorder by thermal sensors at 8 or 16 minute intervals by the operator Eneco, during cold water discharge. The sensors are integrated in the supply and discharge pipes inside, (Boderie & van Geest, 2014). At the point *outlet* colder water is discharged in *intake* is where the warmer water is extracted, shown on Figure 3.2, cool water flows according to the direction of the arrows. Light blue: channel constructed in December 2010 to January 2011 and darker blue section was constructed from January to March 2012, (Boderie & van Geest, 2014).

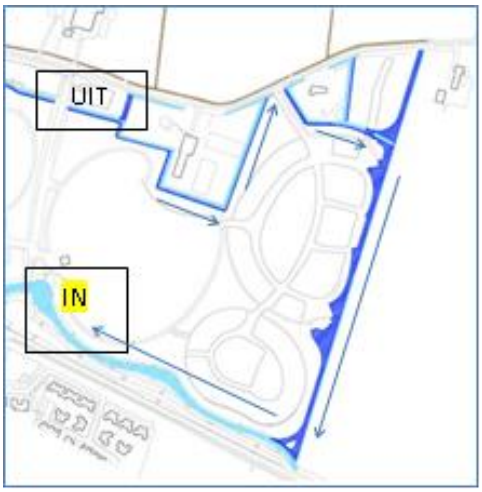


Figure 3.11 Location of watercourses in new residential area, Hoog Dalem

3.3.2.2 INSTREAM TEMPERATURE MEASUREMENTS

Water temperature and pressure was measured hourly using temperature pressure sensors. The timing of in-stream water temperature measurements varied for each year, as presented in the next table. Measuring equipment ("divers") were placed at depths of approximately 60cm and 100cm from the surface at each measuring point; BENL0502 to BENL0505. Months and associated years that measured water temperature was recorded is summarised in the next table, this table includes 2016 observation timing which was recently processed.

Table 3.4 Summary measured water temperature

M	Apr	May	Jun			Jul				Jul				Aug				Sept				Oct	
Y	‘13	‘13	‘13	‘15	‘16	‘12	‘13	‘15	‘16	‘12	‘13	‘15	‘16	‘12	‘13	‘15	‘16	‘12	‘13	‘15	‘16	‘12	‘16

3.3.3 ECOLOGICAL SURVEY DATA

At each of the four sampling locations, riparian vegetation and rooted and floating aquatic plants have been recorded, Figure 3.12 and Figure 3.13 further illustrate the respective zones.

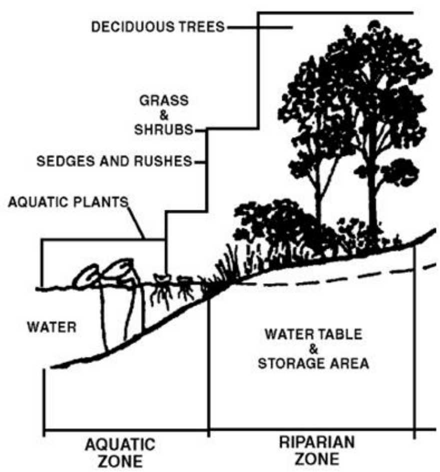


Figure 3.12 The natural shoreline has four components, beginning underwater and extending upland - the aquatic zone, the shoreline, the riparian zone, and the upland zone. The riparian zone is the section of land closest to the shoreline - buffer between the water and the land. (Riparian Zone and Regulations, 2016)

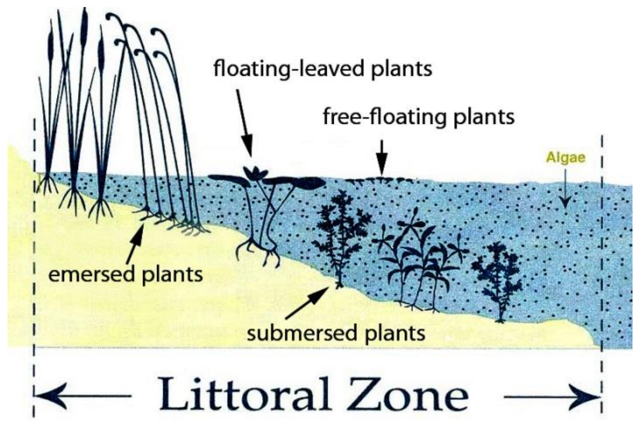


Figure 3.13 Macrophyte illustration within the littoral zone (closest to the shore where light reaches all the way to the bottom). (Aquatic and Wetland Plants in Florida)

Where the Tansley result for the ecological survey was used, a category is assigned rather a percentage cover, the category was converted to an approximate percentage cover. Therefore, when discussing the macrophyte observations, it is important to consider that BwB and WSRL reported the aquatic plants observations differently. Observations from BwB are available and WSRL undertook observations on two separate dates, as shown below.

Table 3.5 Macrophytes survey frequency

Month	May			Jun		Jul			Aug
Year	'12	'15	'16	'13	'12	'13	'15	'16	'13
BwB	1	1	1	1	1	1	1	1	
WSRL							1		1

3.3.4 WATER QUALITY MEASUREMENTS

Water quality measurements were undertaken with two different methods, referred to as:

1. Field Campaigns
2. Yearly bi-monthly measurements

3.3.4.1 FIELD CAMPAIGNS

The field campaigns were completed twice in 2013 and once in 2015:

- Campaign A - June 2013
- Campaign B - August 2013
- Campaign C - July 2015

Measurements of 6 parameters were taken on 3 separate days, during cold water discharge, at times varying throughout the day, from 05:40 (earliest) to 20:10 (latest). Field campaigns were undertaken at up to six measuring points:

1. 0 – OUT (cold water discharge point)
2. 1 – OUT (interim point between cold water discharge and BENL0502) (Campaign B only)
3. BENL0502
4. BENL0503
5. BENL0504
6. BENL0505 (farthest from cold water discharge)

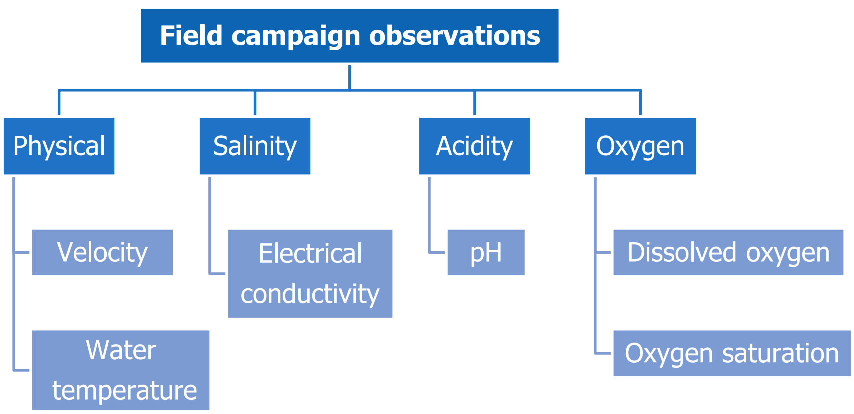


Figure 3.14 Field campaign mesured water quality observations

3.3.4.2 YEARLY BI-MONTHLY LABROATORY MEASUREMENTS

Water quality measurements were taken at BENL0502 to BENL0505, from 29-Feb-2012 to 20-Oct-2016 and excluding 2014. Measurements were taken at times varying throughout the day from 07:00 to 15:00. The typical frequency of sampling is twice per month and the maximum number of observations for a parameter measured is 209. However, the frequency of sampling was variable, sometimes once up to three times a month and not every parameter had the same frequency of sampling, as indicated in the next two schematics.

The next two figures summarise the parameters that were measured. The bi-monthly measurements were undertaken by a laboratory and are often referred to as laboratory data throughout the report.

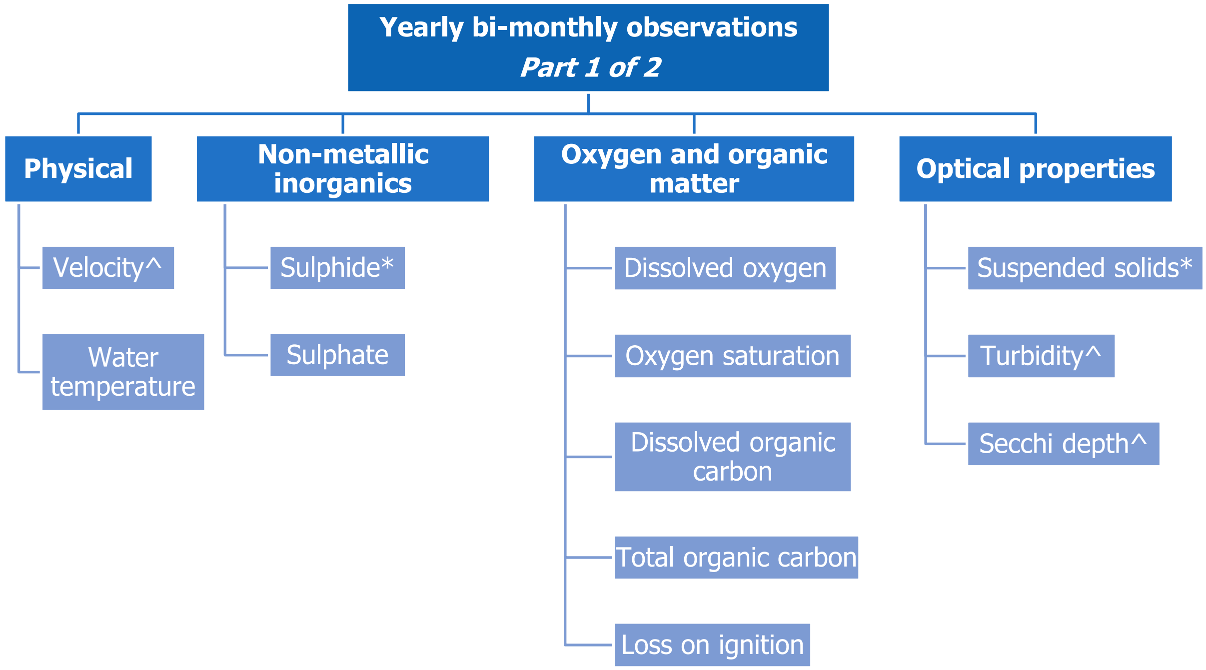


Figure 3.15 Yearly bi-monthly mesured water quality observation parameters (Part 1 of 2)[8]

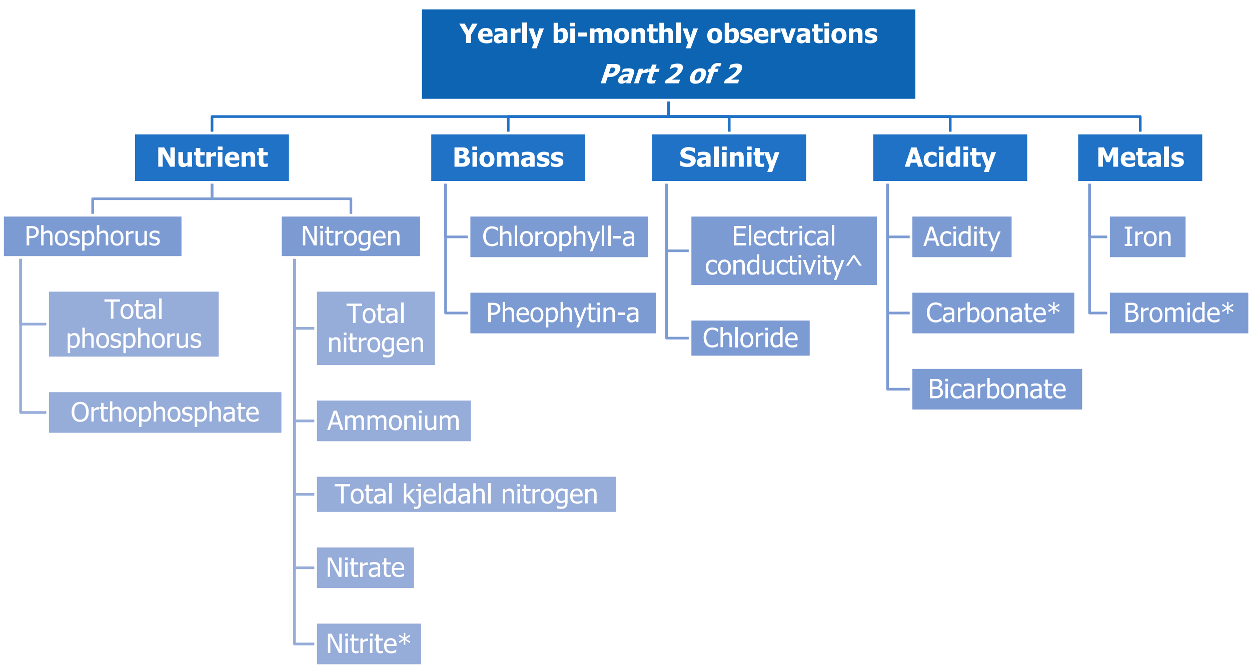


Figure 3.16 Yearly bi-monthly mesured water quality observation parameters (Part 2 of 2)[8]

[8] a) Categories based on NWQMS Guidelines, Volume 2 b) * parameter measured has limitation due values below minimal detectable limit c) ^ parameter measured for fewer years

3.3.5 SUMMARY

This section outlined the data available for the study site. As outlined in Section 2.2.2, the ANZECC guidelines recommend monthly data collection for a 2 year duration to assess the effects of artificially modifying the thermal regime of a water body. The duration and frequency of water quality data would satisfy this recommendation. The frequency of the ecology surveys was twice per year and would not meet with this recommendation.

3.4 STUDY SITE INDICATOR METRICS

Hoog Dalem is defined as an artificial water body since it was constructed by humans. STOWA guidelines general objective was to retain the modified status with aims for improvement (STOWA, 2012). Artificial water bodies, such as canals and ditches, are considered to be irreversible, not able to reach a natural status. Therefore, not being able to reach MEP, within The Netherlands an approach has been derived for an artificial water body reference status; the best of similar water bodies in the respective region, (Ministry of Transport, Public Works and Water, 2005).

Hoog Dalem is a freshwater channel, this water body type is categorised as M1A based on Table 1.1 of the STOWA Guidelines (STOWA, 2012, p. 3). Hoog Dalem is not categorised as a waterway significant enough to have a status determined by WVL. STOWA metrics are based on similar waterway types, water quality observations from Hoog Dalem were compared to the STOWA metrics. The following sections outline STOWA metrics for M1A type waterways, results are discussed in a Section 3.6.1.

3.4.1.1 TEMPERATURE

To give context to acceptability of temperature changes in a type M1A waterway, the next table outlines the metric for water temperature (STOWA, 2012, p. 151). For GEP, water temperature should not exceed 25°C. Warmer temperatures are considered to be a deviation from GEP, temperatures cooler are considered an improvement.

Table 3.6 Water temperature metric M1A waterway

Quality level	MEP	GEP	Moderate	Poor	Bad
Temperature (°C)	≤ 23	≤ 25	25 – 27.5	27.5 – 30	> 30

3.4.1.2 ECOLOGICAL

The list of ecological species is provided with a score from 1 up to 5, where 1 indicates a desirable species and 5 indicates that the species is not desirable for the type of waterway. The ecological categories considered from STOWA are:

1. Macrophytes
2. Macrofauna (macroinvertebrate)

3.4.1.2.1 WATER PLANTS

The table below outlines the percentage coverage range for water plants and flab based on "good" ecological potential, for category M1A (Hood Dalem category). For example, to be considered "good" ecological potential, flab[9] coverage should be less than 15% and submerged macrophytes should be in the range of 30-90% coverage.

Water plant, macrophyte, types were described in Figure 3.13. Since some macrophytes act as both floating and submerged or bottom growing and floating, decisions on which type most represented the plants observed were made.

Table 3.7 STOWA recommended plant coverage (%) for GEP (STOWA, 2012-34, p. 106)

Category	Description	% cover (GEP/M1A)
Submerged (submers)	GEP considers a range, "not too much, not too little"	30-90
Floating (drijvend)		30-90
Emergent (Emers)		5-25
Flob (Flab en Kroos)	Flab is a nuisance – pioneer species, typically in abundance in new waterways and quantity declines as waterway biota matures. Some is considered GEP, but not more than some.	<15

3.4.1.2.2 MACROFAUNA

Macrofauna / macroinvertebrate species in canals and ditches are common in The Netherlands, (STOWA, 2012). There are between 300-400 species of macrofauna, including many types of brush worms, snails, flatworms, leeches, larger snails, flatworms, leeches, and a high quantity of the water insects and water mites (STOWA, 2012). Typical species include flatworm *Dugesia lugubris*, mayflies *Caenis horaria, C. robusta and Cloeon simile*, water bugs, *Ilyocoris cimicoides* and *Sigara striata*, water beetles *Agabus undulatus*, *Hygrobia hermanni*, *Laccobius biguttatus L. minutus* and *peltodytes caesus* and mosquito larva *ablabesmyia monilis*. The next table outlines the macrofauna metrics for a M1A water body.

Table 3.8 Macrofauna metrics for WFD type M1A (STOWA, 2012-34, p. 114)

	Definition	Description
DN	Negative taxa	Less desirable. Higher abundance, leads to a more negative value. Quantities by - counting population.
PT	Positive taxa	Species that indicate GEP. Quantity by - is "1 present", then that contributes to a positive rating.

[9] Flab refers to "floating algal bed" and it generally develops as filamentous algae / draadwier, which then floats, due to gases, to the top of the water column.

Table 3.9 Macrofauna score description (STOWA, 2012-34, p. 114)

Score	≥50
Good	≥50
Moderate	≥ 40 - <50
Inadequate	≥15 - <40
Poor	< 15

3.4.1.3 WATER QUALITY

STOWA indicator metrics for water quality are outlined in the next table. These metrics are based on results from the analysis of similar waterway types as Hoog Dalem. The ranges of acidity and oxygen levels are broad as a result of differentiation within the types and natural daily fluctuations. The time of the measurement in particular greatly influences oxygen, the lowest values early in the morning, at midday the highest values and the pH also fluctuates during the day. Regarding nutrients and transparency, displayed as both the 10 and 50 percentile, it is an arbitrary choice by STOWA and both can be used. (STOWA, 2012)

Table 3.10 STOWA M1A water quality metrics

Category	Abbre-viation	Unit	M1A"typical[10]"	M1A "good"[11]	"high ecological level"[12]	M1A GEP[13]
Physical	T	°C				**≤25**
Acidity	pH	-	5.5 to 8.5	6.25 to 9	6 to 8.5	**5.5 to 8.5**
Optical properties	SD	M	≤1.4 (10%)	≤1.4 (10%)		**≥0.65**
Dissolved oxygen and organic matter	O	mg/l				
	O%	%	35-120%	35-120%		**35-120**
Nutrient	TP	mg/l	≤0.10 (10%) ≤2.4 (50%)	≤0.10 (10%) ≤2.4 (50%)	< 0.15	**≤ 0.22**
	TN	mg/l	≤0.22		<1.5	**<2.4**
Anions	Cl	mg/l	≤150	<150-<250	< 70	**≤150**
	SO_4	mg/l		<50 - <160	2 to 30	

[10] (STOWA, 2012, pp. 147-148).
[11] "Good" value is an indication of the 'target aquatic systems Noord-Holland' for M1A WFD water type. Value is designated to the summer where deemed necessary for the mid-ecological level. N.B. The phosphorus contents are specified in the majority of cases as a P-PO4. The corresponding total phosphate is at least as high, generally higher (STOWA, 2012, p. 149).
[12] Indicator ie chemical control parameters associated with well-developed closed ecosystems in Utrecht (End-Utrecht, see, Fellinger et al. 1996). Indicated summer values that are considered necessary for the high ecological level, for and finally merged with the mid-level ecological. For type "Polder Locks. Clay type" (STOWA, 2012, p. 149).
[13] (STOWA, 2012, p. 29).

3.4.1.3.1 OTHER RELEVENT WATER QUALITY PARAMETERS

3.4.1.3.1.1 VELOCITY

Velocity (v) is an indicator of residence time and can be used to indicate a water body's susceptibility to stratification, since stagnant water is more susceptible to stratification than moving water (ANZECC, 2000). There are many water quality issues that may occur in stagnant water, residence time is an important factor when considering biological processes, such as algae/flab. Waterway types similar to Hoog Dalem were observed to experience periodic flow around inlets and from groundwater, this may be up to or in excess of 10 cm/s, typically lower than a few centimetre's per second, (STOWA, 2012). Similar to Hoog Dalem, flow directions in these types of waterways experience flow reversal.

3.4.1.3.1.2 CHLOROPHYLL-A

Chlorophyll-a (chl-a) is an alternative indicator of nutrient pollution and is an important indicator of algal biomass, since algae contain approximately 1-2% (dry weight) Chl-a., increasing Chl-a typically indicates algae growth. However, due to interspecies variation and variation, a clear relationship between Chl-a concentration and algae biomass is not always present. Based on STOWA guidelines for canal type waterways, different to M1A, chl-a concentration of 23µg/l is considered GEP (EQR 0.6), higher than 184 is considered extremely poor (EQR 0) and lower than 6.8 (EQR 1, MEP) is higher quality (STOWA, 2012, p. 93).

An annual median maximum chl-a of 2µg/l is considered to be oligotrophic, aesthetically pleasing and to have very low phytoplankton levels. In contrast, annual median maximum chl-a in excessive of 15µg/l is considered hypereutrophic, extensive algal turbidity, experiences loss of amenity, serious oxygen depletion at the bottom, (ANZECC, 2000, pp. 8.2 - 9). For fresh waterways with a recreational use, it is recommended that the concentration is maintained below 20µg/l (ANZECC, 2000, pp. 8.2 - 9).

3.4.1.3.1.3 ELECTRICAL CONDUCTIVITY

Electrical conductivity (EC) measures the total concentration of inorganic ions (salts) present in the water, in freshwater it is typically less than 100mS/m. An elevation of EC is more important than a decrease, in freshwater, and EC can have direct and indirect effects on water quality and species composition. EC may become an issue when 150mS/m is exceeded. (ANZECC, 2000, pp. 8.2 - 16).

3.5 RESULTS

3.5.1 TEMPERATURE

Water temperature distribution

This section presents results from two methods of recording water temperature, the operational intake and discharge temperature and flow and the in situ temperature measurements along the channel. Measured water temperature without cold water discharge indicates the extent of disturbance without (direct) influence when compared to normal temperature (no cold water discharge) (ANZECC, 2000).

3.5.1.1 COLD WATER DISCHARGE – OPERATIONAL DATA

The section presents operational cold water discharge data for 2013, 2015 and 2016, detailing the severity (-ΔT°C), frequency and duration. The next two tables summarise the total monthly energy (million MJ) and the total monthly cold water discharge (in m^3). Cold water discharge was not operational in 2014 due to ATES technical problems. March 2015 discharge was essentially negligible, likely (not confirmed) this discharge was for testing of the ATES.

Table 3.11 Cold water discharge – total monthly flow (m^3)

Month:	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
2013	-	-	-	70,511	112,452	75,038	17,557	**275,600**
2014	-	-	-	-	-	-	-	-
2015	144	4,141	20,255	31,096	80,150	31,276	-	**167,000**
2016	-	-	11,018	43,866	30,283	43,489	-	**128,700**

Table 3.12 Cold water discharge – total monthly energy (million MJ)

Month:	Apr	May	Jun	Jul	Aug	Sep	Total
2013	-	-	0.7	1.6	0.9	0.2	**3.4**
2014	-	-	-	-	-	-	-
2015	0.1	0.5	0.7	1.6	0.6	-	**3.4**
2016	-	0.2	0.8	0.5	0.9	-	**2.5**

Total monthly energy was calculated based on the cooling power for the pair of wells connected to the heat exchanger, energy was calculated based on the below formula and constants (Medrano, 2008).

$$Pc = \rho c_P Q_e (T_{IN} - T_{RETURN})$$

- Pc cooling power (W)
- ρ density of water, 998.3 (kg m^{-3})
- c_P heat capacity of water, 4182 (J kg^{-1} K^{-1})
- Q_e Flow rate, based on operational data (m^3 s^{-1}]
- T_{IN} Temperature warm water, based on operational data (K)
- T_{RETURN} Temperature cooled water, based on operational data (K)
- Monthly energy = per month $\sum(Pc(MW) \times dT\ (min) \times 60)/1{,}000{,}000$

Each year of cold water discharge experienced variability with on and off periods and short periods of off during mostly on periods. The below summarises the most representative cold water discharge durations, without elaborating an extensive list for each time the system turns on and off.

1. 2013:
   a. June-07 to June-11, June-19 to July-21, July-26 to August-24 and August-30 to September-20
2. 2015
   a. April-24 to May-18 and June-18 to August-14
3. 2016
   a. May-16 to July-13 and July-22 to August-21

To gain further insight into the monthly operational distribution, the next box plots present monthly flow and temperature distribution in 2013, 2015 and 2016. Box plot whisker line extends 1.5 times the value of the 75th percentile, the points outside of this value are outliers from the whisker. Lower -ΔT°C during 2013 was due to technical problems, such as blockages in the heat exchanger (Boderie & van Geest, 2014). The resultant impact on the system in 2013 can be further observed by the decreasing flow rate from July. The flow rate in 2015 and 2016 was more consistent than 2013 and the -ΔT°C was cooler.

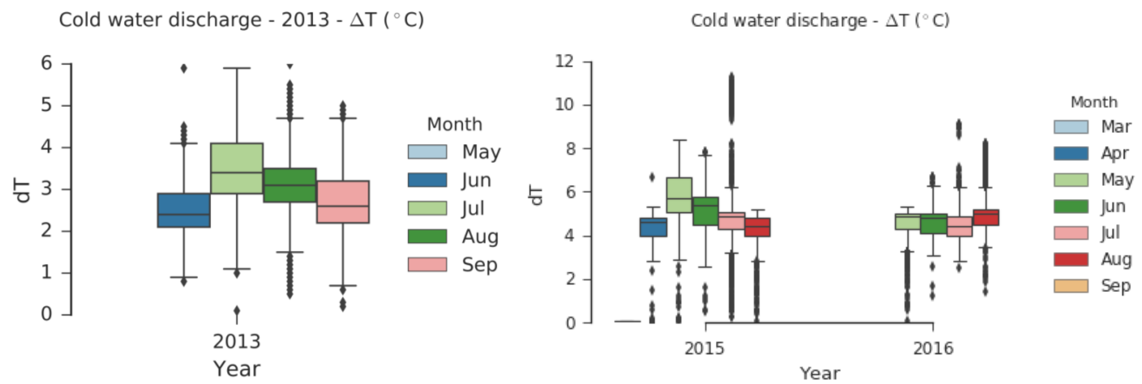


Figure 3.17 Operational cold water discharge -ΔT°C

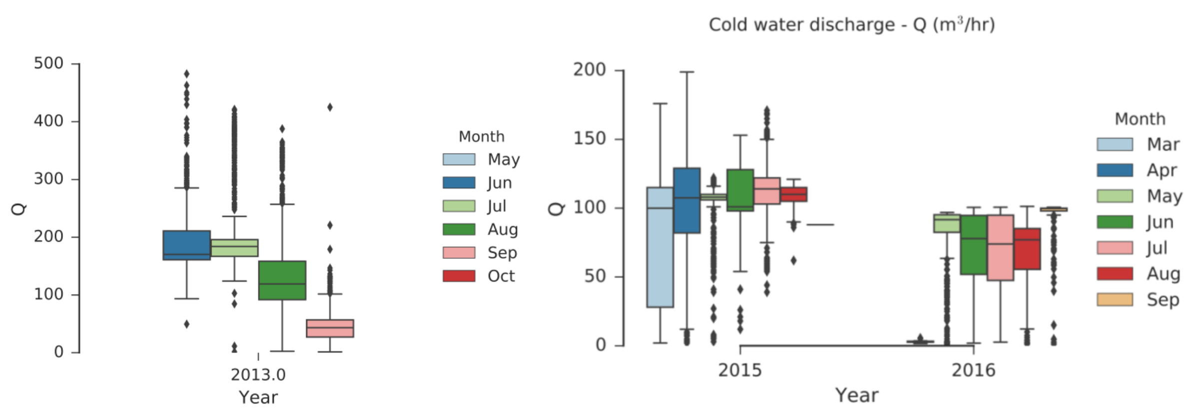


Figure 3.18 Operational cold water discharge – Q

Recorded temperature of cooled water discharged (T-return), warmer water intake temperature (T-in) and the effective power (P) for 2013, 2015 and 2016 is presented in Figure 3.19 to Figure 3.21. Operational cool water discharge was most consistent throughout 2016.

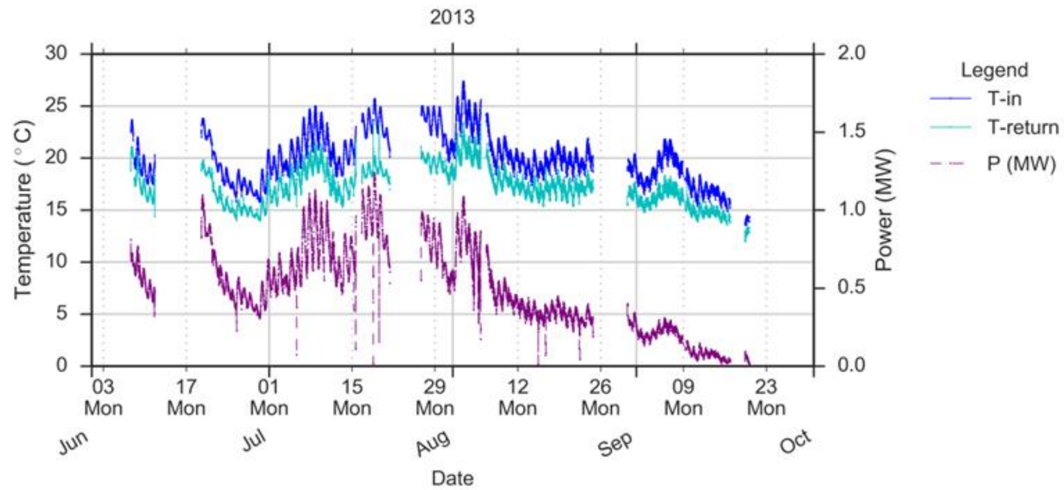


Figure 3.19 Cold water discharge– intake and discharge temperature – 2013

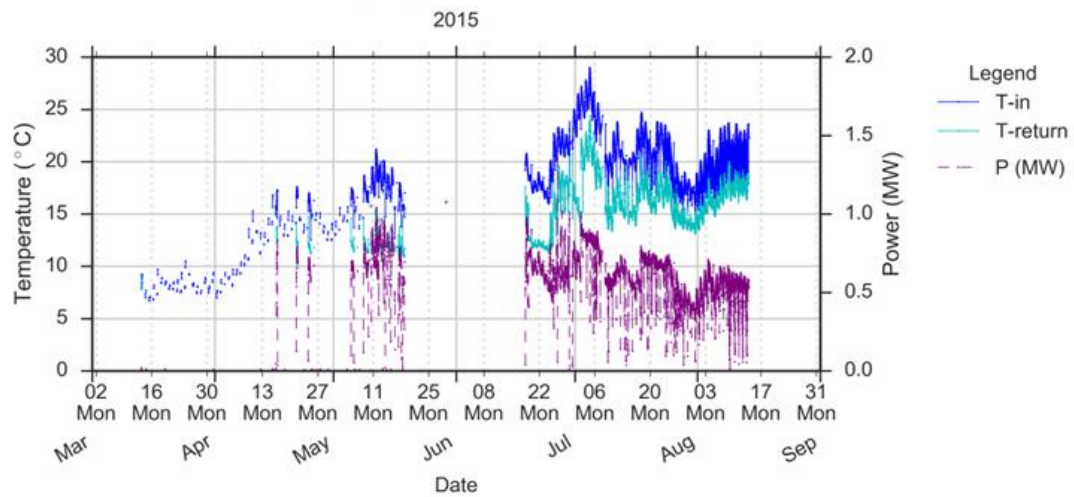


Figure 3.20 Cold water discharge– intake and discharge temperature – 2015

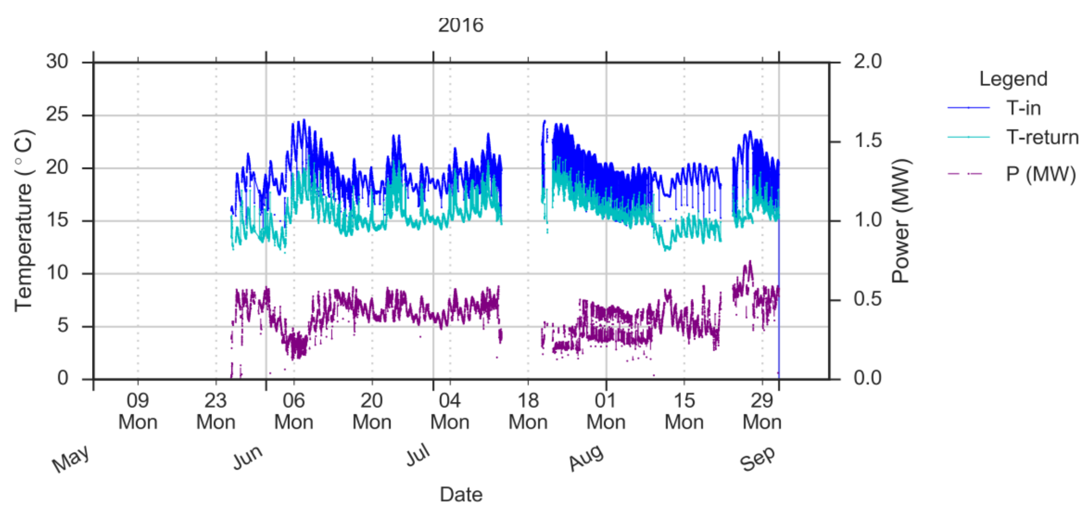


Figure 3.21 Cold water discharge– intake and discharge temperature – 2016

3.5.1.2 IN-STREAM MESAUREMENTS

Water temperature observations along the channel, for each measuring point at two different depths during 2015 and 2016 are presented in Figure 3.22 to Figure 3.25. Without cold water discharge, the water temperature along the channel is similar, with minor differences in temperature mainly due to location, such as shading effects and also differences in depth. During cold water discharge an approximately 5 °C difference can be observed between MP 1 and MP 4. The brief period of no cold water discharge in July 2016 can be clearly observed from the water temperature observations, where MP 1 temperature is similar to MP 4.

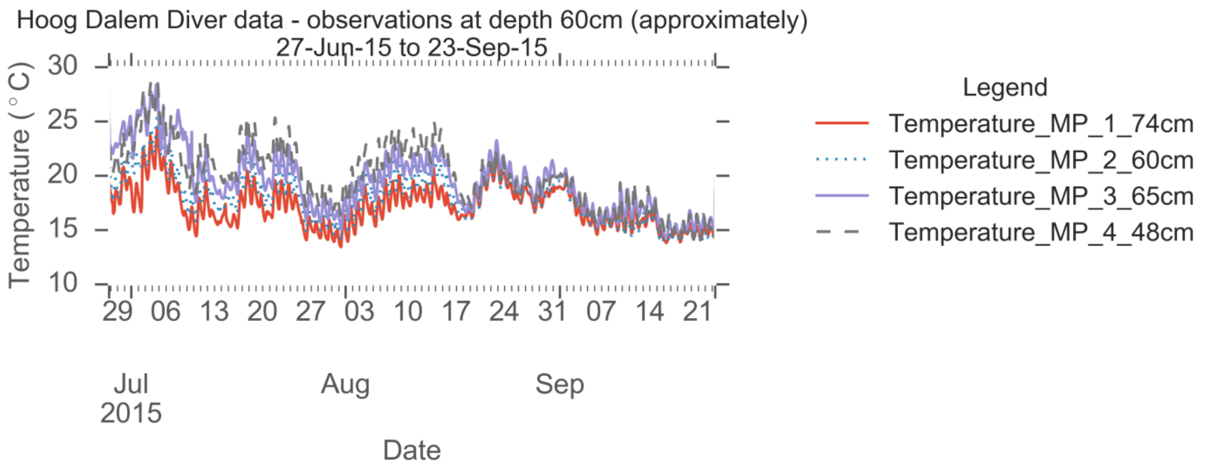


Figure 3.22 Water temperature –2015 – 60cm

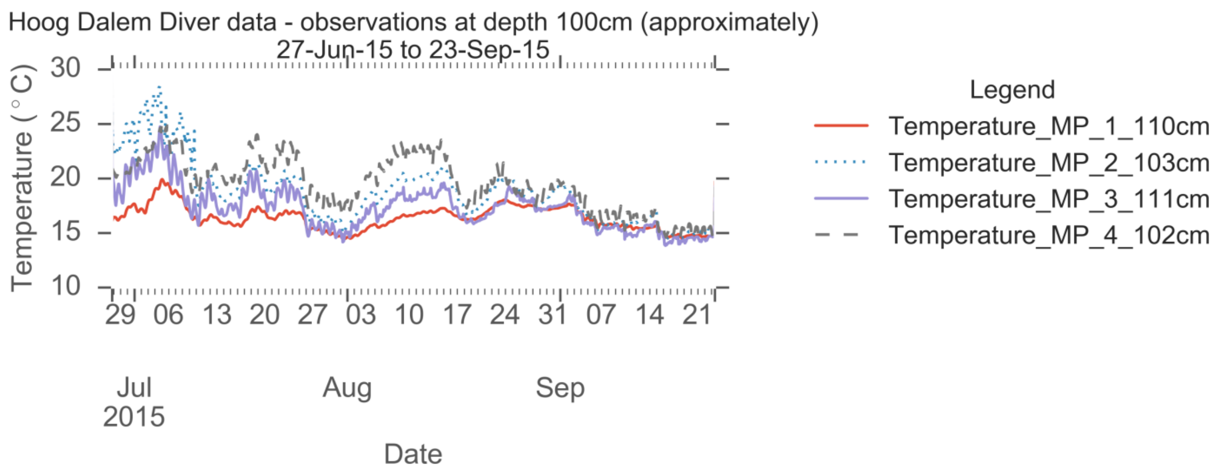


Figure 3.23 Water temperature –2015 – 100cm

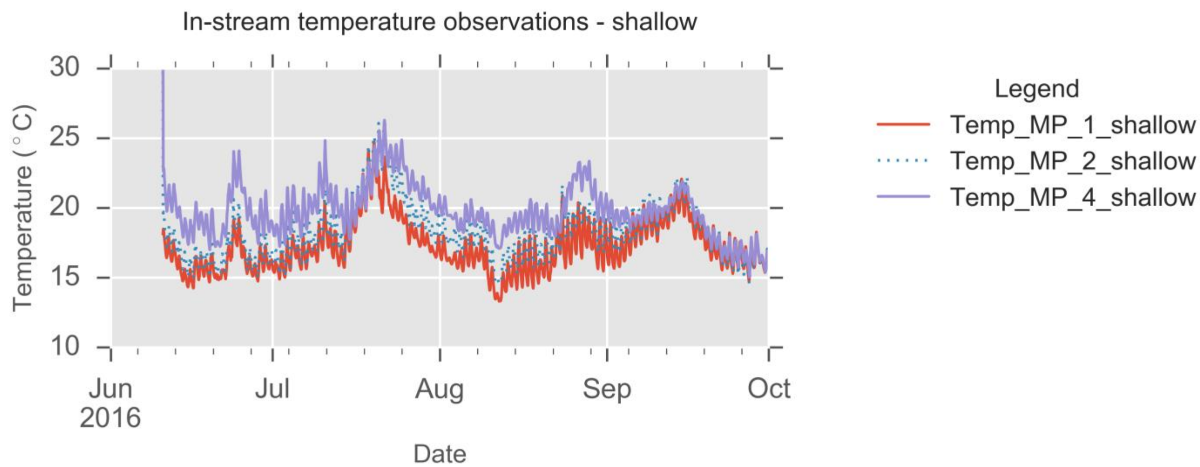


Figure 3.24 Water temperature – 2016 – shallow (50cm from surface)

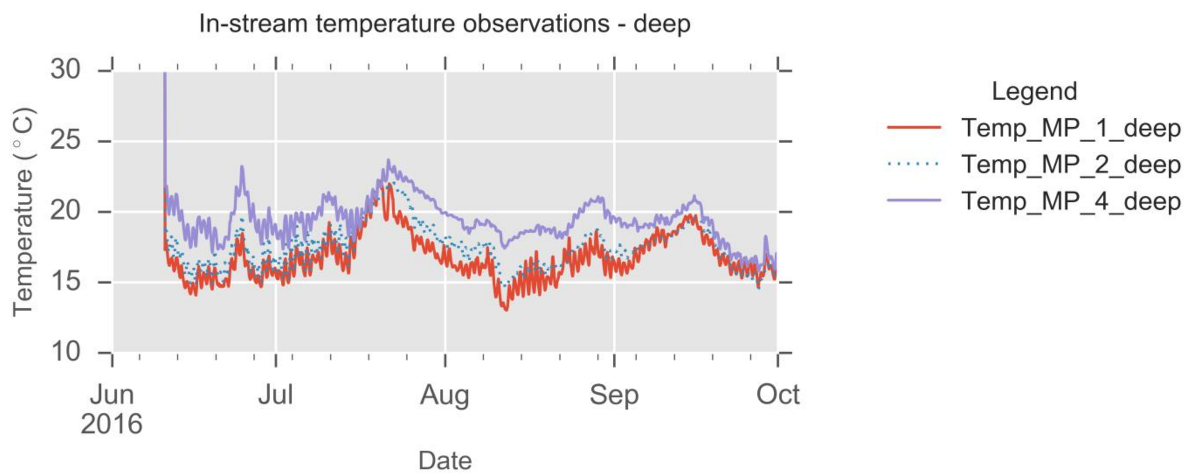


Figure 3.25 Water temperature –2015 – deeper (70cm from surface for MP1 and 100cm from surface for other points)

3.5.2 ECOLOGY

3.5.2.1 AQUATIC PLANTS

The STOWA guidelines, Table B5.1, outlines the water plants that are desirable to undesirable for Dutch water ways, based on a 1-5 metric. Metric 1 is most venerable and desirable and 5 is eutrophic or a less desirable species (STOWA, 2012-34). Each species identified during ecology field observations is graphed with the relevant STOWA score in the legend, where a score is available for the species. Graphed results for the ecology surveys are provided in Appendix IV.

3.5.2.2 MACROFAUNA

There were two surveys for macrofauna undertaken, graphs presenting results from the 2015 macrofauna quick scan are provided in Appendix IV.

3.5.3 WATER QUALITY

To present the results from the monthly laboratory, two types of graphs have been prepared for each parameter:

1. Box plots divided by cold water discharge on or off for each measuring point
2. Variation throughout the year for each measuring point

Box plots were selected to clearly present the range and skewness of the water quality measurements with cold water discharge on or off. Box plot whisker line extends 1.5 times the value of the 75^{th} percentile, points outside of this value are outliers from the whisker. The time series plots for each parameter present the variation throughout the year at each measuring point, with periods of cold water discharge shaded blue on each graph. The following sections summarise observations for each parameter, the results are provided in Appendix V.

There are several types of graphs prepared for the field campaigns, observations were undertaken during cold water, results are provided in Appendix V.

3.5.3.1 FIELD CAMPAIGNS

The operational cold water discharge during the three field campaigns is presented in Figure 7.16 and Figure 7.18. For campaign A, the data from Eneco for flow is not present for the entire day, as illustrated in Figure 7.16. Cold water discharge was in operation throughout the day for campaigns B and C. The field campaigns undertaken in 2013 had more frequent observations than in 2015. However, as can be observed the temperature difference between the intake water (T-in) and discharged water (T-return) is higher in 2015 than in 2013. In summary for the field campaigns, Campaign A experienced the least impact from cold water discharge, Campaign B experience consistent cold water discharge and Campaign C experienced the coolest cold water discharge.

Since field campaigns were not undertaken in periods where cold water discharge has not been present for a longer period of time prior to the campaign, it is not possible compare if this effect at this specific location is due to the effect of cold water discharge. The data collected throughout the year has been taken closer to the water surface, around 0.3m.

3.5.3.2 YEARLY BI-MONTHLY LABROATORY MEASUREMENTS

The next scatter matrix distinguishes observations between -ΔT°C on or off for each measuring point. DO concentration was observed to decrease with temperature when -ΔT°C is off, conversely DO increases for increasing temperature when -ΔT°C is on. Chl-*a* concentration was lower during -ΔT°C on and pH showed the closest correlation to water temperature during on and off. Overall, there is a high variation in data points, with low confidence in most of the trend lines.

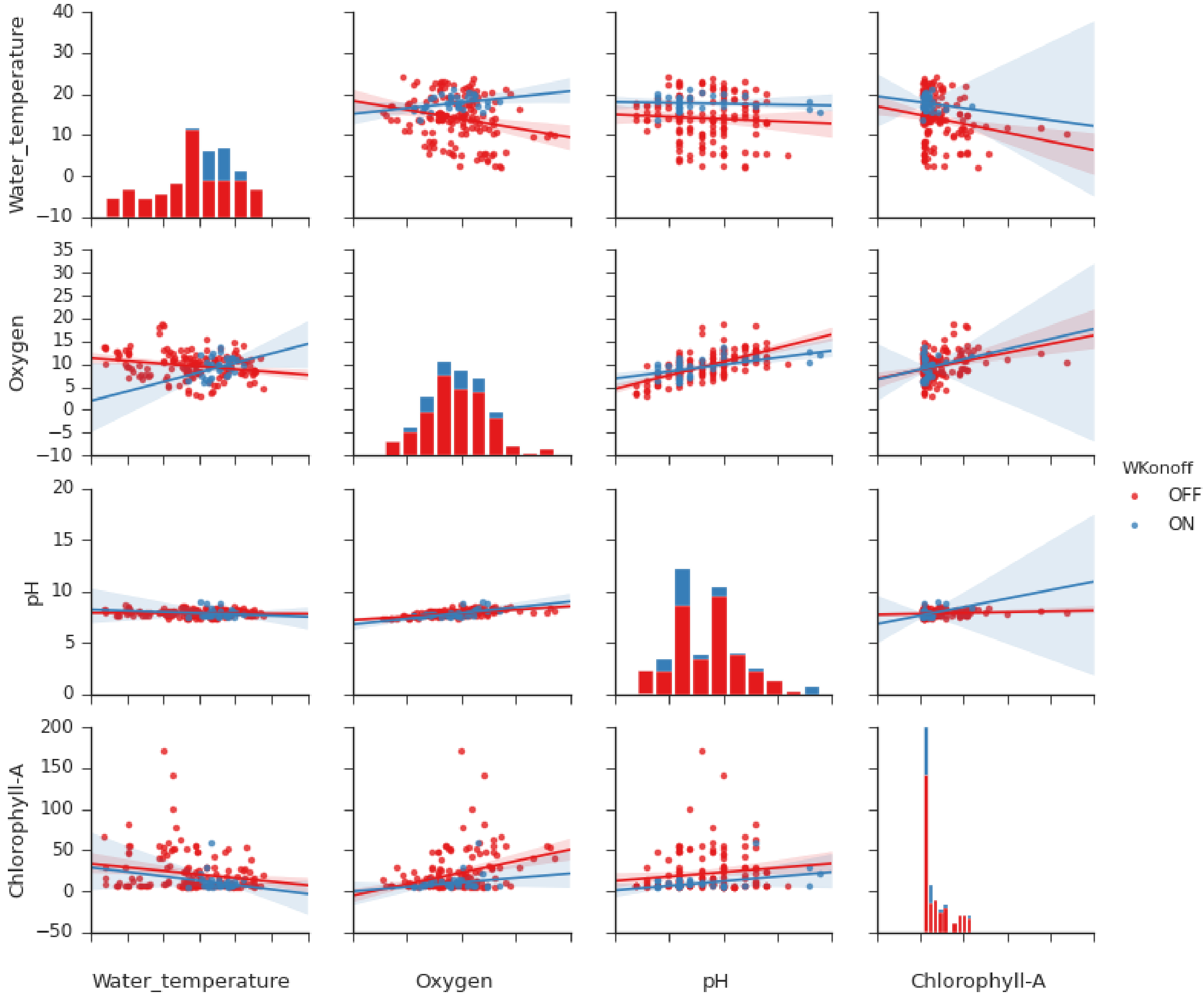


Figure 3.26 Scatter matric for -ΔT°C ON / OFF –for Chl-a (ug/l), pH, DO (mg/), water temperature (°C)

3.5.3.2.1 PHYSICAL

Temperature in the waterway did not exceed 25°C during water quality sampling. Measured water temperature without cold water discharge indicated the extent of disturbance without (direct) influence when compared to normal temperature (no cold water discharge).

Most velocity measurements were taken during 2015 and 201, the observations were considered to be realistic based on similar waterway types (STOWA, 2012, p. 37). During 2015, the velocity measurements were divided by 10 since all of the results appeared to be a factor of 10 higher than for the other observation years.

Table 3.13 Summary water quality observations - physical

Abbre-viation	Unit	Without -ΔTºC	With -ΔTºC
T Refer: Figure 7.50 Figure 7.51	°C	• Median ~14ºC • Minimal variation along the channel	• Median ~17 ºC at BENL0502 to ~20 ºC at BENL0505 • Median higher with -ΔTºC since system operates when water is warmer • Temperature increases from BENL0502 to BENL0505 • Temperature increases with distance from BENL0502
v Refer: Figure 7.52 Figure 7.53	cm/s	• Median ~0.25 at BENL0502 to ~0.2, very slightly lower at BENL0505 • Minimal variation along the channel	• Median 1 at BENL0502 to ~0.7 at BENL0505 • Almost constant median BENL0502 to BENL0503, reduces at observations BENL0504 to BENL0505 • Increased velocity during cold water discharge associated with discharge • Width of channel increases with distance from outlet and is wider near the intake point (near BENL0505)

3.5.3.2.2 NON-METALLIC INORGANICS

A trend could be observed for the median SO_4 concentration during cold water discharge, the concentration increased furthest from the outlet. Lower concentration was most likely related with flow during -ΔTºC since SO_4 is weakly bound to sediment particles, a lower retention where there is shorter retention time (Scheffer, 1998).

Table 3.14 Summary water quality observations – non-metallic inorganics

Abbre-viation	Unit	Without -ΔTºC	With -ΔTºC
SO_3^-	mg/l	• Maximum detectable concentration was 0.1mg/l • Measurements were below the detectable limit, therefore results were not graphed	
SO_4 Refer: Figure 7.54 Figure 7.55	mg/l	• Similar peak occurrences for each of the measuring points, with a different magnitude in peak • BENL0503 varied the most and experienced the highest concentrations, compared to the other measuring points • Major peaks occurred during January, February, March and September, with the highest peak occurring in February. Without -ΔTºC: • Median ~80mg/l at BENL0502, increases to ~100mg/l at BENL0504 and then significantly decreases to ~40mg/l at BENL0505 • Variation along the channel of +/-60mg/l	SO_4concentration during cold water discharge, the concentration increased furthest from the cold water discharge • Median ~30mg/l at BENL0502 steadily and gradually increasing to ~40mg/l at BENL0505 • Variation along the channel of +/-10mg/l • Range +/-25% from median was significantly less then without -ΔTºC • BENL0502 median is ~50mg/l lower than without -ΔTºC • BENL0505 median is slightly lower <10mg/l than without -ΔTºC

3.5.3.2.3 DISSOLVED OXYGEN AND ORGANIC MATTER

DO and organic matter are indirect stressors (or parameters), which means they do not have a direct effect on biota (ANZECC, 2000, pp. 3.3 - 4). Variations of these parameters can influence other parameters in a positive or negative way.

Table 3.15 Summary water quality observations – dissolved oxygen and organic matter

Abbre-viation	Unit	Without -ΔTºC	With -ΔTºC
DO Refer: Figure 7.56 Figure 7.57	mg/l	• Median ~8mg/l at BENL0502, increases to ~10.5mg/l at BENL0504 and then slightly decreases to ~10mg/l at BENL0505 • Median variation along the channel of +/- 2mg/l	• Median ~9mg/l at BENL0502 steadily and gradually increasing to ~11mg/l at BENL0504 and then decreases to ~10mg/l at BENL0505 • Variation along the channel of +/- 2mg/l • Median at BENL0502 higher with -ΔTºC on than off • Median at BENL0503 lower with -ΔTºC on than off • Median at BENL0505 same for -ΔTºC on or off
O% Refer: Figure 7.58 Figure 7.59	%	• Median ~80% at BENL0502, increases to ~100% at BENL0504 and then slightly decreases to ~90% at BENL0505 • Median variation along the channel of +/- 20% • Minimum 20% • Maximum 160%	• Median ~95% at BENL0502, increases to ~120% at BENL0504 and then slightly decreases to ~105% at BENL0505 • Median variation along the channel of +/- 25% • Median at BENL0502 higher with -ΔTºC on • Median at BENL0503 slightly higher with -ΔTºC on, opposite than for DO • Median at BENL0505 higher for -ΔTºC on, different than for DO • +/-25% range from median smallest at BENL0502 with -ΔTºC
DOC Refer: Figure 7.60 Figure 7.61	mg/l	• Median ~7.5mg/l at BENL0502, increases to ~8.5mg/l at BENL0504 and then slightly decreases to ~7mg/l at BENL0505 • Median variation along the channel of +/- 1.5mg/l	There does not appear to be a strong difference in median or trend when comparing DOC for cold water discharge when on or off • Median ~7.5mg/l at BENL0502 increasing to ~8mg/l at BENL0504 and then decreases to ~7.5mg/l at BENL0505 • Variation along the channel of +/- 0.5mg/l • Median at BENL0502 slightly higher <0.2mg/l with -ΔTºC on than off • Median at BENL0504 0.5mg/l lower with -ΔTºC on than off • Median at BENL0505 ~0.5mg/l higher with -ΔTºC on than off

TOC Refer: Figure 7.62 Figure 7.63	mg/l	• Median ~8mg/l at BENL0502, increases to ~9.5mg/l at BENL0504 and then slightly decreases to ~8mg/l at BENL0505 • Median variation along the channel of +/- 1.5mg/l • With -ΔTºC	There did not appear to be a strong trend along the waterway when comparing TOC for cold water discharge off • Median ~7.8mg/l at BENL0502 increasing to ~8mg/l at BENL0504 and then very slightly decreases BENL0505 • Variation along the channel of +/- <0.5mg/l • Median at BENL0502 slightly lower <0.5mg/l with -ΔTºC on than off • Median at BENL0504 1.5mg/l lower with -ΔTºC on than off • Median at BENL0505 ~0.1mg/l higher with -ΔTºC on than off

3.5.3.2.4 OPTICAL PROPERTIES

Optical properties describe the particles suspended or matter that is in the water column, typically an increase is caused by direct point sources, such as sediment laden run-off during storm events. Increase in matter suspended in the water column reduces light into water profile, this can effect species composition and abundance and can cause, by varying degrees, "smothering". (ANZECC, 2000, pp. 3.3 - 5)

For Dutch waterways, with the purpose of being used for drinking water, SS should be <50mg/l (Overheid, 2016). Measured SS concentration did not exceed 40mg/l and the lowest is 4mgl/l. During cold water discharge, median SS concentration is 4mg/l, approximately and 6mg/l without cold water discharge. During no cold water discharge, there was a much higher variation around the median concentration than during cold water discharge. SS concentration along the channel was considered GEP and during cold water discharge was very low. SS was typically <20mg/l, except for a very high peak between early 2015.

Turbidity, a non-toxic water quality indicator, is generally in the range 6-50 NTU for lowland rivers (0.5 – 10 NTU for estuarine and marine waters) (ANZECC, 2000, pp. 3.3 - 11). Turbidity did not exceed 9 NTU, which indicated decent quality for freshwater systems and was also even lower during field campaigns, 4 NTU. Measured median turbidity, without cold water discharge, varied along the waterway and it typically 4-5 NTU for laboratory data and 2-3 during field campaigns. During cold water discharge, the median turbidity declines from BENL0502 to BENL0505, this could indicate that a type of relationship between temperature and turbidity is present. For each measuring point, median turbidity during cold water discharge is lower than when there is no cold water discharge.

SD, or transparency, is an indicator for the amount of light that is available for photosynthesis at varying depths, it is a measure of how clear and transparent the water is, (ANZECC, 2000, pp. 8.2–26). Measured SD ranged from 0.3 to 0.6m, which was cloudy to clearer, generally 0.6-0.8 is typical. Since the channel was typically 1.2m deep, this means that full light penetration of the water column was not observed during laboratory measurements.

The mean, without cold water discharge, varied along the waterway and it typically measured 0.4m. During cold water discharge, the median declined from 0.55m at BENL0502 to 0.4m at BENL0504 and then increased at to 0.45 at BENL0505. For each measuring point, median during cold water discharge was higher than when there was no cold water discharge, which means generally there was greater light penetration during cold water discharge.

Table 3.16 Summary water quality observations – optical properties

Abbre-viation	Unit	Without -ΔTºC	With -ΔTºC
SS Refer: Figure 7.64 Figure 7.65	mg/l	• Minimum detectable concentration was 4mg/l, except in 2012 • Without -ΔTºC • Higher for all observation points, except 2012	• Often 4 at all observation points • Measurements were likely below the detectable limit during -ΔTºC

Turb
 	
Refer:
Figure 7.66
Figure 7.67
	FTU	• Limited observations, 2012 and 2013
		• Higher closer to discharge point during -ΔTºC
		• Overall very low values
		• Without -ΔTºC
		  • 2012 consistent decrease from ~6.5 at BENL0502 to 3.5 at BENL0505
		  • 2013 less variation along channel ~3.5
			• 2013 ~4 at BENL0502 and 0503 reducing to ~2 at BENL0504 and 0505

SD Refer: Figure 7.68 Figure 7.69	m	• Most observations in 2015 and 2016, few in 2012 and 2013 • Ranged from 0.2 to 0.6m, which was very cloudy (low) to clearer • Measuring equipment used had varying maximums from 0.3 to 0.6m, which makes it difficult to understand how the observations varied • Channel was typically 1.2m deep, this means that full light penetration of the water column was not observed	• Median ~0.075 at BENL0502 and BENL0503, reduces to ~0.05 at BENL0504 and then increases to ~0.06 at BENL0505

3.5.3.2.5 NUTRIENTS

The following section presents results from nutrients parameters, N and P. N and P are vital for plant growth and indicate the eutrophication level in a waterway and subsequent susceptibility to undesirable plant growth, such as flab, since plant growth is stimulated by excess in N and P. TP concentration is typically ≤ 0.15 mg/l in M1A waterways (STOWA, 2012, p. 144). For fresh waterways, lowland rivers, lakes and estuaries, TP in the range 5-50µg/l (0.005-0.05mg/l) was considered suitable for freshwater systems (ANZECC, 2000, pp. 3.3–10). Generally the TP concentration was less than 0.1mg/l, which demonstrated there was relatively high TP in the waterway.

For waterways similar to M1A, TN concentration is typically ≤ 3.2 mg/l, (STOWA, 2012, p. 144). For fresh waterways, lowland rivers and lakes, TP in the range 0.1-0.5mg/l was considered suitable for freshwater systems (ANZECC, 2000, pp. 3.3–10). There was high TN measured in the waterway.

Table 3.17 Summary water quality observations – nutrients

Abbre-viation	Unit	Without -ΔTºC	With -ΔTºC

TP
 	
Refer:
Figure 7.70
Figure 7.71
	mg/l	Highest concentrations (>0.2mg/l) occurred during winter and spring, highest peak occurring in January 2016
		• Without -ΔTºC
		  ◦ Median ~0.075 at BENL0502 and BENL0503, reduces to ~0.05 at BENL0504 and then increases to ~0.10 at BENL0505
		  ◦ Minimum ~0.025, maximum ~0.2
			• Median ~0.075 at BENL0502 and BENL0503, reduced to ~0.05 at BENL0504 and then increases to ~0.06 at BENL0505
			• This may have indicated there was a trend between cold water discharge and TP, although, when the variation around the median (+/- 25%) was taken into consideration, there did not appear to be a strong trend present

PO_4
 	
Refer:
Figure 7.72
Figure 7.73
	mg/l	Concentration ranged from 0.05 up to 0.005mg/l
		• Without -ΔTºC
		  ◦ Median ~0.01 at BENL0502, increases slightly to ~0.02 at BENL0503 and BENL0504 and then slightly reduced to ~0.015 at BENL0505
		  ◦ Minimum ~0.025, maximum ~0.2
		  ◦ Much more variation +/-25 from the median
			• Median ~0.02 at BENL0502 and BENL0503, reduces to ~0.01 at BENL0504 and then increases slightly to ~0.015 at BENL0505
			• Less variation +/-25 from the median

TN
 	
Refer:
Figure 7.74
Figure 7.75
	mg/l	Concentration typically ranged from 0.5 up to 1.5mg/l, high TN in the waterway
		Highest concentrations (>2.5mg/l) occurred during winter January 2015 and 2016
		• Without -ΔTºC
		  ◦ Median ~1.1 at BENL0502 and BENL0503, reduces slightly to ~1 at BENL0504 and BENL0504
		  ◦ Minimum ~0.5, maximum ~2.2
		  ◦ Much more variation +/-25 from the median
			• Median ~0.8 at BENL0502 and BENL0503, increases slightly to ~0.9 at BENL0504 and BENL0505
			• Minimum ~0.5, maximum ~1.4
			• Less variation +/-25 from the median

NH_4^+
 	
Refer:
Figure 7.76
Figure 7.77
	mg/L	• Overall, ammonium concentration quite low along the channel
		• Easily consumed by algae and macrophytes as a nitrogen source and not readily absorbed by sediment particles (Scheffer, 1998, p. 62)
		• Influenced by flow
		  ◦ Major peaks occurred between November to May, possibly due to flushing of the waterway
		• For all of the measuring points the median concentration relatively low
		• Without -ΔTºC
		  ◦ Median ~0.1 along the channel
			• Median slightly lower
			• Minimum ~0.05, maximum ~0.2
			• Less variation +/-25 from the median

		• Minimum ~0.05, maximum ~0.6, excluding outliers • More variation +/-25 from the median	
N-TKN Refer: Figure 7.78 Figure 7.79	mg/l	• TKN is the ammonia and nitrogen together with organically bound nitrogen and excludes nitrate-nitrogen and nitrite-nitrogen • Without -ΔTºC • Median ~0.9 at BENL0502 and BENL0503, reduces to ~0.8 at BENL0504 and BENL0505	• During cold water discharge, median TKN concentration did not appear to have a strong trend along the channel • Median consistently slightly lower at all points, by ~0.2

NO_3^-
 	
Refer:
Figure 7.80
Figure 7.81
	mg/l	• Not readily absorbed by sediment particles (Scheffer, 1998, p. 62)
		• Influenced by flow
		• For all of the measuring points the concentration was relatively low
		• Without -ΔTºC
		  • Median ~0.05 along the channel
		  • Minimum ~0.01, maximum ~0.5, excluding outliers
		  • More variation +/-25 from the median
			• Median slightly lower for all points
			• Minimum ~0.05, maximum ~0.1
			• Less variation +/-25 from the median

NO_2^- Refer: Figure 7.82 Figure 7.83	mg/l	• Concentration did not exceed 0.14mg/l • For fresh waterways with a recreational purpose, recommended concentration <1000µg/l (1mg/l) and for protection of aquaculture species <100 µg/l (0.1gm/l) is recommended (ANZECC, 2000, pp. 4.4–8 and 5-9) • On occasion the result is presented as "<0.01mg/l", this indicated the measuring equipment could not analyse lower concentrations ○ Laboratory advises that there were differences with the guidelines found that may have affected the reliability of the results of the sample or analysis • Therefore, it was not possible to draw a conclusion whether or not nitrite concentrations experience a trend during cold water discharge	

Two dominant sources of elevated ammonium in surface waterways similar to Hoog Dalem are decomposing organic material and fertiliser from adjacent farmlands discharged via storm water run-off into the waterways. Ammonium is easily consumed by algae and macrophytes as a nitrogen source and is not readily absorbed by sediment particles (Scheffer, 1998, p. 62). Since minimal ammonium is bound to sediment particles, this means that there is typically a higher retention of ammonium in a system where there is a higher retention time particles (Scheffer, 1998, p. 62). Therefore, it is important to consider the combined effect of cold water, thermal change and increased flow in the system during cold water discharge. The smaller range during cold water discharge was likely associated with other factors, such as flow generation during cold water discharge or seasonality factors.

Elevated measured ammonium at Hoog Dalem could be due to the adjacent farmlands near the channel or decomposing organic material, especially during autumn. The highest peak occurred in January, well into the cooler months and concentrations higher than 0.5mg/l occurred in September, October and November (autumn) and in March (spring). The peak in January showed similar ammonium concentrations along the whole channel (1.1-1.5mg/l), combined with the knowledge that minimal plant growth occurs during winter in The Netherlands, it could be that this peak is due to a higher rainfall event rather than decomposing plant material. The cause of elevated ammonium during the shoulder seasons would need further analysis of climatic conditions and ecological information, which is only available at Hoog Dalem during May, June, July and August.

3.5.3.2.6 BIOMASS

The following section discusses results from biomass parameters, which indicate the algae in the waterway.

Table 3.18 Summary water quality observations – biomass

Abbre-viation	Unit	Without -ΔTºC	With -ΔTºC
Chl-*a* Refer: Figure 7.84Figure 7.85	ug/l	• Median ~10 along the channel • Minimum 3 (the minimum detectable), maximum ~60, excluding outliers • More variation +/-25 from the median	• Median slightly lower for all points, except BENL0505 is same • Minimum ~0.05, maximum ~0.1 • Less variation +/-25 from the median

Pheo-*a*
 	
Refer: Figure 7.86 Figure 7.87
	ug/l	• Degradation product of chl-a, used to correct for the estimation of chl-a
		• Minimal pheo-a closest to outlet
		• During
		• Without -ΔTºC
		  • Median ~10 along the channel
		  • Minimum 3 (minimum detectable), maximum ~60, excluding outliers
		  • More variation +/-25 from the median
			• Median slightly lower for all points, except BENL0505 is same
			• Minimum ~0.05, maximum ~0.1
			• Less variation +/-25 from the median

3.5.3.2.7 SALINITY

At BENL0502 the median Cl during cold water discharge was in the order of 10 units less than when there was no cold water discharge, while the trend of lower Cl level during cold water discharge was not similar for the next observation point (BENL0503). Along the channel during cold water discharge, a clear trend was not observed, however there was also minimal variation in median along the channel during cold water discharge.

Cl highest peaks occurred during May and the lowest concentrations occurring between May – November. A source of Cl could be the use of salt on roadways during winter. However, most of the winters where observations were undertaken were during mild winters where there was not significant icing of roads. During the highest peak concentration, 1 May 2013, the air temperature ranged from 1.1°C up to 17.8°C, with a median of 10.2°C, measured at Herwijnen station (KNMI).

Table 3.19 Summary water quality observations – salinity

Abbre-viation	Unit	Without -ΔT°C	With -ΔT°C
EC Refer: Figure 7.88 Figure 7.89	mS/m	• Does not exceed 110mS/m	• 100mS/m was not exceeded • EC during cold water discharge was consistently lower than when there was no cold water discharge • The median EC concentration at BENL0505 is higher then no -ΔT°C
Cl Refer: Figure 7.90 Figure 7.91	mg/l	• Median ~80mg/l at BENL0502, reduces to ~65mg/l at BENL0504 and then increases to ~70mg/l at BENL0505 • Variation along the channel of +/- 20mg/l	• Median ~70-75mg/l at BENL0502 to BENL0505 • Variation along the channel of +/- 5mg/l • BENL0502 median is ~10mg/l lower than without -ΔT°C • BENL0505 median is slightly higher than without -ΔT°C

3.5.3.2.8 ACIDITY

For waterways similar to M1A, pH is typically 5.5-8.5 (STOWA, 2012, p. 147). Measured acidity in the waterway ranges between 7.2- 9 and for field data 7.2-8.4.

Table 3.20 Summary water quality observations – acidity

Abbre-viation	Unit	Without -ΔT°C	With -ΔT°C
pH Refer: Figure 7.92 Figure 7.93	-	• Median ~7.6 at BENL0502 increasing to ~7.8mg/l at BENL0504 and then slightly decreases to BENL0505 • Median variation along the channel of +/- <0.2 • BENL0502 experienced most variation around July in 2012, 7.5-8	• Median ~7.6 at BENL0502 and BENL0503 increasing to ~7.7 at BENL0504 and BENL0505 • Variation along the channel of +/- <0.1 • Median at BENL0502 same with -ΔT°C on than off • Median at BENL0503, BENL0504, BENL0505 lower with -ΔT°C on than off • BENL0502 ○ 2013 experienced minimal variation, almost consistent • Decreased during -ΔT°C, except one outlier in 2015
CO_3	mmol/l	• Two different minimal detectable limits: ○ 0.10 in 2012 and 2013 ○ 0.065 in 2015 and 2016 • Observations for each year did not exceed respective minimal detectable limits	

HCO_3^-
 	
Refer:
Figure 7.94
Figure 7.95
	mmol/l	• Period around July 2012 experienced minimal variation. Similar period in 2014, 2015 and 2016 experienced significantly reduction when -ΔT°C on and then increased when -ΔT°C was turned off
		• Without -ΔT°C
		  • Median ~5 at BENL0502 to BENL0504 and then decreases to ~4 at BENL0505
		  • Median variation along the channel of +/- ~1
		  • Minimum ~3, maximum ~7.8, excluding outliers
			• Median ~3.2 at BENL0502, increasing to ~4 at BENL0503 and BENL0504 and reducing to ~3.8 BENL0505
			• Variation along the channel of +/- <1
			• Minimum ~3, maximum ~5.5, excluding outliers
			• Median consistently lower at all points for -ΔT°C on
			• Median increases from outlet to BENL0503

3.5.3.2.9 IRON AND BROMIDE

For Dutch waterways, with the purpose of being used for drinking water, iron of <0.3mg/l (300μg/l) is considered acceptable (Overheid, 2016). Iron in the waterway exceeded 300μg/l, while the iron concentration was quite high, iron is not toxic.

Table 3.21 Summary water quality observations – bromide

Abbre-viation	Unit	Without -ΔT°C	With -ΔT°C

Fe
 	
Refer:
Figure 7.96
Figure 7.97
	ug/l	• Seasonal variation observed, reduction towards July and increases from July
		• Without -ΔT°C
		  • Median ~550 at BENL0502, slightly reducing towards ~400 at BENL0504 and then increases at BENL0505 to ~500
		  • Minimal median variation along the channel
		  • Minimum ~300, maximum ~1700, excluding outliers
			• Median ~500 at BENL0502, decreases to ~350 at BENL0504 and BENL0505
			• Minimal median variation along the channel
			• Minimum ~300, maximum ~1000, excluding outliers
			• Median consistently lower or equal at all points for -ΔT°C on

Br	mg/l	• Minimal detectable: 0.20 in 2013, 2015 and 2016 • In 2012 minimum observations was 0.6 and maximum was 0.22. For 2013, 2015 and 2016 0.2 was reported • Due to minimum detectable limits, no graphs are provided	

3.5.3.3 COMBINED EFFECTS

The following section presents combined time series graphs that provide an overview for each year and each measuring point:

1. Operational cold water discharge (Eneco data)
2. In-stream water temperature observations
3. Water quality (laboratory data):

- Oxygen saturation
- Chl-*a* concentration
- Duckweed cover

3.5.4 OVERVIEW OF STATUS BASED ON STOWA INDICATORS

To gain insight to the general status of the waterway with and without cold water discharge, the water quality observations and ecology survey results have been compared to the STOWA metrics and are presented in this section.

3.5.4.1 WATER QUALITY

The next table summarised the channels water quality observations with and without cold water discharge. Overall, the channel meets GEP status, most of the time, based on water quality measurements. The optical property, SD, was the indicator where the channel did not meet GEP status, there were minimal SD observations for 2012 to conclude if the cold water discharge regime has negatively impacted SD.

Table 3.22 Compare results to STOWA M1A water quality metrics

Category	Abbre-viation	Unit	M1A"typical[14]"	M1A GEP[15]	OFF -ΔT°C	ON -ΔT°C
Physical	T	°C		**≤25**	Does not meet GEP	Benefits by cooling
Acidity	pH	-	5.5 to 8.5	**5.5 to 8.5**	GEP most of the time	GEP, lower during -ΔT°C
Optical properties	SD	M	≤1.4 (10%)	**≥0.65**	Does not meet GEP	Does not meet GEP, benefits system towards GEP
Dissolved oxygen and organic matter	O%	%	35-120%	**35-120**	Majority of the time meets GEP for all points	Benefits towards GEP, majority of the time meets GEP
Nutrient	TP	mg/l	≤0.10 (10%) ≤2.4 (50%)	**≤ 0.22**	Nearly always GEP	GEP, 1 outlier
	TN	mg/l	≤0.22	**<2.4**	Nearly always GEP, few outliers	Always GEP
Anions	Cl	mg/l	≤150	**≤150**	Nearly always GEP	Nearly always GEP

[14] (STOWA, 2012, pp. 147-148).
[15] (STOWA, 2012, p. 29).

3.5.4.2 ECOLOGY

3.5.4.2.1 MACROPHYTES

The changes in water plant composition during 2012, 2013, and 2015 and along the channel for each measuring point based on STOWA metric are presented in this section. It was estimated if a species should be categorised as floating or submerged, overall the ecological information was to be used as indicative, especially for the WSRL data which was interpreted from the Tansley scale. To understand if the macrophytes observed at Hoog Dalem are indicators of "good" or "bad" ecological health.

Table 3.23 STOWA macrophyte metrics

Category	% cover (GEP/M1A)	Summary of observations
Submerged	30-90	Majority of observations were close to GEP
Floating	30-90	Majority of observations did not meet GEP
Emergent	5-25	Does not meet GEP
Flab	<15	Majority of observations cover is not too high, meets with GEP. For this undesirable category, it should be noted that draadwier (the source of flab) was observed at much higher percentage cover for many observations. Therefore, it is considered not to meet with GEP.

3.5.4.2.1.1 SUBMERGED

For submerged water plants, an example shown in Figure 3.27, cover in the range of 30-90% indicates GEP. For the majority of the observations submerged vegetation presence was in excess of 30%. This indicates that, for the majority of the observations, the waterway is close to GEP in terms of submerged vegetation.

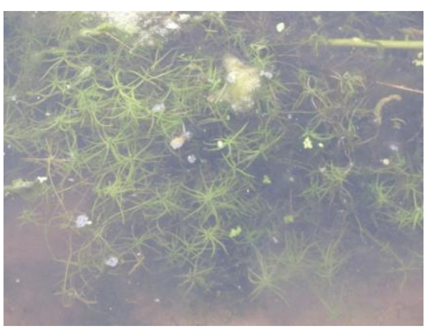


Figure 3.27 Closer view of water plants, north of BNL0504, likely *Callitriche platycarpa* (based on advice from Gerben van Geest, 23/08/2016)

3.5.4.2.1.2 FLOATING

Cover in the range of 30-90% indicates GEP for floating plants. As illustrated in Figure 3.28, most of the floating aquatic plant coverage is algae and flab, the floating plants discussed in this section are for macrophytes only. Floating vegetation cover was less than 30% for the majority of the observations. On one occasion floating vegetation exceeded 30%, at BENL0505, the remainder of the observations did not exceed 5%. This indicated that, for the majority of the observations, the waterway does not meet GEP in terms of floating vegetation, similar as for emerged applies to floating leaved vegetation, because they are also more 'late successional' species) (van Geest, 2017).

Figure 3.28 BNL0505 measuring point, high coverage of algae on water surface and emerged macrophytes near the banks

3.5.4.2.1.3 EMERGED

For emerged water plants, Figure 3.28, a percentage cover in the range of 5-25% indicates GEP. For the majority of the observations, emergent vegetation presence was less than 5%. On three occasions emergent vegetation exceeded 5% and on one occasion exceeded 25% cover (50% at BENL0503). This indicated that the waterway does not meet GEP in terms of emergent vegetation, which could be due to the young age of the waterway (emergent species are somewhat more 'late successional' species) (van Geest, 2017).

3.5.4.2.1.4 FLAB

Flab, see Figure 3.29, is a nuisance, pioneer species, typically higher abundance in new waterways, quantity theoretically declines as waterway biota matures. For flab, a percentage cover less than 15% indicates GEP. For the majority of the observations, flab presence was less than 15%. On five occasions flab exceeded 15%, once for each measuring point, except at BENL0505. This indicated that, for the majority of the observations, the flab cover presence is not too high, which indicates higher quality ecology status. However, for this undesirable category, it should be noted that draadwier was observed at much higher percentage cover for many observations; the STOWA guidelines do not outline metrics for draadwier since flab is considered representative of draadwier.

Figure 3.29 Closer view of algae / flab floating on channel surface between BENL0505 and intake

Since flab is a pioneering species, its presence would be expected to decrease with time since the new construction of the waterway. However, the observations do not appear to have a strong trend throughout the year for the observation points along the waterway.

3.5.4.2.2 MACROFAUNA

Based on the macrofauna surveys, the study site does not meet with GEP, <50.

3.6 DISCUSSION

What does the case study data available indicate?

This section discusses the results presented in Section 3.5 for the case study site. A summary of the observations based on the case study data were compared to the theoretical expectations that were outlined in Chapter 2, refer to Figure 3.30.

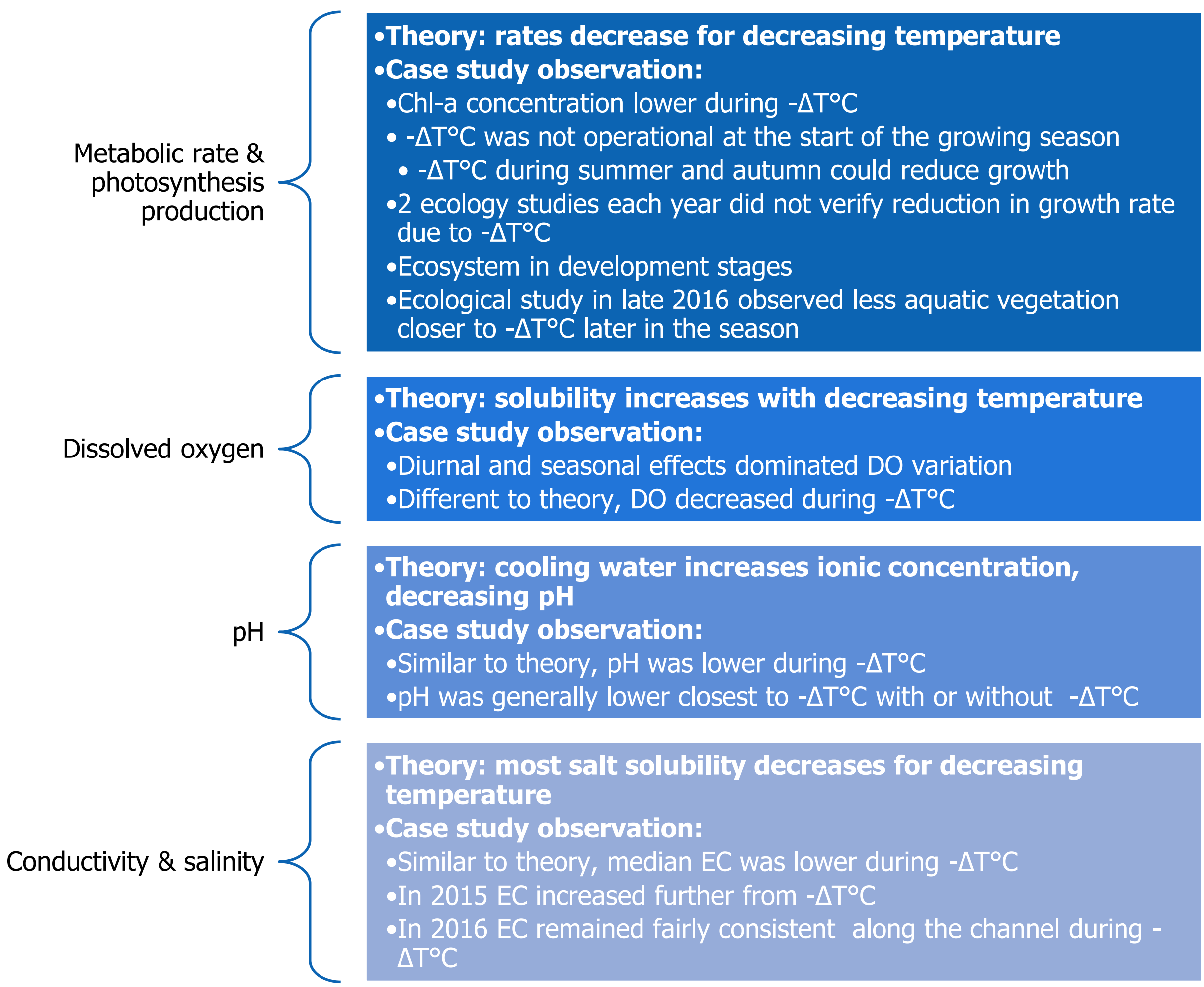


Figure 3.30 Case study data observations compared to theoretical expected effects

3.6.1 WATERWAY STATUS EFFECTS

Does cold water discharge prevent the waterway from achieving good ecological potential?

STOWA water quality and ecological indicators were compared to the GEP metrics for M1A type waterway.

Ecological indicator metrics for macrophytes were found not to meet with GEP for the majority of observations. Further, flab observations were considered to meet with GEP, the great abundance of draadwier (source of flab) means that the status based on flab / draadwier would not meet with GEP. Since the majority of macrophyte observations did not meet with GEP, a separation between cold water discharge on or off was not considered necessary. Further, it was not possible to draw a conclusion based on the macrofauna studies.

Based on the water quality results, cold water discharge was not found to prevent the waterway from achieving GEP. For the majority of water quality observations it was found that water quality generally met with GEP. From comparing the waterway status with and without cold water discharge it was found that cold water discharge could benefit this waterways water quality. This benefit could be associated with the flow, additional flow in a mostly stagnant water body is likely to benefit the system. Another potential benefit could be mitigating the impacts from extremely hot days (>25°C), which often leads to issues with algal out breaks and subsequent reduced water quality, as discussed in Chapter 2.

For all of the measuring points, median oxygen saturation was approximately 90-120%. Oxygen saturation met with GEP most of the time, 60-120%. For an M1A waterway, oxygen saturation GEP ranges from 35 to 120%, 60-120% for MEP and <25 or >145% is considered extremely poor (STOWA, 2012, p. 29). Oxygen saturation less than 60% occurred, which indicated less than good conditions for biota. Based on laboratory data, pH ranged from 7.2 to 9 and field campaigns from 7.2 to 8.4, generally within GEP, 5.5-8.5 (STOWA, 2012, p. 147).

The water quality observations generally meet with GEP for a M1A waterway and the ecological observations did not meet with GEP. Given the waterway was newly constructed a cause of the ecological indicators not meeting with GEP could be that the ecosystem has not fully developed. This concept is supported by 2016 water plant observations that show a higher diversity in species present than in previous years observations.

3.6.2 TEMPERATURE EFFECTS

Channel temperature distribution

The median monthly air temperature was assessed to observe how the summer months, during cool water discharge compare with the historic average summer temperatures. Based Figure 7.2 in Appendix III, most of the cold water discharge summer months are located near or above historic median monthly temperature, refer to Appendix III for further discussion on air temperature. Therefore the observation years are considered reasonable, in terms of drawing conclusions, since they are not “extreme warm” or “extreme cold” summers, which could influence the observations.

Cold water discharge was observed during warmer times of the year, in agreement with cold water discharge only operating when the water temperature exceeds 15°C. It was found that June, July and August were the months that experienced the most cold water discharge, end of Spring (up to 21 June) to Summer. The magnitude of cold water discharge was typically 5°C. Given the timing and magnitude of the cold water discharge it is likely to influence the water temperature in terms of a summer suppression and potential amplitude reduction in the water closest to the discharge point. However, it should be taken into consideration that the temperature recovery distance is relatively short. Therefore, it is unlikely that the whole of the channel is significantly influenced by the cold water discharge.

If the cold water discharge was to commence early in the biological spring, there could be issues with seasonal displacement, inhibiting biological growth. Potential effects could include delaying spring, when the water temperature lowers below the required temperature for growth. In theory this could negatively impact species that have limited, very specific temperature envelopes for growth.

Based on the 2015 and 2016 measured water temperature, a positive effect of cold water discharge was observed during very warm days, especially in 2015 when water temperature exceeded 25°C. The water temperature remained below 25°C at BENL0502 and BENL0503 (except for early July).

In 2013, cold water discharge did not achieve the desired ΔT°C of 5°C. 2015 showed more consistent cold water discharge and ΔT°C than in 2013. In 2016 the flow and ΔT°C was the most year and the amount of energy produced was similar to 2013. During 2016 it appeared from the data that the system operated differently from 2013 and 2015, that at times the flow was likely reversed in the system, possibly to avoid clogging, approximately occurring every 2 hours, with flow decreasing before and after each “reversal”. The data around the flow reversals was omitted from the results presented, which means that the amount of energy produced in 2016 may not be truly representative.

2015 in-stream temperature measurements were the most complete for observing cold water effects. The 2015 measured water temperature showed that cold water discharge effects were present at 60cm and 100cm depth. The temperature at 100cm depth was generally slightly lower than at 60cm and experienced less fluctuation (diurnal effect) than at 60cm depth.

The measurement equipment at point 3 was destroyed in 2016 and therefore in-stream temperature observations are not available for this point. The measured water temperature during 2016, specifically observed in the 50cm depth profile, show that the system was more consistently discharging cold water throughout the year than in 2016. Combining the intake water temperature, discharge temperature and measured water temperature for points BENL0502 and BENL0505 (Appendix VI Figure 7.43 to Figure 7.48), water temperature has mostly “recovered” by BENL0504.

Based on the water temperature box plot (Appendix VI Figure 7.50), the median does not significantly vary across the four measuring points when there is no cold water discharge. During cold water discharge median water temperature increases along the channel by 3°C, approximately. This increase in median temperature along the channel, during cold water discharge, shows that the measurements for water temperature reflect the water temperature increasing along the channel, in agreement with the in-stream temperature measurements.

Based on the median, water temperature difference along the channel is minimal when there is no cold water discharge. Water temperature fluctuations were strongly seasonal, cooler temperature during winter and warmer temperatures during summer. In general, warmer temperatures were recorded in 2012 and 2013 than in 2015.

3.6.3 EFFECTS ON ECOLOGY

Is there a strong relationship between ecological studies and -ΔTºC?

A strong relationship between macrophyte observations and cold water discharges were not observed. Most macrophytes commence growing when water temperatures exceed between 0-8°C, biological spring. Cold water discharge was not in operation at the start of the macrophyte growth season, therefore the macrophytes present when cold water discharge commenced in 2013, 2015 and 2016 were not affected until the cold water discharge commenced.

Due to macrophyte temperature growth dependence, as discussed in Chapter 2, the lowered water temperatures from late spring into summer means that it is expected that the same macrophyte species closer to cold water discharge would have reduced growth throughout summer compared to a location further from cold water discharge. However, this was not clearly observed in the ecology observations.

Another reason why a strong relationship was not observed could be due to the system being relatively new and the species abundance and composition was not fully formed prior to commencing cold water discharge. It could also be due to there being only two ecological surveys each year.

Algae and flab / draadwier, see Figure 3.29, are more likely to be effected by the modified water temperatures throughout summer than the macrophytes since they have a greater response to temperature. Reducing the "extreme" summer water temperatures may benefit the system by mitigating unsustainable growth of algae/flab. However, this was not directly observed in the data and to confirm this would require observations before, during and after "extreme" warm periods, while cold water discharge was operation.

3.6.3.1 AQUATIC PLANTS

The section of waterway near the road (sampling point BENL0505) was constructed one year earlier than the other parts of the water way. This has a significant impact on the colonization and hence species composition of macrophytes in 2012, (Boderie & van Geest, 2014). 28-May-2012 is the first observation where vegetation was recorded, a year where there was no cold water discharge. During this observation, there was minimal vegetation observed along the reach, prior to point BENL0505. The dominant vegetation at BENL0505 was Draadwier*, Elodea nuttallii*, *Chari* and Flab. While some *Callitriche platycarpa* was observed, overall minimal desirable species were observed.

Ecology observations on 11-July-2012 showed similar coverage at BENL0505, with more vegetation present at BENL0503, than in the 28-May-2012 observations. The dominant species at BENL0505 were Draadwier and *Chara*. At BENL0502 the dominant plants present were Flab and *Potamogeton pusillus*. During 2012, the Chl-a concentrations at BENL0502 and BENL0503 were almost double that of BENL0504 and BENL0505.

During 2013, cold water commenced 7 June. Observations taken on 3-June-2013 showed a higher amount of vegetation present along the whole reach, predominantly Draadwier, with a relatively high amount of *Callitriche platycarpa* and some *Elodea nuttallii* present at BENL0503. On the day of this observation, there was no cold water discharge and the TP, TN and chl-a concentrations were highest at BENL0502, at least double than at the successive monitoring points.

Observations on 15-July-2013 showed a greater species diversity than had been observed on prior occasions. The Draadwier and *Elodea nuttallii* were once again dominant. At BENL0503 *Alisma lanceolatum* was present. Along BENL0502-0504 the abundance of *Potamageton pusillus* increased from previous recordings. During this observation, cold water discharge was operating with a typical temperature difference of 3°C, with a flow of 175m^3/hr. The chl-a concentrations were very low and the concentrations for TN and TP were similar for all measuring points.

During 2015, cold water discharge commenced April-24 to May-18 and then from June-18 to August-14. The ecology observation on 27-May-2015 there was once again a high abundance of Draadwier and a relatively high amount of *Elodea nuttallii* observed at BENL0505. Along the reach, the coverage of Draadwier was very similar. During this observation, there was no cold water discharge, cold water discharge was recorded almost every day from 1st to 18th of May (average dT°C 5, 107.5m^3/hr). Water quality observations undertaken on 20 May showed low Chl-a (5µg/l), TN and TP were similar along the reach, except for BENL0503 which had concentrations almost double the other measuring points. In addition, the SS were almost four times higher than the other three measuring points.

The 7-July-2015 observations showed a high abundance of *Elodea nuttallii* and *Draadwier*, almost consistent along the whole channel. At BENL0505 a high amount of *Wolffia arrhiza* was present for the first time. During this observation, there was no cold water discharge, cold water discharge was recorded almost every day of July and on 7 July there was an average dT°C 5, flow 124m^3/hr. Water quality observations undertaken on 9 July showed higher Chl-a (10µg/l), slightly higher at BENL0505, TN and TP concentrations were similar along the reach. Flow ranged from 13cm/s at BENL0505 and BENL0504 and up to 26.5cm/s at BENL0502.

There were two observations conducted by Riverland Waterboard. The first observation, 8-August-2013 recorded higher coverage of water plants along the whole of the reach. Similar to Bureau Waardenburg observations, *Elodea nuttalli*i was dominant along the reach. Differing from Bureau Waardenburg observations, Draadwier*Vaucheria* and *Utricularia* vulgaris were recorded at relatively high percentage cover at BENL0504, with some *Vaucheria* at BENL0502 and BENL0503. Cold water discharge was operating on and for at least a week before 8 August, dT 2.6°C and 160m^3/hr. Water quality observations were undertaken on 6 August 2015, TN and TP concentrations were similar for all measuring points and chl-a, typically 5µ/l, was slightly higher at BENL0505 (8µg/l).

During 2016, cold water discharge commenced May-16 to July-13 and then July-22 to August-21. The macrophyte observations conducted on 26-May-2016 show that a range of species were present contributing to the cover, differing from previous years observations where typically one to two plants dominated. The 13-July-2016 observations showed a higher abundance of *Elodea nuttallii*, almost consistent along the whole channel. The observations in 2016 show a higher diversity in species which is likely associated with the timing of construction of the channel.

3.6.3.2 MACROFAUNA

In 2013 the quick scan for macrofauna was undertaken, which showed that measuring point BENL0502 and BENL0503 received a lower score for the ecological quality (resp. 30 and 33) than sample points 3 and 4 (both 46). Therefore sampling point BENL0502 and BENL0503 were classified as 'inadequate' based on the EWFD, and sample point BENL0504 and BENL0505 as 'moderate'. Oxygen content at 70 cm depth for Location BENL0502 and BENL0503 was lower than at BENL0504 and BENL0505. Possibly poorer oxygen levels are responsible for the reduced ecological quality of BENL0502 and BENL0503. Other factors may also play a role, such as the high coverage of floating algal beds or small temperature differences over the vertical water column when the cold discharge is operating. Other factors unrelated to the cold discharge may also be important, such as differences in timing of construction or the width of the locks. (Boderie & van Geest, 2014)

The quick scan for July 2015 showed that all measuring points had a score lower than 40, from measuring point BENL0502; 38, 32, 24 and 25 at BENL0505, Figure 7.14 and Figure 7.15 present results from the quick scan. In contrast to the 2013 results, BENL0504 and BENL0505 macrofauna score was much lower than BENL0503 and BENL0502. BENL0502 had the highest score, closer to moderate stage than in 2013. This could indicate an improvement in conditions at BENL0502 since 2013, especially since macrofauna are a key indicator used by the STOWA guidelines for canals and ditches, (STOWA, 2012-34).

Based on the two macrofauna quick scans, a relationship between cold water discharge and macrofauna cannot be made.

3.6.4 EFFECTS ON WATER QUALITY

> *Is there a strong relationship between measured water quality properties and -ΔTºC?*

For most parameters there was minimal difference measured that could be directly accounted by cold water discharge, summarised in the tables from Table 3.13 to Table 3.21. This is due to a number of factors, seasonality is a dominant factor for consideration. Since the site was constructed just before observations commenced and a full year of observations for 2012, including the transition from winter to spring were not available, it was not possible to clearly define if the cold water discharge had a significant effect.

The water temperature during cold water discharge was higher than when there was no cold water discharge. Median water temperature when cold water was being discharged is in agreement with cold water only being discharged when water temperature is warm enough. Warmer median water temperature during cold water discharge could median that other water quality parameters could be influenced more by a median warmer temperature, rather than the cold water discharge. As discussed in Chapter 2, diurnal and seasonal variations influence water chemistry.

Since there is a visible relationship between the measuring points during cold water discharge, water increasing in temperature along the canal, then when observing water quality parameters, the difference from near cold water discharge point to furthest downstream will be analysed.

3.6.4.1 OXYGEN

Is there a strong relationship between measured oxygen and -ΔTºC?

Organic processes and sources have the greatest influence on DO, such as decomposition of plant material and effluent. DO should be above 5mg/l for good biota conditions, preferable 6mg/l. (ANZECC, 2000, pp. 3.3–25). Due to being influenced by organic process, there is a strongly season and diurnal influence up to +/-10mg/l, observable in the field data presented in Appendix V, Figure 7.43 to Figure 7.48. DO represent the balance between oxygen consuming and oxygen releasing processes and is strongly dependent on the water temperature, salinity, biological activity and transfer rate with the atmosphere (ANZECC, 2000, pp. 3.3–25).

During cold water discharge, DO increased from BENL0502 to BENL0504 and then decreased to BENL0505, Figure 7.28 and Figure 7.29. Increase in DO along the channel during cold water discharge indicates a relationship was present. Further, results of the field campaigns found DO was lower during cold water discharge at point BENL0502 than BENL0505. DO range during cold water discharge was considered conductive to aquatic ecology needs.

Based on bi-monthly yearly data, Figure 7.56 and Figure 7.57, DO concentration did not exceed 19mg/l and the lowest concentration observed is 3mgl/l, approximately, similar to field campaign results. DO lower than 5mg/l occurred at BENL0502 and BENL0505 when there was no cold water discharge. For all of the measuring points, median DO was approximately 9-12mg/l.

DO <5mg/l occurred in spring and summer, during the months June (4.8mg/l at BENL0502), August (4.6mg/l at BENL0502), September (five occurrences) and October (2.9mg/l at BENL0505). September, the first month of autumn, experienced the most frequent low DO along the waterway, which would be associated with decomposition of plant material. Lowest DO was observed in June and August, close to 5mg/l, and occurred at one measuring point only. Most low DO occurred during autumn, which indicated that plant decomposition is a contributing factor. Highest concentrations, nearly 19mg/l, occurred during spring in April.

3.6.4.1.1 OXYGEN SATURATION

Oxygen saturation is associated with DO, 100% saturation in fresh water at 25°C = 8.3 mg/L DO, (ANZECC, 2000, pp. 8.2–12). The trend in oxygen saturation was similar to DO, Figure 7.58 and Figure 7.59. For waterways similar to M1A, oxygen saturation is typically 35-120% (STOWA, 2012, p. 147). Based on the laboratory data, oxygen saturation did not exceed 160% and the lowest observation was approximately 35%. Oxygen concentrations lower than 60% occurred at BENL0502 and BENL0505, when there was no cold water discharge.

3.6.4.2 PH

Is there a strong relationship between measured pH and -ΔTºC?

Median pH during cold water discharge was generally lower than when there was no cold water discharge, Figure 7.92 and Figure 7.93. Median pH at BENL0502 was lower than BENL0505, this shows that there was a trend between pH and temperature, which was anticipated based on pH relationship with oxygen, as discussed in Section 2.1. Overall, a strong trend in pH during cold water discharge did not appear to be present based on Figure 7.92.

3.6.4.3 CHLOROPHYLL-A

Is there a strong relationship between measured chlorophyll-a and -ΔTºC?

The chl-a concentration for each year showed differing times of peak occurrence for each of the measuring points and varying magnitudes in peak where the peaks coincide. Major peaks (>60µg/l) occurred during winter, spring and autumn, February 2013, May 2013, October 2014 and November 2012, with the highest peak (170µg/l) occurring in January. For all of the measuring points, median chl-a concentration was much higher than 2µg/l, and therefore was closer to eutrophic conditions, this is further elaborated on the section on Trophic State Index in Appendix VI.

When there was no cold water discharge, median concentration ranged from 10 up to 15µg/l, for at least 50% of the observations, chl-a concentration was less than 23µg/l. Based on the laboratory data, chl-a in the waterway exceeds 23µg/l, predominantly when there was no cold water discharge (except on a few occasions).

During cold water discharge, median concentration decreased further from BENL0502 and increased after BENL0504, Figure 7.84 and Figure 7.85. This indicates there was a trend measured between cold water discharge and chl-a. Chl-a concentration was very good based on median, ranged from 7µg/l up to 10µg/l (EQR 0.8-1), during cold water discharge. Based on Figure 7.43 to Figure 7.48, a strong trend in chl-a concentration could not be observed.

4 THEORETICAL EFFECTS OF COOL WATER ON AQUATIC ECOSYSTEM

Chapter 4 elaborates on the theoretical effect of cool water on fish and aquatic plants

Fish were chosen to be incorporated into the study since they are an important indicator for assessing the effect of cold water pollution, as addressed in Chapter 2. Further, since the ecological assessment frequency was relatively coarse, twice per year, the theoretical growth limitations for two undesirable aquatic plants was studied to find if cool water effects would encourage or discourage growth, presented in this section.

4.1 FISH

The approach taken, in the hypothetical scenario that all other conditions are suitable for all of the M1A likely fish species, would the modification in thermal regime have a negative effect on fish species? This approach has been taken in order to address the potential effect of cold water discharge on likely fish species, it should be noted that only one fish was observed onsite. Research undertaken for AqMad fishing advises the following key factors for fish success: temperature, light, air exposure, flow, connectivity, depth, surface substrate, acidity, oxygen, ammonia / nitrite / sulphide, macrophytes (Buijse, 2016).

4.1.1 FISH SPECIES LIKELY PRESENT AT CASE STUDY

The type of fish found in similar waterways in The Netherlands is summarised in the next table (STOWA, 2012-34, p. 135). The fish base website was reviewed to find if there had been fish observations near Hoog Dalem or in similar waterways. However, there were only nine observations for all of The Netherlands on the fish base website, most were in the Oosterschelde, which is marine waterway type.

Table 4.1 Fish species found for WFD type M1A[16] (STOWA, 2012-34, p. 135)

Category	Plant-loving and migratory fish	
Plant-loving	**Bitter roach** (Bittervoorn) *Rhodeus sericeus*	**Giebel** (Giebel) *Carassius gibelio*
	Rudd (Ruisvoorn) *Scardinius erythrophthalmus*	**Small loach** (Kleine modderkruiper) *Cobitis taenia taenia Linnaeus*
	Nine-spined stickleback (Tiendoornige stekelbaars) *Pungitius pungitius pungitius Linnaeus*	**Pike** (Snoek) *Esox lucius*
	Smee (Vetje) *Leucaspius delineates*	**Big loach** (Grote modderkruiper) *Misgurnus fossilis*
Plant-loving and oxygen tolerant	**Crucian carp** (Kroeskarper) *Carassius carassius*	**Tench** (Zeelt) *Tinca tinca*
Migrant	**Eel** (Paling (Aal))	**Three-spined stickleback** (Driedoornige stekelbaars) *Gasterosteus aculeatus aculeatus*

[16] Dutch fish names provided in brackets.

The table for fish temperature ranges is provided in Appendix IV for the fish species likely for M1A waterways, excluding eel. For each fish type, a temperature range is indicated for each life stage; egg/larvae, juvenile and adult. The most venerable life stage is egg and larvae, water temperature envelope for this growth stage is presented in the next graph with operational water temperature in 2015, since 2015 is the only year that experienced discharge during biological spring, 1 March to 1 June.

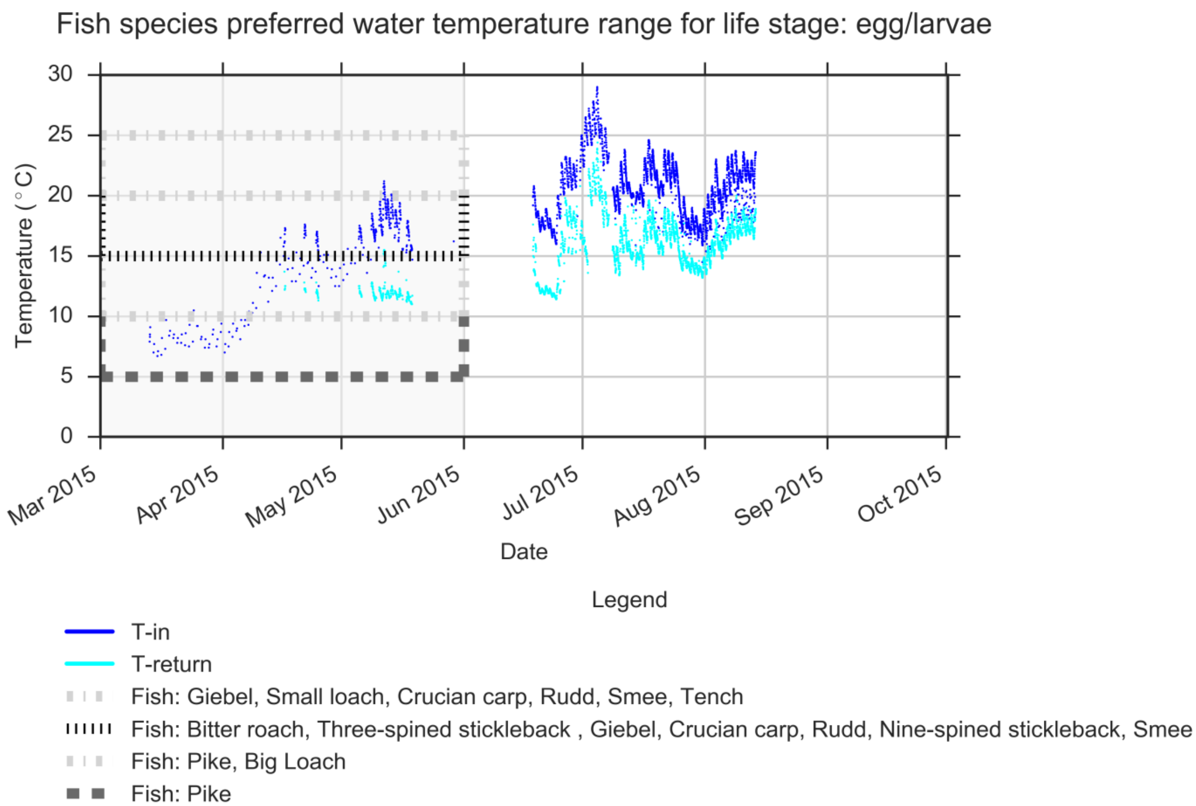


Figure 4.1 Fish egg/larvae [referred water temperature range with potential effect based on 2015

4.1.2 STOWA METRICS FOR FISH

As stated within the STOWA Guidelines, fish fauna is very limited, the most common species are the three-spined stickleback (Gasterosteus aculeatus) and the Nine-spined stickleback is also frequently encountered (STOWA, 2012-34), the table below outlines the fish metrics.

Table 4.2 STOWA M1A fish metrics (STOWA, 2012-34, p. 135)

EQR	Proportion bream + carp (%)	Proportion plant-loving fish (%)	Number of plant-loving and migratory fish
0.0	100	0	2
0.6	**25**	**50**	**5**
1.0	10	80	7

4.1.3 DISCUSSION

Based on the theoretical study for fish species, biological spring is the timing that could potentially effect fish, based on M1A waterway likely fish and temperature tolerances. The reduction in peak summer temperature is most likely to benefit fish. Overall, considering the type of waterway, the temperature recovery distance from cold water discharge and the timing of cold water discharge typically during summer, a significant effect on fish is not anticipated based on this studied thermal modification.

4.1.3.1 RELATIONSHIP BETWEEN FISH AND OXYGEN

For the fish considered, the maximum oxygen tolerance ranged from 8 up to 11mg/l and the minimum oxygen ranged from 7 down to 4.5mg/l, (Buijse, 2016). The oxygen concentrations observed, see Figure 7.56 and Figure 7.57, were typically on the higher range for the fish likely to be present in M1A waterways or exceeded the maximum concentration suitable and it was not found that cold water discharge negatively impacted this.

4.1.3.2 RELATIONSHIP BETWEEN FISH AND ΔTºC

From guidelines discussed in Chapter 2, an approach for determining likely effects on fish due to modifying a thermal regime could be to consider the most sensitive life stage of three of the most sensitive fish, such as endemic or endangered species (ANZECC, 2000). Further, Dutch CIW guidelines advise that potential effects in freshwater systems should be evaluated during biological spring (1 March - 1 June) (Rijkswaterstaat, 2004). Throughout this section, the most critical indicator for fish will be focussed on during spring. Further, it should be noted that cold water discharge, during the observed period, did not occur during the early months of biological spring which are March and April.

For fish, the egg/larvae stage and juvenile was observed to be the most critical; this can further be observed Table 4.2, showing the limited temperature ranges for egg/larvae life stage compared with an adult fish temperature range tolerance (Astles, et al., 2003). An example of how cold water can effect fish; Golden perch hatch in 24 hours at 27 – 31°C, for temperature below this range may take up to 50 hours to hatch (Astles, et al., 2003). Based on the information presented in Table 4.2, 15 to 20°C is the egg/larvae water temperature tolerance range for the majority of the fish species that hypothetically could be present at Hoog Dalem. Pike eggs/larvae prefer cooler waters, 5 to 15°C, while Tench and Small Loach prefer warmer waters in the range 20-25°C.

Spring, particularly May, is the most critical time of the year for fish due to spawning, a higher sensitivity to thermal changes for eggs/larvae. For this reason, the effect of cold water discharge on the channel water temperature during May will be further explored in this section. 2015 is the only year where there was cold water discharge during spring, in May, therefore water temperature during May 2015 will be explored, in addition with June and July.

Operational data for cold water discharge intake and return temperatures was combined with fish sensitive temperature ranges, Figure 4.1. During May 2015 water temperature at the outlet rarely exceeded 15 °C and without cold water discharge reached up to 20 °C in mid-May. Cold water discharge commenced again towards the end of June and July, during this operational time water temperature was typically warmer and the cold water discharge temperature typically ranged from 15-20 °C.

Measured water temperature for 2015 is available from late June until September. The measurement taken at 100cm depth at BENL0502 (Point 1) recoded water temperature from 15 up to 20 °C, typically around 17 °C, presented in Figure 3.23. For the remaining measuring points, the water temperature, for the time recorded varied from 15 up to 25 °C with a maximum of approximately 28 °C at BENL0502. At 60 cm depth, Figure 3.22, temperature observed had a higher variation than at 100 cm depth. The water temperature at the measuring point closest to cold water discharge did not exceed 25 °C and typically varied from 15 up to 20°C. At the remaining measuring points, the water temperature reached up to approximately 28°C and was typically between 15 and 25 °C.

The critical egg/larvae temperature range for the majority of likely fish species was found to be 15 to 20°C, with the exceptions of Pike (5 to 15 °C), Tench and Small Loach (20-25 °C). Without cold water discharge, the water temperature observed (May-September 2015) is typically too warm for Pike and too cool for Tench and Small Loach, with the exception of a few very warm occurrences.

Based on further investigating water temperature during spring of 2015, during May water temperature at the cold water outlet was below 15 °C and based on the measured water temperature, during June and July, the water temperature was higher than 15 °C. The cold water discharge temperature during May did not exceed 20 °C, which may have a positive effect given the majority of species prefer 15-20 °C during egg/larvae life stage. Since there is no measured water temperature during May, or a different year to compare with, a conclusion on the water temperature variation along the channel during May cannot be drawn based on the data available.

During June and July, at the cold water discharge point, temperatures below 15°C, but higher than 10°C were observed. At the measuring point closest to cold water discharge, the deeper diver did not record temperatures in excess of 20°C, while the shallower diver did exceed 25°C on three occasions, where at the most extreme warm was almost 5°C cooler than BENL0503 and BENL0505 (Point 4).

4.2 MODELLING TWO AQUATIC PLANTS

The modelling objective was to gain insight into the theoretical effect of cool water discharge on ecology and water quality at the case study site, to compliment the case study. This section presents theoretical growth considerations and temperature dependency for two macrophytes, aquatic plants. Aquatic vegetation is positively correlated to temperature and studies have found that temperature can effect the growth of submerged plants as strongly as light. An extensive study of submerged plants in six lakes found higher biomass during warmer years and also higher turbidity. Since temperature effects all aquatic organisms, a clear correlation for the six lake study was not able to be drawn on if the increase in plant biomass was solely due to temperature. This study used a growth model to verify the observed biomass variation with temperature, which was used to confirm that temperature had a significant effect on the studied plant biomass. (Scheffer, 1998, p. 253)

The species selected to study further was based on being either highly desirable (STOWA rating 1) or highly undesirable (STOWA rating 5) and importantly, have sufficient literature on temperature and growth dependence. It was found that there was insufficient temperature dependency literature available for the most desirable species identified at Hoog Dalem. The two undesirable species, *Lemna* (duckweed) and *Elodea nuttalli were* observed during ecological studies and were found to have sufficient theoretical information available on temperature growth dependency and to support modelling. Whether cold water discharge encouraged or discouraged the growth of the undesirable species was investigated based on literature and modelling, discussed further in this section.

4.2.1 THEORETICAL GROWTH DESCRIPTION FOR TWO MACROPHYTES

4.2.1.1 DUCKWEED

Lemnaceae, commonly known as duckweed, is categorised as an undesirable water plant family in The Netherlands, based on the STOWA score of 5. During ecological field surveys at Hoog Dalem, three types of *Lemna* were observed, these include: *Lemna minor*, *Lemna minuta* and *Lemna trisulca*. Throughout this discussion the three *Lemna* species will be referred to as *Lemna* or duckweed, most of the data available for this species is for *Lemna minor*.

Duckweed surface coverage at Hoog Dalem ranged from very low, 0.01% up to 2%. While the surface coverage was low, duckweed was often observed along the channel during ecological surveys, graphed results are presented in Appendix VII Figure 7.109 to Figure 7.111. On one occasion, the species was identified simply as *Lemna*, observed abundance is show in Figure 7.108. The observed abundance of *Lemna minor*, Figure 7.110, was very low, less than 1%. *Lemna minuta* abundance, Figure 7.109, was less than 1% coverage. *Lemna trisulca*, similar as the previous *Lemna* observed, was less than 2% surface coverage, presented in Figure 7.111. The frequency of *Lemna trisulca* observed is higher than the other two *Lemna* species, *Lemna trisulca* is the most desireable *Lemna*.

Table 4.3 Duckweed preferred habitat (Floran, 2016)

Habitat description	***Lemna minor***	***Lemna trisulca***	***Lemna minuta***
Freshwater	✓	✓	✓
Sunny to lightly shaded locations	✓	✓	
Sunny locations			✓
Moderately nutrient rich to nutrient rich waterways	✓	✓	
Nutrient rich waterways			✓
Stagnant to slightly flowing	✓		✓
Small to larger lakes, channels, canals, streams, ephemeral ponds	✓	✓	✓

4.2.1.1.1 LEMNA MINOR

Lemna minor has small green floating curved non-transparent disc leaves of 1.5-5.5mm, images are provided within the next figures. The flowering months are April to June and on occasion September and October. *Lemna minor* grows across Europe and several other continents, as indicated in Figure 4.2. As can be observed in Figure 4.2, *Lemna minor* grows in cooler climates, further north of The Netherlands, including Scotland and Scandinavian countries.

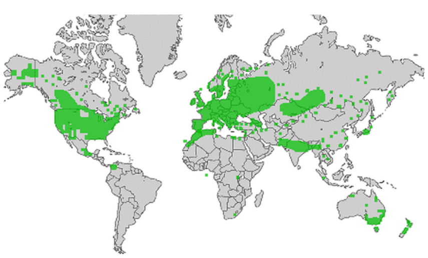


Figure 4.2 Lemna minor global abundance map
Image source: http://wilde-planten.nl/gewoon%20sterrenkroos.htm, accessed 18/08/2016.

Figure 4.3 Lemna minor image
Image source: http://titanarum.uconn.edu/198502634.html, accessed 18/08/2016.

4.2.1.1.2 LEMNA MINUTA

Lemna minuta is similar to *Lemna minor*, it has small green floating curved non-transparent disc leaves of 1-3mm, images are provided within Figure 4.5. *Lemna minuta* is originally from North and South America it grows across Europe and several other continents, as indicated in Figure 4.4.

Figure 4.4*Lemna minuta* global abundance map
Image source: http://wilde-planten.nl/dwergkroos.htm, accessed 30/08/2016.

Figure 4.5*Lemna minuta* images
Image source: http://wilde-planten.nl/afbeeldingen/foto/dwergkroos/wortel1-g.jpg, accessed 30/08/2016.

4.2.1.1.3 LEMNA TRISULCA

Lemna trisulca is commonly known as star duckweed, it has small, green, floating, curved, translucent disc leaves of 0.5-1.5 cm, see Figure 4.7. *Lemna trisulca* is the more desirable than *Lemna minor* and *Lemna minuta*. Different from the aforementioned Lemna's, the leaves are narrower and pointier and it floats just below the water surface. Flowering occurs during May and June. *Lemna trisulca* is found across Europe and several other continents, as indicated in Figure 4.6.

Figure 4.6Lemna trisulca global abundance map
Image source: http://wilde-planten.nl/puntkroos.htm, accessed 30/08/2016.

Figure 4.7*Lemna trisulca* images
Image source: http://www.naturespot.org.uk/species/ivy-leaved-duckweed, accessed 15/11/2016.

4.2.1.1.4 GROWTH CHARACTERISTICS

Growth of Duckweed is dependent on the key factors: temperature, photoperiod (day light length), density and biomass per metre square on the water surface and nutrient concentrations for phosphorus and nitrogen (Lasfar, et al., 2007).

4.2.1.1.4.1 NUTRIENTS

Duckweed will grow until complete consumption of nutrients, although research into its growth rate observed minimal increased rate of growth with nutrient concentrations in excess of 0.1mg P/l and 2mg

N/l (Lasfar, et al., 2007). A study of the intrinsic growth rate[17] observed stable intrinsic growth rates for nutrient concentrations in excess of 1mg P/L and 3mg N/L, as presented in Figure 4.8 and Figure 4.9.

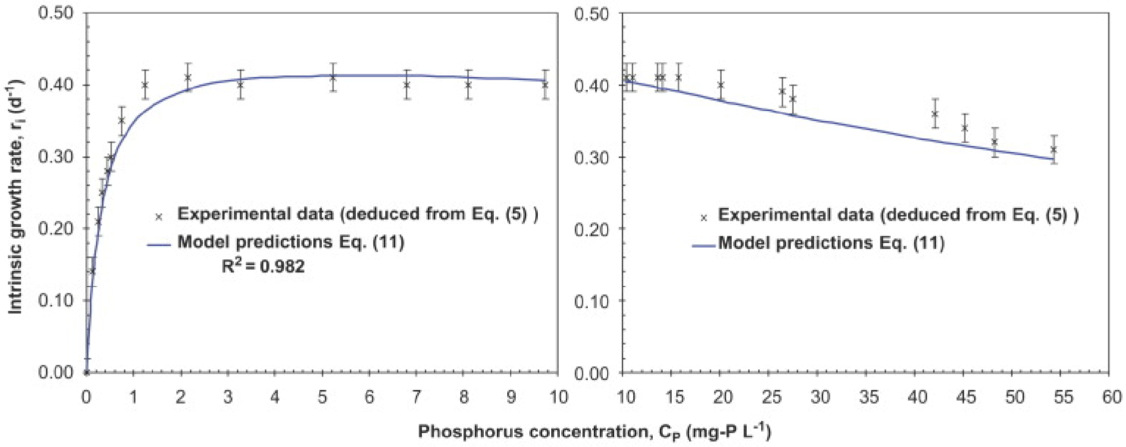


Figure 4.8*Lemna* minor intrinsic growth rate in dependence of phosphorus concentration; the bars represent the maximum error deduced from the nitrogen and phosphorus mass balances. (Lasfar, et al., 2007)

At Hoog Dalem, the median phosphorus concentration fluctuated along the measuring points, typically in the range 0.05-0.1mg P/l, the lowest concentration was 0.02mg P/l. The highest concentration of 0.24mg P/L was recorded once at BENL0502 during relatively higher flow, 3.9cm/s in January 2016. During the months May to November, the maximum phosphorus concentration observed was 0.17mg P/L. During cold water discharge, phosphorus concentrations were typically lower than 0.1mg P/L, except at BENL0503 the maximum concentration just exceeded 0.1mg P/L. Based on typical phosphorus concentrations in eutrophic waterways within The Netherlands, the phosphorus concentrations at Hoog Dalem were quite low. Further, if hypothetically basing the growth rate of Duckweed on phosphorus concentration, it is likely to vary between higher than 0 d^{-1} up to a maximum of approximately 0.3 d^{-1}.

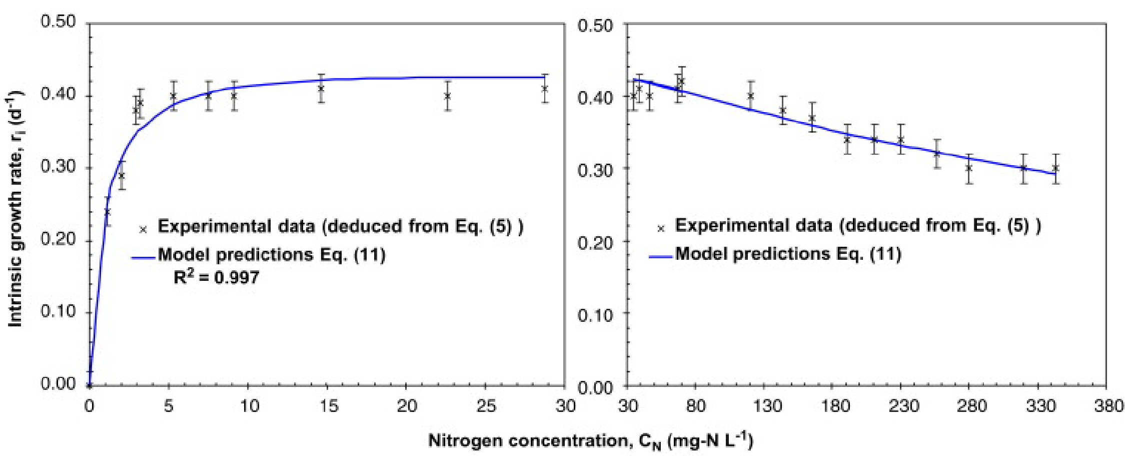


Figure 4.9*Lemna* minor intrinsic growth rate in dependence of nitrogen concentration; the bars represent the maximum error deduced from the nitrogen and phosphorus mass balances. (Lasfar, et al., 2007)

[17] Growth rate that differentiates the effect of duckweed mat density from temperature, photoperiod and phosphorus–nitrogen concentrations.

The median nitrogen concentration fluctuated along the measuring points, typically in the range 0.7-1.0 mg N/l, with few observations exceeding 2 mg N/l, the lowest concentration was 0.5 mg N/l. During cold water discharge, nitrogen concentrations were lower than 1.5 mg/l. Therefore, during cold water discharge, it is not anticipated that duckweed growth is effected by an excess in nutrients. Based on typical nitrogen concentrations in eutrophic waterways within The Netherlands, the nitrogen concentrations at Hoog Dalem were low (Janse & Van Puijenbroek, 1998). Taking an approach of hypothetically basing the growth rate of Duckweed on nitrogen concentration, it is likely to vary between higher than 0.1 d^{-1} up to a maximum of approximately 0.3 d^{-1}.

Another study researching Duckweed growth in The Netherlands (Holland's Noorderkwartier), observed nitrogen and phosphorus concentrations, where Duckweed was present, in the range 3.4 mg N/l (ranging 1.0-19.6) and 1.1 mg P/l (ranging 0.05-7.9) (Janse & Van Puijenbroek, 1998). Further, it was found that nitrogen concentrations did not considerably vary in Duckweed dominated ditches and higher median phosphorus concentrations were observed (Janse & Van Puijenbroek, 1998).

The maximum Duckweed cover observed was 1.5% BENL0505 on 11 July 2012, when there was no cold water discharge. In July 2012 two laboratory samplings were undertaken for each observation point, the observed phosphorus ranged from 0.07 up to 0.09mg P/L, nitrogen (TKN) ranged from 0.82 up to 1.2 mg N/L and oxygen ranged from 7.4 up to 10.7 mg/L.

4.2.1.1.4.2 DENSITY

The density of the Duckweed, which can also be referred to as the "matt density", is a very important factor effecting the growth. Since Duckweed is used in water cleaning for sewerage and slug application, there is considerable research on optimum matt density, based on various studies the optimal matt density can range from 400 up to 1600 g wet/m^2.

4.2.1.1.4.3 DAY LENGTH

The photoperiod or day length was found to strongly influence growth of Duckweed, for the species studied *Lemna minor.* The quantity and magnitude of the plant leaves is directly dependent on the day length, growth was found to be inhibited by a light-dark ratio lower than 0.3 and radiation exceeding 2 was found to slow the growth rate. The optimum light-dark ratio was observed to be 0.7-1.4. (Lasfar, et al., 2007)

4.2.1.1.4.4 TEMPERATURE

In general, the optimum temperature range for *Lemna* growth is 20-31°C and growth can occur for temperatures ranging from 5°C up to 35°C (Lasfar, et al., 2007). Based on a study undertaken to find the intrinsic growth rate using *Lemna minor*, the optimum growth rate was found to be between 23 and 28°C, as illustrated in Figure 4.10 (Lasfar, et al., 2007).

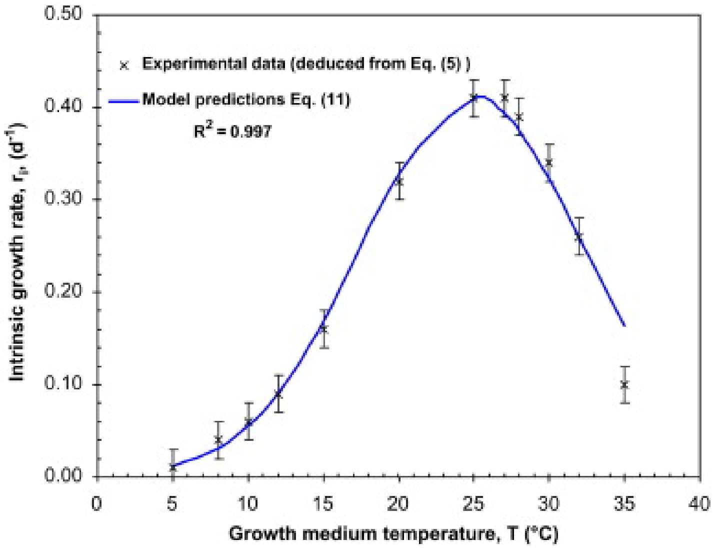


Figure 4.10 *Lemna minor* intrinsic growth rate in dependence of temperature, the bars represent the maximum error deduced from the nitrogen and phosphorus mass balances. (Lasfar, et al., 2007)

A study into the influence of floating vascular plants on the diurnal fluctuations of temperature near the water surface, conducted in early spring, observed on clear days floating Duckweed was 4-11°C warmer than the surface of the open water (Gillespie & Dale, 1976). Compared to the open water, the floating plant matt reflects more energy and transmits less energy and due to this less temperature fluctuations occurs for at least 10cm below the plant (Gillespie & Dale, 1976). Below the floating matt the water temperature was on average 2°C warmer than at open water areas (Gillespie & Dale, 1976).

4.2.1.1.4.5 SUMMARY

The growth rate of Duckweed was been found to vary depending on research, for similar temperature, photoperiod and nitrogen and phosphorus concentrations. The intrinsic growth rate study on Duckweed found growth was strongly dependent on temperature and day length. The intrinsic growth rate study was focused on waste waters that have very high nutrient concentrations, Hoog Dalem nutrient concentrations were lower than those concentrations found to trigger stable growth.

4.2.1.2 ELODEA NUTTALII

Elodea Nuttalli, commonly known as Nuttall’s waterweed, is categorised as an undesirable water plant in The Netherlands. *Elodea Nuttalli* is an invasive species, originally from North America, it was first found in The Netherlands in 1941 (Cook & Urmi-König, 1985). *Elodea nuttallii* is an abundant exotic species that tolerates a relatively broad temperature range (Greulich & Tremolieres, 2006, p. 252).The plant is opaque, dark green with leaves that are typically flat, spread with straight margins and are usually longer than 10mm (Cook & Urmi-König, 1985). Images of the plant are provided within Figure 4.12. The preferred habitat for the species is summarised below (Cook & Urmi-König, 1985):

- Calcareous waters
- Lakes, ponds, slowly flowing streams and canals and tidal flats
- Salinity up to 14.4 ppt (almost half of normal sea water)

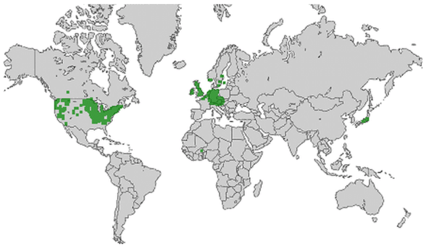


Figure 4.11 *Elodea nuttallii* species global abundance map (Image source: http://wilde-planten.nl/gewoon%20sterrenkroos.htm, accessed 18/08/2016.)

Figure 4.12 Photo of *Elodea nuttallii* observed at Hoog Dalem (dark green)

Elodea Nuttalli grows in climates cooler than The Netherlands, including Scotland and patches located in Norway and Sweden, see Figure 4.11. During cool seasons, December or January to March, *Ellodea nuttallii* is present as dense matts on the bed with prostrate shoots with green leaves (Cook & Urmi-König, 1985). When the water temperature exceeds 4°C, the shoots begin to grow and growth accelarates when the water reaches 10°, new shoots develop from the prostrate shoots and grow rapidly upwards almost without branch until they approach the surface when vigorous branching takes place.

The roots of the plant decay from middle of June to November, with the maximum root biomass occuring in June, minimum in September (Cook & Urmi-König, 1985). The maximum shoot biomass occurs in September (1693 g dry/m $^{-2}$) with most biomass in the top 30 cm later (Cook & Urmi-König, 1985). During November and Devember, the branched shoots become detached and sink towards the bed. (Cook & Urmi-König, 1985):

The observed abundance of *Ellodea nuttallii* ranged from almost 0% up to 90% coverage, presented in Figure 7.107, Appendix VII. The highest coverage was at BENL0503 and BENL0505 in 2013. Based on BwB observations, BENL0505 had the highest abundance of *Ellodea nuttallii*. At measuring point BENL0502, the point closest to cold water discharge, a strong observable pattern of *Ellodea nuttalli* percentage cover was not observed based on the ecological survey data.

4.2.2 MODEL DESCRIPTION

To gain further insight into the theoretical consequences of cooling the surface water on aquatic plants (macrophytes), modelling was undertaken. Modelling was carried out using Delft3D, D-Water Quality and D-Ecology (DELWAQ), Figure 4.13 provides an overview of the model configuration and below describes the general modelling methodology undertaken.

1. Adapt existing Delft3D-Flow model
2. Develop DELWAQ model
    a. Data collection
    b. Development of inputs not available based on literature
3. Addition of DELWAQ model to Delft3D-Flow model
4. Develop additional scenarios
5. Draw conclusions from the modelling

Delft3D is an open source software package and modelling suite. DELWAQ contains a water quality and aquatic plant module that can be used to simulate various water quality aspects and can be linked to Delft3D-Flow. A review of equations in the thermal Delft3D model and relationships between Delft3D and DELWAQ is outlined in this section to describe the model framework and interactions.

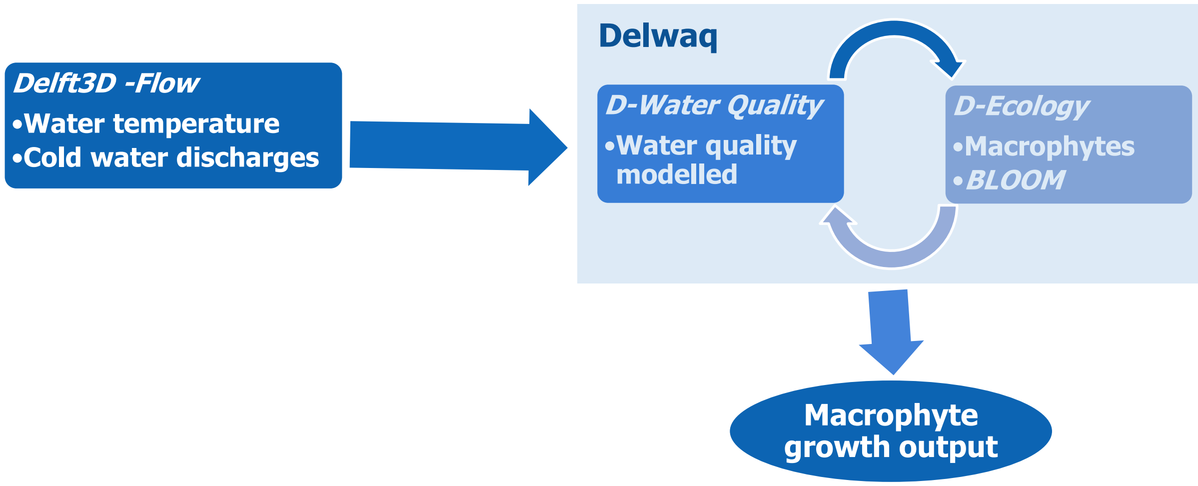


Figure 4.13 Overview model configuration

As discussed in Section 3.6, 2015 was a year with very warm weather (>25 °C) and with more consistent -ΔT°C, than 2013. Therefore, the year 2015 was selected to model the two macrophyte species and associated water quality. The model benefits the study by demonstrating potential effects from cold water discharge on the growth of macrophytes, which was not significantly evident from the ecological surveys. Modelling was undertaken to compliment the case study data analysis and to gain insight into theoretical expectations for macrophyte growth. Two base case models, one without flow or cooling and another with flow and no cooling were modelled to provide insight to how modelled water quality is influenced by flow. The model simulations completed include:

- Scenario 1: 2015 to 2016 no – ΔT and Q *'base case'*
- Scenario 2: 2015 no – ΔT without Q *'base case no Q'*
- Scenario 3: 2015 realised –ΔT and Q *'actual'*
- Scenario 4: 2015 10°C – ΔT and Q *'predict - ΔT 10 °C'*

Model limitations include:

1. Still water body without inflows from the adjacent farmlands
2. Information on water circulation from adjacent channels and locks was not available

The next schematic presents the observation locations along the channel, cold water was discharged at the outlet and warmer water was extracted at the intake.

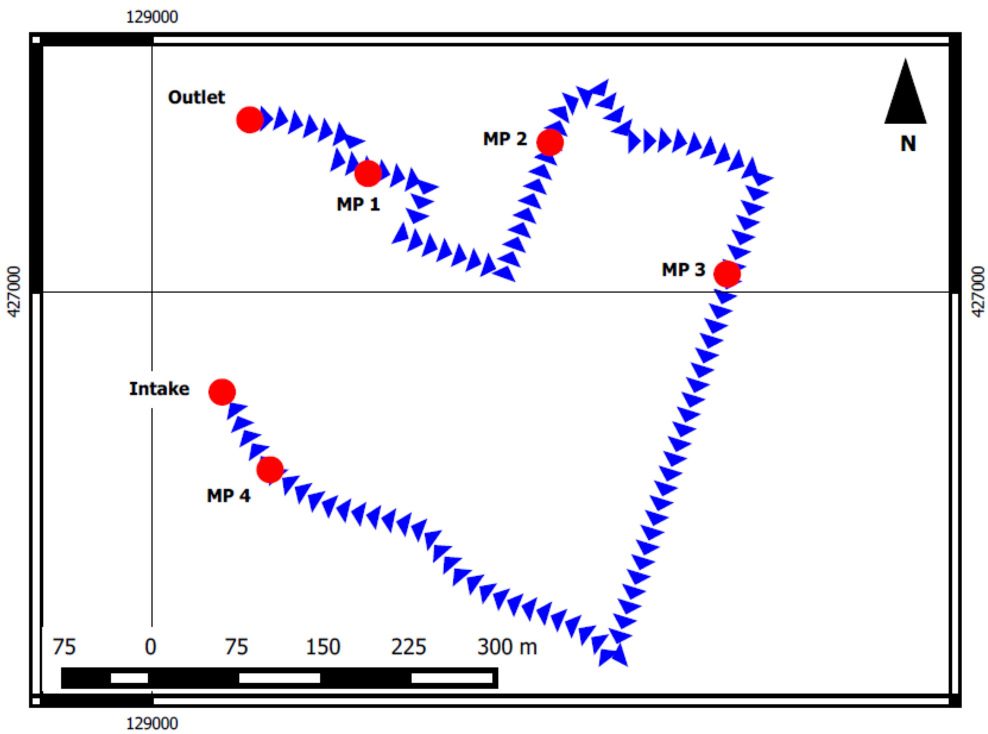


Figure 4.14 Channel schematic, model point locations and naming (sometimes Outlet is stated as Uitstroom and Intake is Inname)

4.2.2.1 TEMPERATURE MODEL CONFIGURATION AND INPUTS

Hoog Dalem channel water temperature was modelled in Delft3D-Flow for the three model scenarios, previously outlined. The modelling objective was to gain insight into the theoretical effect of cool water discharge on ecology and water quality at the case study site. In order to achieve this objective, modelled water temperature for the case study channel was required. The Hoog Dalem temperature model configuration was developed by Pascal Boderie, Deltares. This section presents modelling information sufficient to explain how the case study water temperature was modelled, the heat flux equation is presented and the modelling options, inputs and limitations are descried. For further elaboration of the temperature modelling and inputs, the Delft3D-Flow user manual is referred to.

A previous study on water temperature modelling for a similar water body in The Netherlands, *Urban Surface Water as Energy Source & Collector*, verified Delft3D-Flow is suitable for modelling shallow surface water temperature, similar to Hoog Dalem (Medrano, 2008, p. 136). Channel water temperature was modelled in 3D since a previous study confirmed that it is necessary to model shallow surface water temperature in 3D (Medrano, 2008).

Water temperature is influenced by the heat exchanged at the surface and bed material and the hydrodynamics, presented in the next figure and described by the equation below (Medrano, 2008). Total heat flux during the day is generally positive towards the water surface, water is warmed, and dominated by solar radiation (Medrano, 2008). During the night there is a negative heat flux towards the water surface due to significantly reduced solar radiation (Medrano, 2008).

$$Q_{tot} = Q_{sol} - Q_{eb} - Q_{sen} - Q_{eva} \qquad \text{(Medrano, 2008)}$$

Where:

- Q_{tot} total heat flux (W m^{-2})
- Q_{sol} solar radiation (W m^{-2}) (short wave)
- Q_{eb} net atmospheric radiation (W m^{-2}) (long wave)
- Q_{sen} sensible heat flux (W m^{-2})
- Q_{eva} latent heat flux (W m^{-2})
- Additional components:
    - Q_{si} incident solar radiation (W m^{-2})
    - Q_{sr} reflected solar radiation (W m^{-2})
    - Q_{al} atmospheric radiation (W m^{-2})
    - Q_{alr} reflected atmospheric radiation (W m^{-2})
    - Q_{bl} water surface back radiation (W m^{-2})

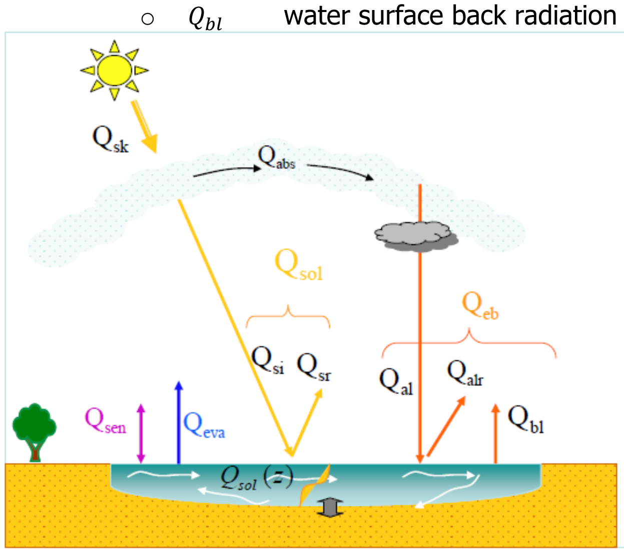


Figure 4.15 Heat transfer mechanisms at the water surface (Medrano, 2008)

Delft3D-Flow temperature model computes the water surface heat fluxes, taking into account incoming radiation, back radiation, evaporation and convection. The evaporation and convection are dependent on air temperature, water temperature, relative humidity and wind speed. Delft3D-Flow heat balance model limitations include (Deltares, 2014, p. 244):

1. Heat exchange at the bed is not taken into consideration
    i. May over-predict water temperature in shallow areas
2. Precipitation effect on the water temperature is not taken into account

There are five different heat flux model options in Delft3D-Flow. The ocean option was selected, which comprises relative humidity, air temperature and the percent of cloud coverage, the only option that includes cloud coverage (Deltares, 2014, p. 76). For the model scenarios with cold water discharge, the operational discharge data from Eneco was input as a discharge to the channel. The next table presents the main inputs for Hoog Dalem temperature and flow model.

Table 4.4 Water temperature and flow model description

Input	Description
Activated processed	Temperature and wind, water quality modelled separately from flow model
Channel layout	• Grid input • Constant depth 1 m • 5 water layers, each water layer is 0.2 m (20% of total depth)
Coupled intake and outlet	• Water is extracted at the intake and discharged at the outlet • Water temperature difference (-ΔT °C) and flow rate (m^3/s) of the discharged water is based on the operational data ▪ Intake and outlet operational at water layer 3
Model timing	• Simulated from 2012 to end 2015 • Model time step was 0.5 min • Smoothing time of 60 mins • 2010 was the reference year
Climate input data	• Location: Herwijnen station ▪ Frequency: hourly ▪ Data: Air temperature (°C), Relative humidity (%), Cloud coverage (%), Solar radiation (w/m^2), Wind speed (m/s) and direction (degrees)
Physical parameters	• Hydrodynamic constants: ▪ Gravity 9.81 m/s^2 ▪ Water density 1000 kg/m^3 ▪ Salinity 31 ppt • Roughness ▪ Bottom roughness based on Chezy formula with uniform constants ▪ No wall roughness specified • Heat flux model ▪ Model setting - ocean option ▪ Dalton number for evaporative heat flux, default value 0.0013 (-) (Deltares, 2014, p. 77) ▪ Stanton number for heat convection, default value 0.0013 (-)
Viscosity	• Constant horizontal eddy viscosity and diffusivity 1 m^2/s • No vertical eddy viscosity and diffusivity (0 m^2/s) • Option selected for 3D turbulence was k-Epsilon ▪ Coefficients determined by transport equations for both the turbulent kinetic energy and the turbulent kinetic energy dissipation (Deltares, 2014, p. 72)

4.2.2.2 WATER QUALITY MODEL INPUTS

Water quality modelling was required to support the modelling of macrophytes since growth dependency includes water quality, especially nutrients and dissolved oxygen. The water quality parameters, initial conditions and constants are the same input for each of the three Delft3D-Flow model scenarios. Water quality modelling is based on the flow and temperature output from the Delft3D-Flow models.

The water quality model was developed based on an existing 1D "column model" for algae. The "column model" was modified to suit Hoog Dalem by updating to the new process definitions, expanding to include additional substances and inclusion of submerged and emerged macrophyte model inputs. The water quality modelling was undertaken with support from the D-Water Quality Processes Technical

Reference Manual[18], process description file[19]and guidance from Pascal Boderie, Michel Jeuken, Rudy Schueder and Tineke Troost.

Modelled water quality initial conditions and constants were based on Hoog Dalem measured water quality and model iterations to simulate outputs representative of the case study site. Integration of water quality modelling with the temperature and flow model is described below. An issue was encountered with the coupling of the Intake and Outlet with Delft3D-Flow, it was found that very specific naming is required that was not outlined in the Delwaq manual.

- Intake: Water quality of the extracted water was based on the modelled water quality
- Outlet: Water quality of the cooler water discharged was based on results from the case study data at measuring point BENL0505

The next figure presents interactions between nutrient cycles and macrophyte lifecycle. Shaded in blue are water quality measurements from Hoog Dalem, macrophytes are shaded in darker green and phytoplankton (BLOOM) is shaded in lighter green. Radiation from Herwijnen station was input to the model for the water quality and macrophyte process, described further in the next section.

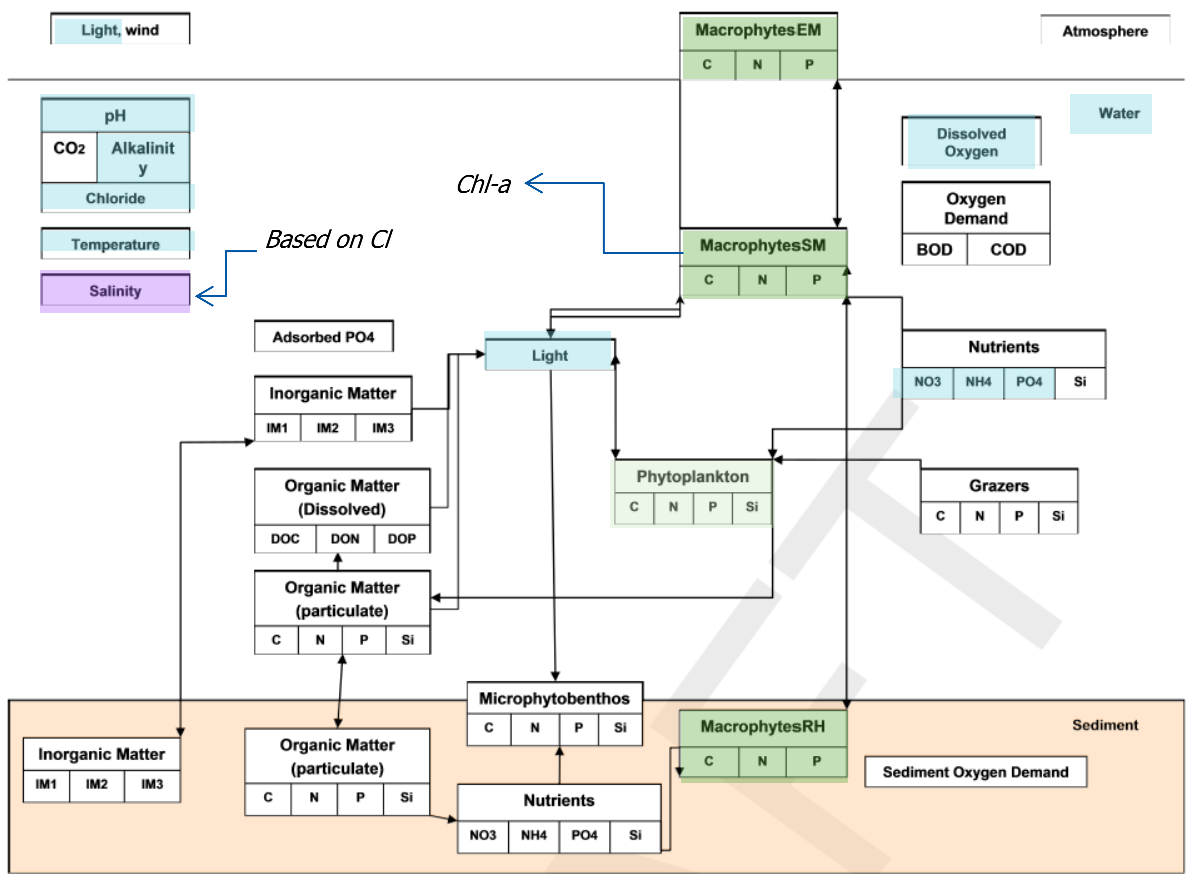


Figure 4.16 Interactions between the nutrient cycles and the life cycle of macrophytes (Deltares, 2017)

[18] "Some processes are not discussed in the D-Water Quality manual either because they have not been integrated into the standard set of processes or because they are under development such as module MICROPHYT for microphytobenthos and a module for aquatic macrophytes." (Deltares, 2016, p. 2)
[19] Water quality, macrophyte and BLOOM input process file provided by Michel Jeuken and Rudy Schueder, 2017

To observe Chl-*a* the BLOOM module was activated, at the time of finalising the study there were existing complications modelling Chl-*a* and therefore results are not presented. Both the BLOOM and macrophyte model require extensive inputs that require iterations and validation. The processes that are not shaded were based on model defaults, iterations or calculated based on other activated process. As can be observed, macrophyte and water quality process are interdependent throughout the water column and bed sediment layer. Important model inputs and processes are described by the previous figure and the next table.

Table 4.5 Overview of included processes working on the state variables (Deltares, 2016, p. 282)

State variable	Processes acting on it
OXY	1. Denitrification in water column 2. Nitrification of ammonium 3. Reaeration of oxygen 4. Mineralisation detritus carbon 5. Net primary production and mortality green algae
NH4	1. Nitrification of ammonium 2. Mineralisation detritus nitrogen 3. Uptake of nutrients by growth of algae 4. Release (nutrients / detritus) by mortality algae 5. Diffusive waste NH4
NO3	1. Denitrification in water column 2. Nitrification of ammonium 3. Uptake of nutrients by growth of algae
PO4	1. Ad(De)Sorption ortho phosphorus to inorganic Matter 2. Mineralisation detritus phosphorus 3. Uptake of nutrients by growth of algae 4. Release (nutrients/detritus) by mortality algae 5. Diffusive waste PO4
Green	1. Net primary production and mortality of green algae (BLOOM)
DetC, DetN, DetP	2. Mineralisation detritus 3. Release (nutrients / detritus) by mortality algae 4. Sedimentation detritus carbon

4.2.2.3 MACROPHYTE MODEL INPUTS

The macrophyte model is designed for modelling emerged and submerged macrophytes, required inputs are summarised in the next schematic. Emerged macrophyte (EM) describes water plants that float on the water surface and submerged macrophyte (SM) describes water plants that grow from the bed, the Delwaq definitions are different to the actual ecology definitions. The model is set with *Elodea Nuttalli* as submerged water plant 1 (SM01) and Duckweed is emerged plant 2 (EM02). A complication was encountered when first attempting to model one of each in one model, the current macrophyte model is designed for up to five submerged or five emerged and not a combination. The model simulated SM02 which it expected since the species was SM01, this was overcome by adding a constant nutrient limitation for SM02 which enabled EM02 to be successfully modelled.

The inputs for the macrophytes as based on theoretical literature, as outlined in Section 4.2.1. Where literature was not available Delwaq defaults were incorporated and adjusted where required to provide more realistic outputs. Submerged macrophyte growth is modelled based on the equations in Appendix

VII, there are some slight differences between emerged and submerged, which is clear based on the constant inputs. The equations are shown to illustrate the processes for the macrophytes.

Growth

- Initial biomass
  - Biomass in water column at beinning of growing season
  - Biomass stored in rhizomes
- Potential growth rate

Limitation factors

- Light limitation factor
- Temperature limitation
  - Critical - no growth
  - Growth increases above 20°C and decreases below 20°C
- Day length limitation - day lenth

Nutrient limitation factor

Decay

- Decay of biomass
  - Temperature and day length dependent
  - Autumn and winter
- Formation of particulate organic carbon

Nutrient sources

- Uptake of carbon, nitrogen and phosphorus from rhizomes
- Growth from rhizomes and root system
- Uptake of nitrogen and phosphorus from sediment
- Uptake of nitrogen and phosphorus from water (only for non-rooted macrophytes)

Oxygen production and comsumption

Figure 4.17 Macrophyte modelling summary of inputs

4.2.3 MODEL RESULTS

The macrophyte modelling was coupled to the Delft3D flow output. The ambient water temperature was simulated for the four model scenarios, Scenario 1, 3 and 4 is presented for discussion. Water temperature is an input to the D-Ecology and D-Water Quality modules, water temperature is used by the water quality model for temperature dependent parameters, such as oxygen saturation.

4.2.3.1 WATER TEMPERATURE

The ambient water temperatures are shown for an extremely warm day observed 4 July 2015, in stream temperature measurements showed water temperature at MP 3 and 4 exceeded 25 °C. Ambient water temperature without cold water discharge reached almost 30 ° C, the realized water temperature maximum was around 28 °C, similar to the observed in Figure 3.22. The prediction scenario, - 10 °C maximum modelled temperature was approximately 26 °C, 2 °C lower than the realised scenario.

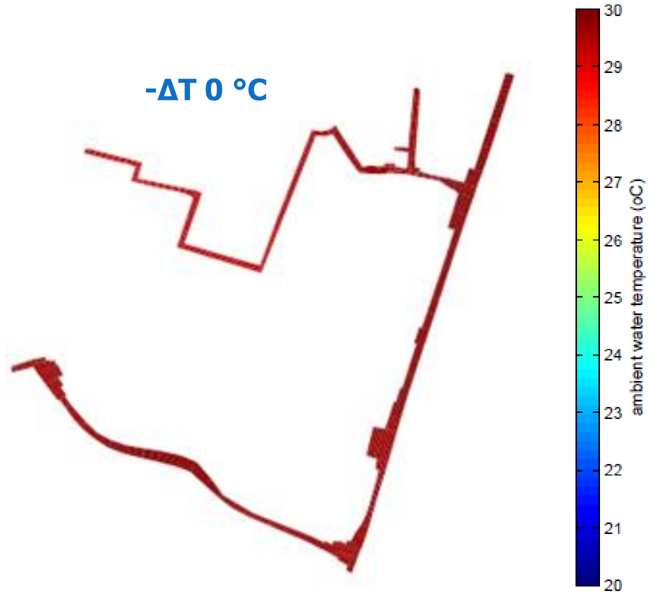


Figure 4.18 Modelled ambient water temperature –ΔT °C OFF during a very warm day – upper layer (1) 4-Jul-2015 14:00

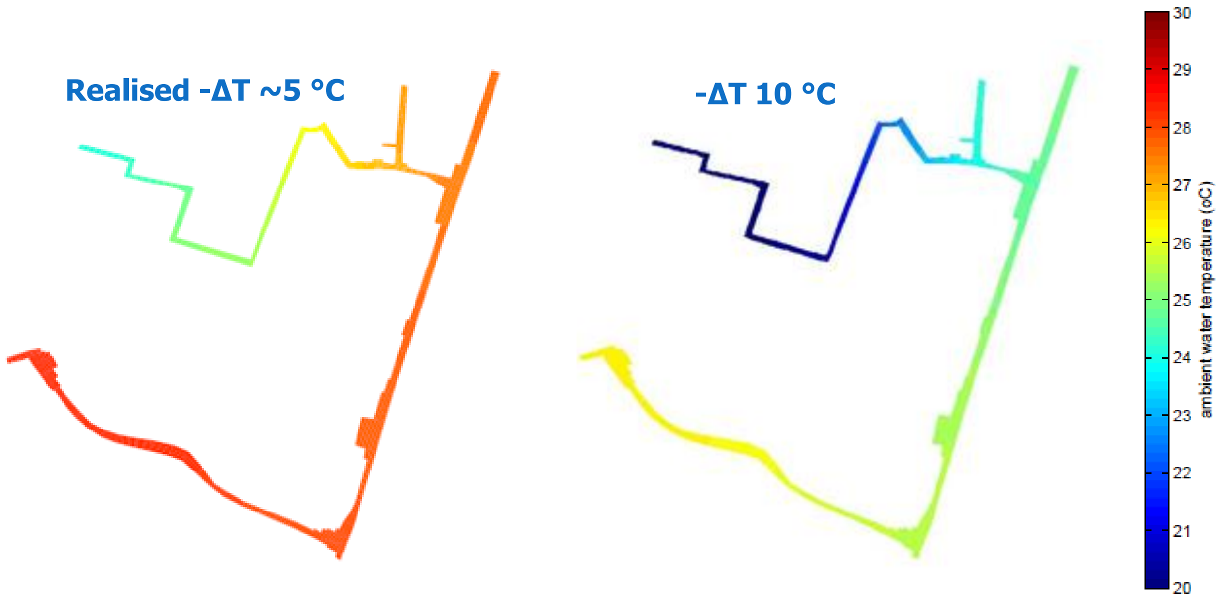


Figure 4.19 Modelled ambient water temperature –ΔT °C ON during a very warm day – upper layer (1) 4-Jul-2015 14:00

4.2.3.2 DELWAQ

This section presents outputs from the four the Delwaq modelling scenarios, the four selected outputs are *Elodea Nuttallii* (SM01), Duckweed (EM01), water temperature (°C) and DO (mg/l), with an hourly time step. Initial mass for EM and SM and for all measuring points was assigned the same initial mass. The initial mass was assigned the same value since growth is influenced by initial mass, therefore dependencies on initial mass do not influence the modelled growth differences between measuring points.

4.2.3.2.1 SCENARIO 1: WITHOUT -ΔT°C

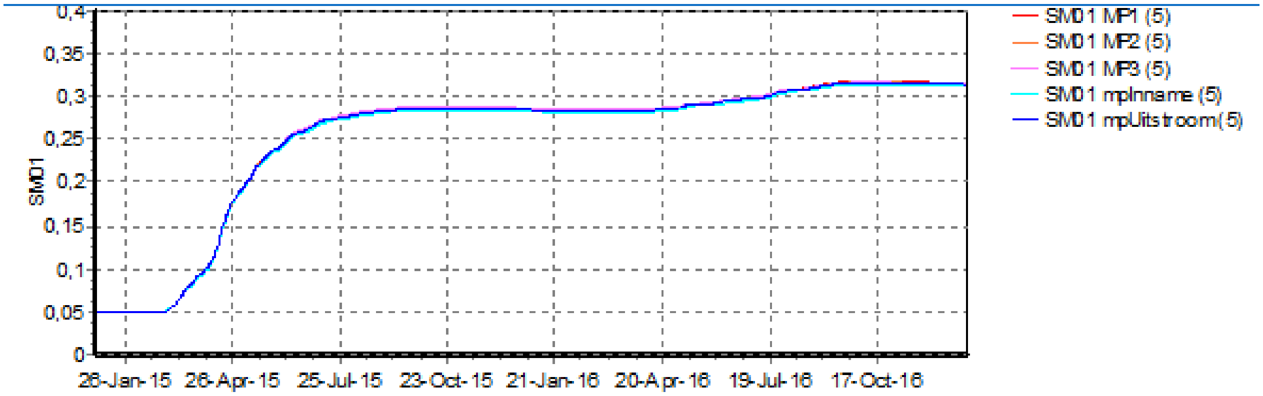


Figure 4.20 Elodea Nuttallii mass (g) - without -ΔT°C

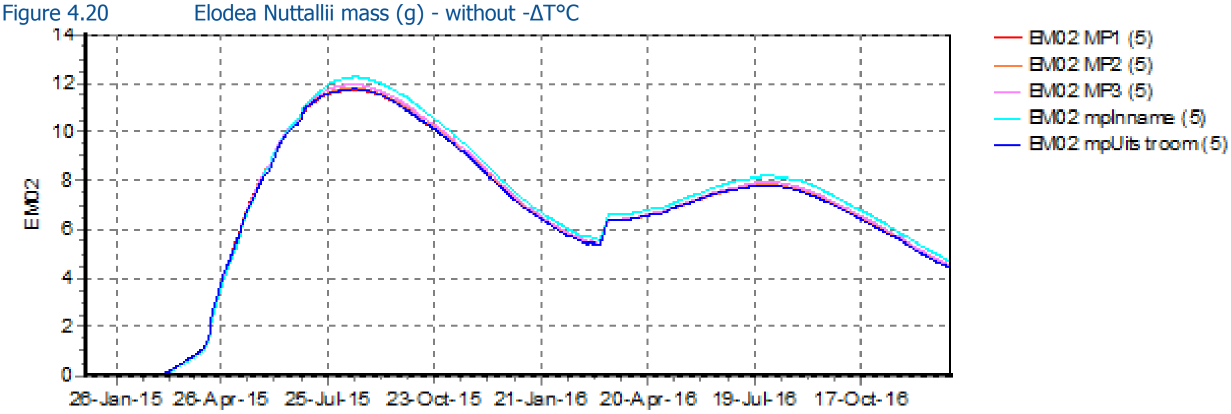


Figure 4.21 Duckweed mass (g) - without -ΔT°C

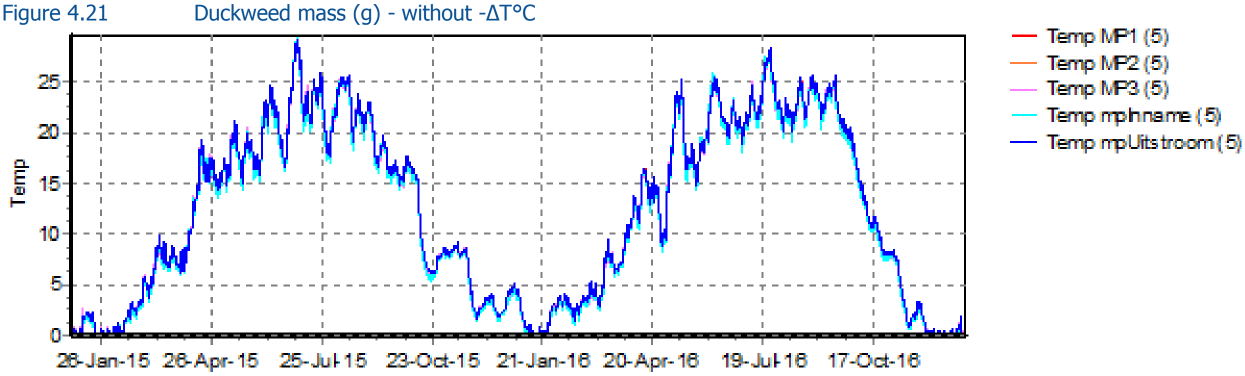


Figure 4.22 Water temperature (°C) without -ΔT°C

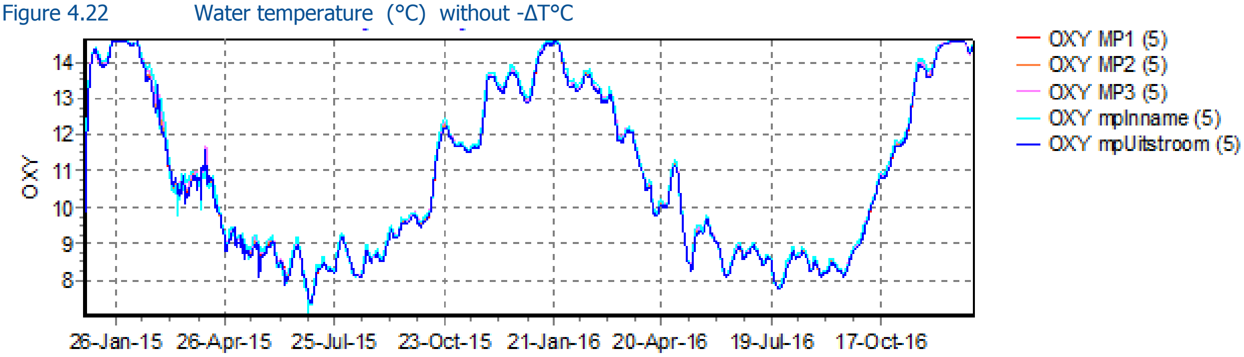


Figure 4.23 Oxygen (mg/l) without -ΔT°C

4.2.3.2.2 SCENARIO 2: WITHOUT -ΔT°C AND NO Q

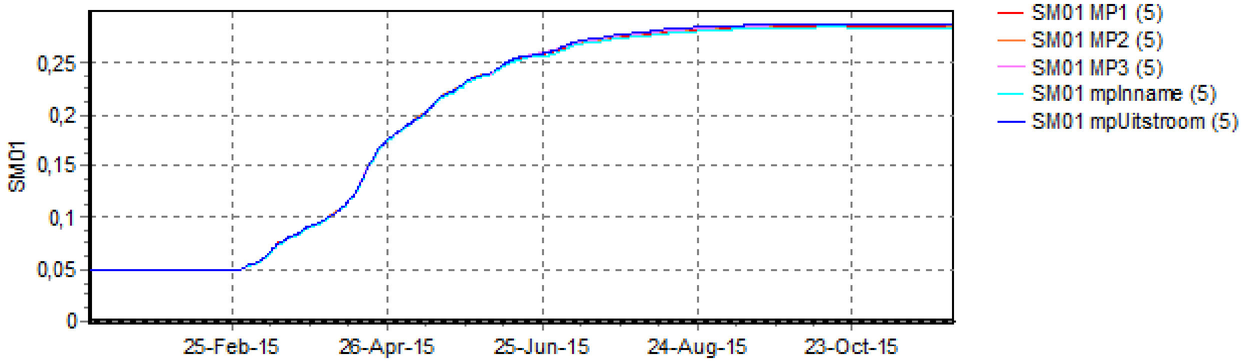


Figure 4.24 Elodea Nuttallii mass (g) - without -ΔT°C and no Q

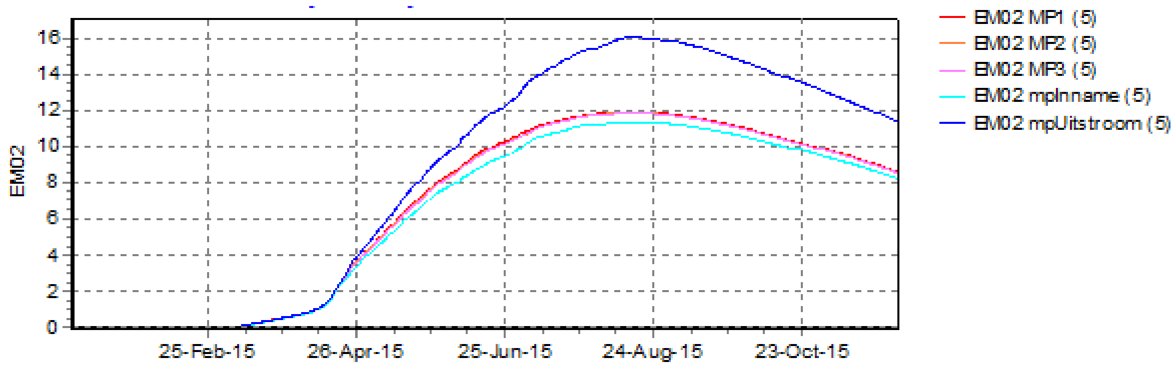


Figure 4.25 Duckweed mass (g) - without -ΔT°C and no Q

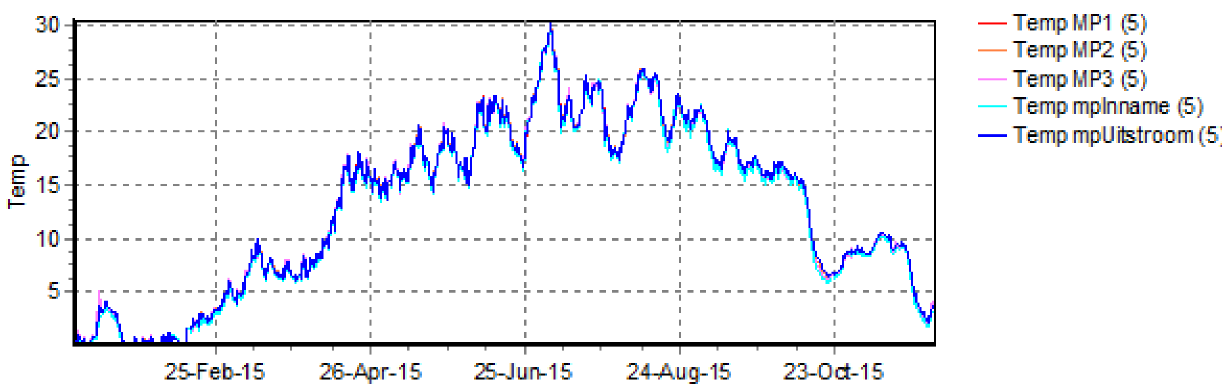


Figure 4.26 Water temperature (°C) without -ΔT°C and no Q

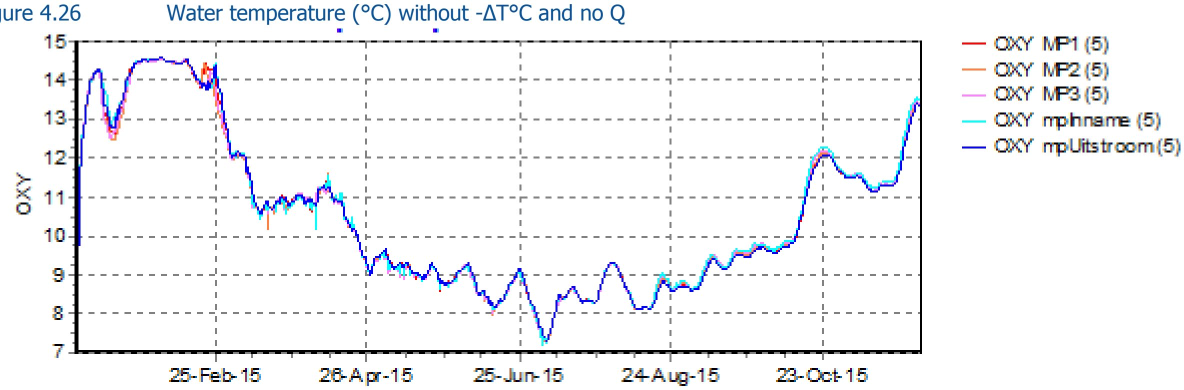


Figure 4.27 Oxygen (mg/l) without -ΔT°C and no Q

4.2.3.2.3 SCENARIO 3: REALISED -ΔT°C

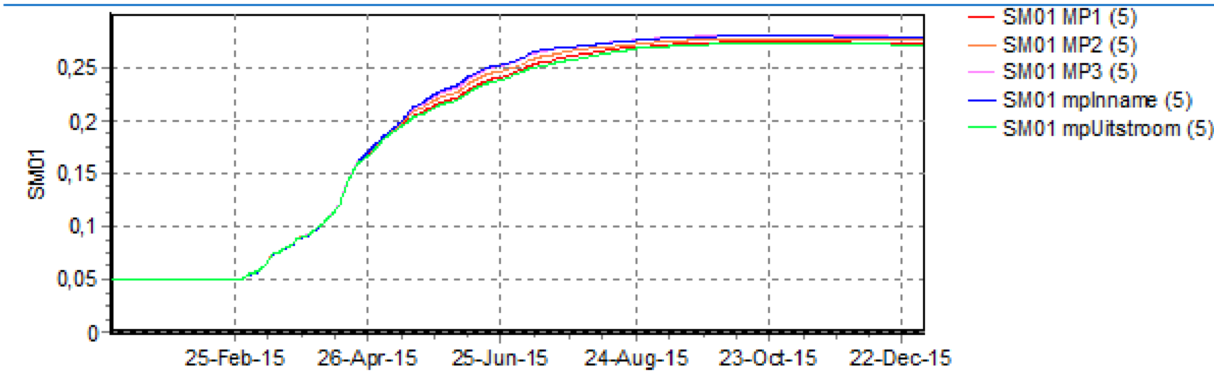


Figure 4.28 Elodea Nuttallii mass (g) - realised -ΔT°C

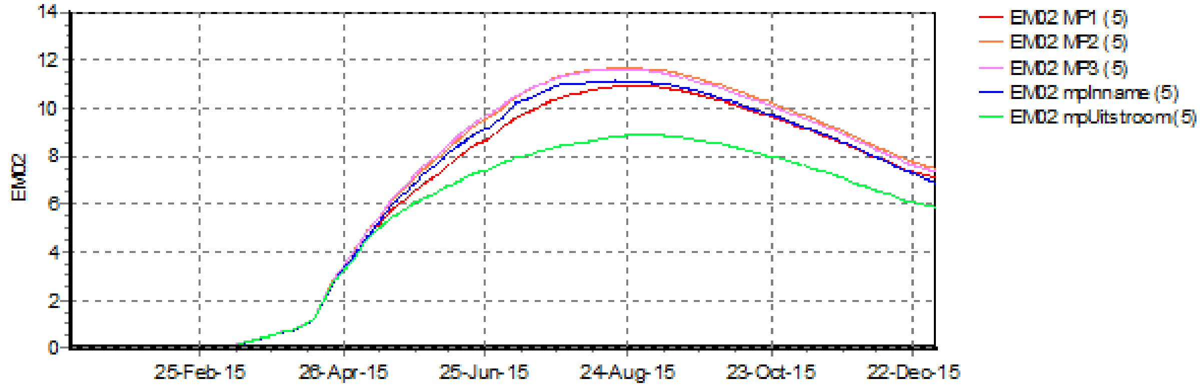


Figure 4.29 Duckweed mass (g) - realised -ΔT°C

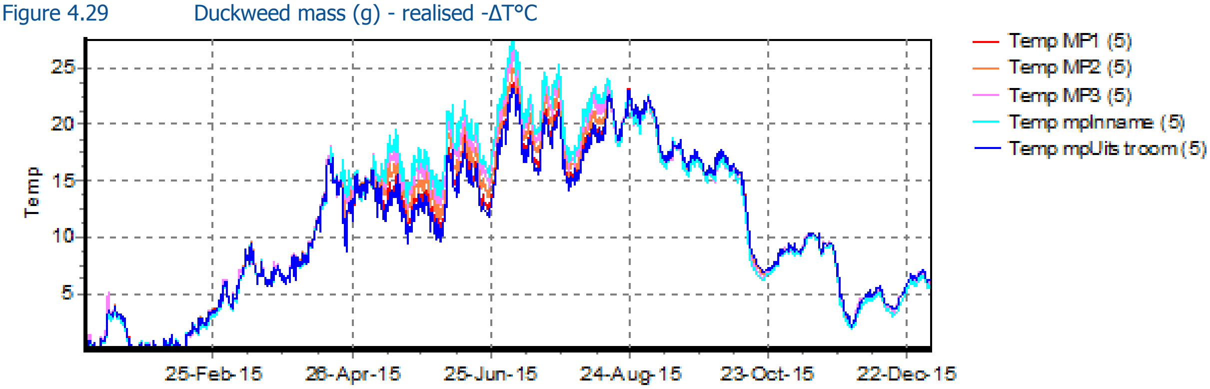


Figure 4.30 Water temperature (°C) realised -ΔT°C

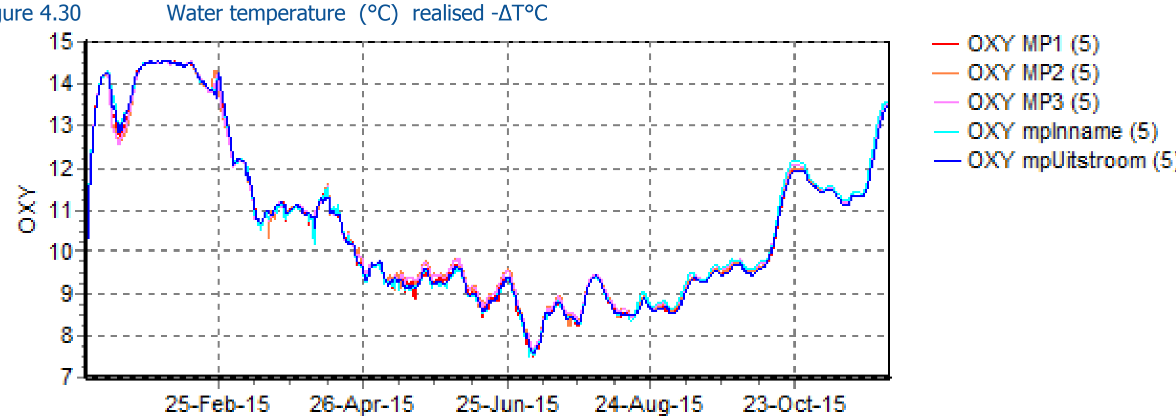


Figure 4.31 Oxygen (mg/l) realised -ΔT°C

4.2.3.2.4 SCENARIO 4: PREDICTION OF -10ΔT°C

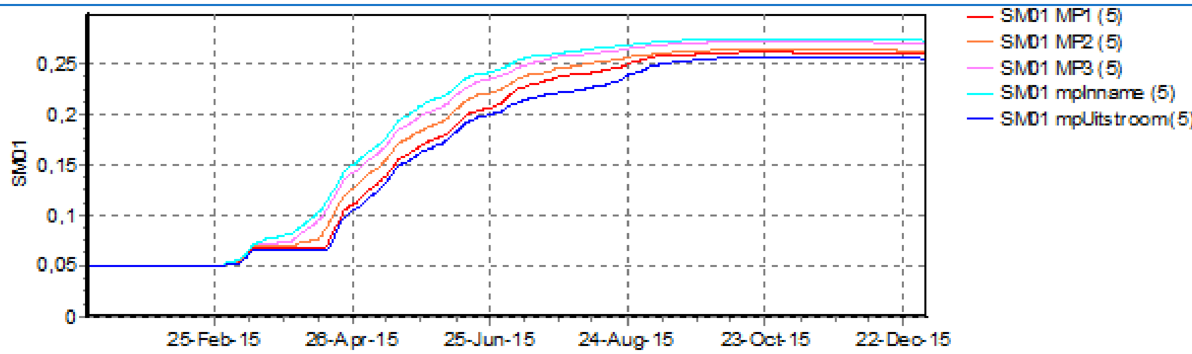


Figure 4.32 Elodea Nuttallii mass (g) - with -10 ΔT°C

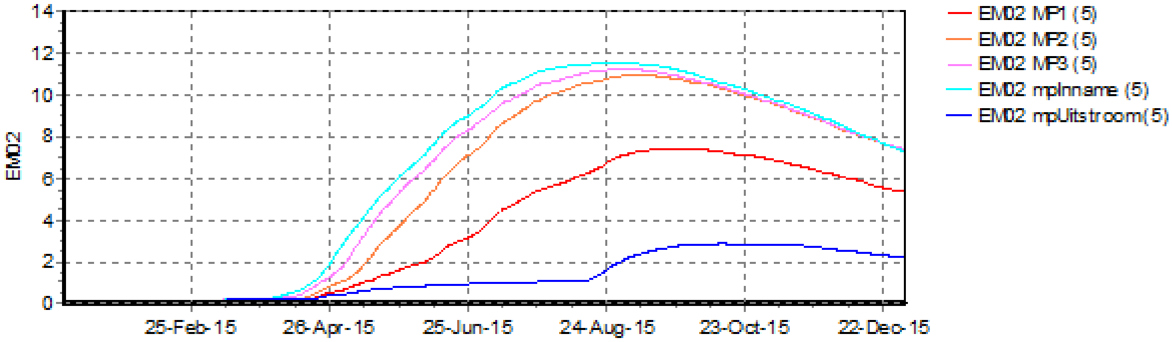


Figure 4.33 Duckweed mass (g) - with -10 ΔT°C

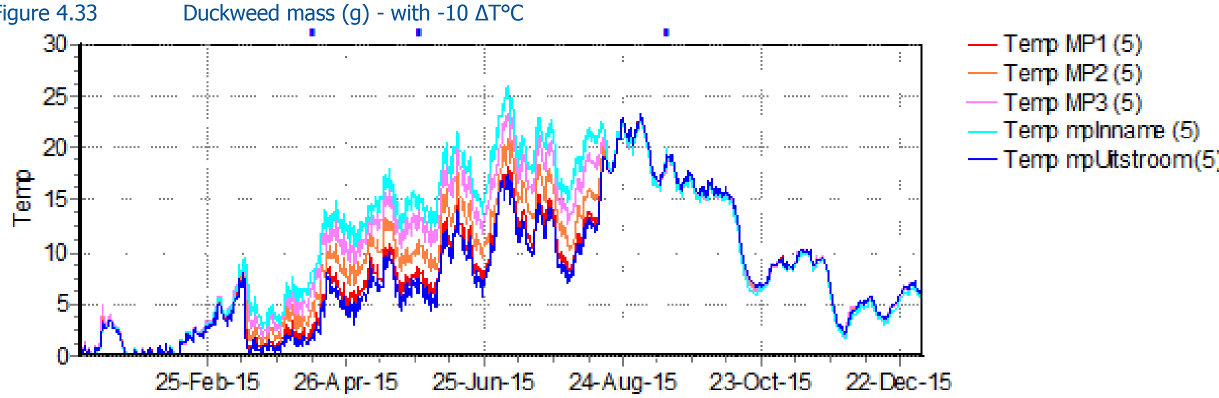


Figure 4.34 Water temperature (°C) with - 10ΔT°C

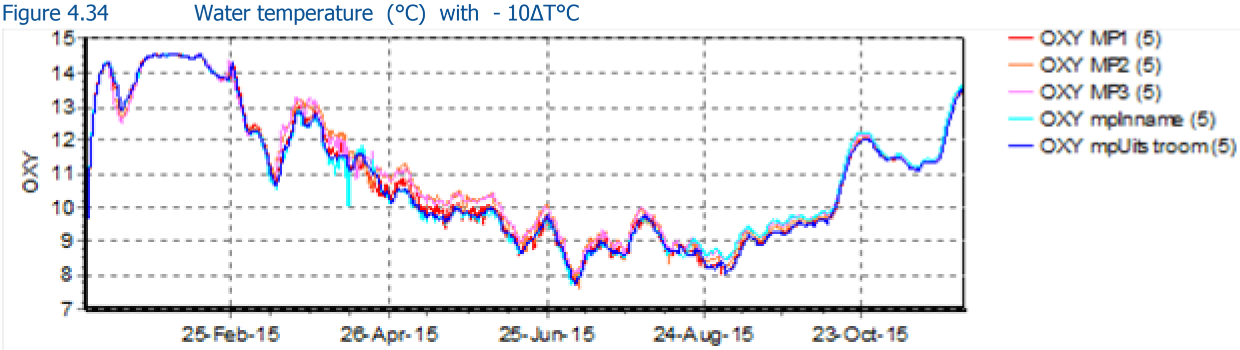


Figure 4.35 Oxygen (mg/l) with -10 ΔT°C

4.2.4 DISCUSSION

A theoretical review of two macrophyte species growth and temperature relationship was undertaken. Although *Elodea Nuttallii* was a prevalent species with significant research available, limited information on the species temperature dependency was available. In contrast, Duckweed species was found to have a considerable amount of information on temperature dependency, owing to Duckweed being lucrative as a relatively new water treatment method. The growth temperature curve, Figure 4.10, presents the influences of temperature on Duckweed growth. Since the growth is also dependent on other factors, such as nutrients and radiation, modelling of the two studied macrophytes was undertaken to further explore the potential effect of cool water and to predict effects with a cooler temperature difference.

Modelling was carried out using Delft3D, D-Water Quality and D-Ecology (DELWAQ). The channel temperature and water quality was modelled as a closed system, with circulation due to cold water discharge. The measured temperature difference between MP 1 and MP 4 was approximately 5 °C difference, Figure 3.22, similar to the modelled results, see Figure 4.19. The water temperature near the intake would be influenced by water temperatures in the adjacent waterway since they are connected, not a closed boundary. Overall, the modelled water temperature at Hoog Dalem was considered to be a realistic and reasonable basis for modelling the aquatic plants.

The Delwaq model needs some spin-up time, as can be observed in January, Figure 4.20 to Figure 4.35, spin up time can be further reduced by running the model for a long enough duration to reach a system equilibrium and subsequent suitable inputs or by further iterations[20].

> *Can a model demonstrate a realistic relationship between -ΔTºC and DO and macrophytes? and*
>
> *Can a model be developed to predict spatial temperature distribution and associated effect on macrophytes with higher -ΔTºC?*

Case study measured DO typically ranged from 5 to 12 mg/l, Figure 7.57, modelling DO ranged from 8 to 15 mg/l, see Figure 4.23, Figure 4.27, Figure 4.31 and Figure 4.35. The modelled DO did not reflect the very higher or very low values, such as the very low concentrations measured during field campaigns, see Figure 7.27, Figure 7.28 and Figure 7.29, adjustments of model inputs could improve on this. There was minimal difference in DO between the outlet and the intake Scenario 3 and 4, which made it difficult to observe the effect of cool water on DO based on a model. From this it can be considered that modelled DO reflects reasonably well the seasonal variation observed at the site and further modification of this model would be required to improve the diurnal variation and effects from cool water discharge.

Temperature profiles for Scenario 3 and 4 confirm the outlet was cooler than the intake during modelled cool water discharge, Figure 4.30 and Figure 4.34.

In general, modelled growth for SM01 was much lower compared to EM02, this is associated with growth inputs and nutrients considerations, further development of these inputs could improve on this, such as further consideration of growth and decompositions rates and nutrient settings and inputs. Scenario 1 aquatic plant growth for all observation points was similar, Figure 4.20 and Figure 4.21. While Scenario 2

[20] Based on advice from Tineke Troost.

showed higher Duckweed growth near the outlet, Figure 4.25, the reason for this higher plant growth was not clear, nutrients and DO were verified as being similar through the channel. Modelling without cool water and modelling without cool water and discharge provided a basis to compare to two cool water scenarios. Scenario 3 and 4 showed that aquatic plant growth closest to cool water discharge was reduced compared to MP 4, Figure 4.32, Figure 4.33, Figure 4.29 and Figure 4.28. Scenario 4 model was developed to discharge even cooler water during biological spring. Cooler water during the most vulnerable growth time of the year, Figure 4.34, illustrated severely reduced growth closest to the discharge point, see Figure 4.33.

Further calibration and verification of Scenario 3 would be required to support the accuracy of Scenario 4, more extensive ecology surveys would be necessary to support this. Regarding a completely realistic relationship, for this type of study site with higher species abundance, modelling of individual species would not replace the need for field ecology surveys to assess cool water effects. Further calibration and verification of Scenario 3 would be required to support the accuracy of using the model to predict effects. Further, development of this model set-up could improve, to at limited extent, the realism of the results presented.

4.2.4.1 SUMMARY

The modelled water quality results compared well to the measurements at Hoog Dalem, such as DO increasing during biological spring, decreasing during summer and increasing towards the end of autumn. The relationships appear to be reasonable based on theory discussed in Chapter 2. Aquatic plant growth was mainly similar for Scenarios 1 and 2, and observed growth was reduced based on results from Scenario 3 and 4. Further developing the model could more accurately represent the case study data, such as improving DO.

In summary, comparisons between Scenarios 1 to 4 provide insight into the potential effects of cool water discharge. Modelling potential is limited by a combination of factors such as the availability of theoretical data, time involved to develop an accurate model and modelling capabilities. Further, the modelled growth of aquatic plants is limited by not taking into consideration competing species, being dependent on the results from the water quality modelling and wind is excluded.

5 DISCUSSION

Chapter 5 discusses general outcomes based on Chapters 2, 3 and 4

This research and analysis has been built combining theoretical literature and collected data, by a targeted case study site, literature study and the development of a theoretical model.

Seasonal changes affect water quality, water plants growth increase during biological spring, establish during summer then decompose in autumn, so that in winter plant biomass is minimal. When plants grow their photosynthesis increases oxygen available in the water, creating an ecological environment conducive to growth of plants and organisms. Toward the end of autumn plant decomposition consumes a significant amount of available oxygen, too much consumption may decline health and numbers of fish and other desirable species.

The magnitude of the negative effects of artificial cooling is dependent on timing. Cooling during biological spring can impede the establishment of aquatic plants and impact fish and other organisms during sensitive breeding stages. The study timing was considered to be optimum in terms of minimising impact on the aquatic ecosystem, operating outside of the most temperature sensitive periods of the year. Study of the ramifications of cooler water discharge, such as 10 °C temperature differences during biological spring may provide further insights into effects on water quality and aquatic ecosystems.

It would be interesting to study cool water discharge effects on aquatic ecosystem and water quality in an established waterway to evaluate the extent to which this study's observations have been influenced by a) the site being an establishing system, b) natural variations within that system, and c) climatic and yearly variations. Further, undertaking ecology surveys at the same time as water quality measurements would improve the likelihood of identifying relationships between water quality and the aquatic ecosystem.

Nuisance plant growth is more sensitive to temperature variation than nutrients, which indicates that cooling the water could positively influence a waterways ecosystem (ANZECC, 2000, pp. 8.2-20). Creating conditions less beneficial for undesirable species could benefit desirable species by reducing shading and competition, understanding of successful growth factors for desired species would be required. In Dutch waterways, undesirable aquatic plants are frequently managed by manual harvesting. This process disturbs the waterway ecosystem and water quality, and regrowth is rapid (Scheffer, 1998, p. 305). Cooling the water has potential to be a less invasive method for managing undesirable species. Aquatic plants have memory effects and the system does not re-set each winter, which means that aquatic plants that were established before winter emerge in spring (Scheffer, 1998). This memory effect was supported by the case study ecological observations, dominant species were observed to remain dominant in successive years.

Therefore, cool water discharge could be beneficially incorporated into planning newly constructed waterways supporting the growth of positive aquatic plant diversity by initially creating a less welcoming environment for undesirable species. If the water temperature results in improved growth of desirable plant life, desirable fish and macroinvertebrate are likely to be more abundant. In the cool water discharge system studied, water temperature was considered recovered within 1.5 km. To cool all of a longer channel, multiple discharge points would be required. Cool water discharge could also be applied to mitigate negative thermal influences on established waterways, especially artificial waterways during extremely high temperatures where undesirable aquatic plant growth is exacerbated. A summary of some potential positive effects:

1. Delaying spring or summer
    a. Mitigating unseasonal growth patterns due to warmer temperatures
2. Summer suppression
    a. Mitigating undesirable consequences from extreme warm weather events
    b. Cooling of water during very warm days, timing of cold water release and temperature could be integrated to prevent excessive algal growth, increasing cooling during very warm days
3. Annual amplitude reduction
    a. Overall reduction in annual temperature to encourage or discourage establishment of certain species

Cold water pollution creates an anthropogenic change to a water body. This has the potential to negatively impact water quality and aquatic ecosystems. Effects of artificially cooling surface water include slowing the growth of aquatic ecology. There was insufficient information on growth temperature relationships for desirable species observed at the study site. Therefore, predicting the effect of cool water discharge on desirable species present at the study site was not undertaken. Literature strongly indicates that undesirable species react more rapidly to temperature variation than desirable species. It is therefore likely that precluding growth of undesirable species has secondary benefits to the desirable species by reducing competition.

The case study was extended by modelling theoretical effects of cool water on two undesirable water plants, undertaken with a water temperature, flow, water quality and ecology model. Given the wide diversity in species present at the case study, purely assessing the effect of cool water discharge on aquatic plants with a model would not sufficiently capture the vast variations that occur in nature. Modelling could be beneficial for planning of new cool water discharge sites, especially where key sensitive desirable species require no negative effect from the regime, sufficient theoretical data is needed to achieve this. Conversely, where there are existing issues caused by undesirable aquatic plants, macrophyte modelling could be utilised during the feasibility and planning stages to assess if cooling water could benefit, by impeding growth.

The macrophyte ecology model has been developed for use outside of Deltares, macrophyte modelling has been recently included in the Delwaq Technical Reference Manual and is understood to have been used for less than ten modelling exercises. Throughout the modelling exercise complications were encountered, such as the macrophyte manual contains misleading information. Further, based on the model being coupled to Delft3D-Flow, it was not possible to use the GUI for Delwaq. The macrophyte model is a very interesting model to work with, incorporating both water temperature and water quality, although applying it to the case study was an extensive exercise.

Based on research literature and previous studies, fish were found to be an indicator of overall waterway health, and the impact of thermal regimes on receiving waterways. Given the importance of fish when considering the effects of a change in thermal regime, it was considered necessary to incorporate fish into the study. Artificially reducing the temperature of a fish’s native environment can lead to reduced reproduction processes, fewer eggs laid, smaller fish sizes and less abundance in the area. The cool water discharge studied is not expected to have a significant effect on fish in the waterway, considering magnitude of flow, timing and the type of waterway.

6 CONCLUSION

Chapter 6 concludes the study by summarising answers to the research questions, addressing the main research topic and presents recommendations

This was the first study on the effect of artificial cool water discharge to a shallow freshwater body within The Netherlands. The objective was to investigate the environmental effects of cooling shallow surface water based on a case study site and to draw conclusions on the magnitude of the effect with an outlook of assisting future forming of guidelines and regulation. The objectives were achieved by providing insight, based on a case study site, literature study and the development of a theoretical model. The case study investigation procedure was a combination of an experimental and theoretical approach.

The main engineering problem addressed:

– Environmental *effects* of *artificially* cooling shallow surface water

Secondary problem addressed:

– *Structure* the results of the first section in an investigation *methodology that is in line with suitable guidance*

The theory of water quality and ecology effects from modifying water temperature was explored. Water quality and aquatic ecosystems were found to be highly influenced by seasonal and diurnal variation. The investigation was structured in a methodology relevant to existing and suitable water temperature guidance, to contribute to future development of guidelines and regulation for cold water discharge. The research project advanced the understanding of effects of cold water discharge pollution in the Netherlands. The main issues focussed on were:

a) Research and investigation of current and relevant guidelines and requirements
b) Defining the cool water discharge regime
c) Impact of cool water on receiving water body temperature
d) Impact of cold water discharge on the aquatic environment
e) Impact of cold water discharge on water quality

Overall, enhancement of ecosystems is considered a likely outcome of this specific cold water inflow, for similar waterway types. The following summarises answers to the study sub questions.

1. What relevant guidelines and frameworks are currently available?

Firstly current guidelines relevant to waterways in The Netherlands, including EU and Dutch guidance were outlined. Current Dutch and EU guidelines for the studied waterway were not found to explicitly outline methods for assessing and managing cold water pollution, therefore international guidelines that addressed cold water pollution were researched. Guidelines and recommendations for assessing cool water effects were explored, relevant guidelines are summarised on the next page.

1. Relevant guidelines and regulations for Dutch waterway water quality
    I. European Water Framework Directive (EWFD), European Union (EU)
    II. Stichting Toegepast Onderzoek Waterbeheer[21] (STOWA), The Netherlands
2. Dutch guidelines for warm water discharge
    I. Rijkswaterstaat. (2004). CIW beoordelingssystematiek warmtelozingen. Rijkswaterstaat
3. International guidelines that address modifying the thermal regime to a waterway
    I. National Water Quality Management Strategy. (2000). Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Environment and Conservation Council (ANZECC). Artarom NSW 2064: Environment Australia.

Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC Guidelines) were found to outline methods and recommendations for managing and assessing effects of modifying a thermal regime on a natural waterway, without being specific about unique aspects associated with geographic location and climate. Findings from the studied international guidelines supported the methodology for assessing the effect of cool water discharge for the case study site.

The Netherlands has defined and developed metrics for each type of water body in accordance with EWFD requirements, which is to achieve Good Ecological Potential (GEP). To give broader context to the investigation, water quality and ecological observations were compared to the STOWA indicator metrics for the related water body type, M1A, and to evaluate if cold water discharge prevented the waterway from achieving its status objective, GEP. This was an implicit approach to assess the effect of cold water pollution in line with current guidelines.

2. What does the case study data available indicate?

The pilot ATES cool water discharge system typically operated from May to September with a 5 °C median temperature difference and a 100 m^3/hr flow rate. A cooler temperature difference of 7 °C is preferred for improved system efficiency, though the permit granted was for 5 °C. The ATES system was operational in 2013, 2015 and 2016. Cooler water was discharged to a 2.5 to 10m wide, 1 to 1.5 m deep, 1.5 km long artificial freshwater channel, constructed between 2010 and 2012. Water quality and ecological data was collected for the site from 2012 to 2016, excluding 2014 due to operational issues.

The water quality data available for the study site was in agreement with the frequency and duration of data collection recommended by the ANZECC guidelines, in order to assess artificially modifying the thermal regime of a water body. Ecology observations were taken at a much lower frequency, twice per year. Water quality observations generally indicated positive for the type of waterway and met with GEP most of the time, although ecology observations generally did not meet with GEP. As the waterway was constructed shortly before observations commenced, it is possible the ecological indicators did not meet GEP due to ecosystems being in the process of developing. This view is supported by 2016 water plant observations displaying a higher diversity in species than in previous years'.

Potential effects from cold water discharge are largely dependent on the type of cold water discharge, extent of temperature variation, including frequency and timing, the climate and type of receiving water body. Both negative and positive effects on water quality and aquatic ecosystem associated with discharging cool water at the study site were identified. The study confirmed that ecosystem triggers and water quality processes dependent on seasonal, diurnal and other natural temperature variations are key

[21] Dutch Foundation for Applied Water Research

indicators determining the effect of cold water discharge on a water body. Based on assessing the data collected at site, overall enhancement of water quality and ecological indicators is considered a likely outcome of this specific cold water inflow.

a. Is there a strong relationship between water quality observations and -ΔTºC?

To observe the influence of cold water discharge on water quality, observations during discharge was compared to when there was no discharge and observations closest to cool water discharge were compared to observations further from the discharge. Where there was no cool water discharge, the temperature during water quality measurements at each observation point was similar. The median water temperature was cooler closer to cool water discharge, increasing with distance from the discharge point. These observations demonstrated the effect of cool water discharge was represented in the water quality data collected at the site. Overall, the natural variation in water quality and the aquatic ecosystem was found to have a much more significant influence on the waterway studied than the operational cool water discharge.

Water quality was found to be greatly influenced by seasonal and diurnal variation as well as location or locations along the waterway of operational cool water discharge. Cool water discharge effects on water quality was most strongly associated with parameters influenced by respiration and photosynthesis, including oxygen, pH and chlorophyll-a. Cool water discharge increased flow in the channel, this increase in flow weakly influenced water quality parameters that are linked with retention time. It was interesting that while the cool water discharge temperature difference was actually relatively low, minor changes in water quality along the channel could still be observed. Sampling dissolved oxygen, an important water quality indicator, along the channel revealed relatively similar results without cold water discharge being present, during operation the concentration essentially decreased at the point closest to the discharge.

b. Is there a strong relationship between ecology surveys and -ΔTºC?

Undesirable aquatic plants were widespread compared with the extant of desirable plants. Although ecology surveys have been undertaken twice a year since construction of the channel, it has not been possible to draw a strong relationship between ecology surveys and cool water discharge. This is likely attributed to the aquatic ecosystem being in the establishment phase, in the newly constructed channel, pioneer species that populate new environments quickly were dominant. Further, since the water temperature was lowered from late spring into summer, based on literature, it is not anticipated that the cold water discharge would significant affect already established macrophyte.

3. Can a model demonstrate a realistic relationship between -ΔTºC, DO and macrophytes? and

Four Delft3D-Flow and Delwaq model scenarios were developed, summarised below.

- Scenario 1: *'base case'*
- Scenario 2: *'base case no Q'*
- Scenario 3: *'actual'*
- Scenario 4: *'predict - ΔT 10 °C'*

Modelled DO reflected well the seasonal variation observed based on case study data, although very high or very low values observed onsite were not reflected in the model. Along the channel during cool water discharge there was minimal difference in modelled DO. Modelled aquatic plant growth was further reduced closer to the cool water discharge outlet, based on Scenario 3 compared with Scenario 1. The model developed could successfully show that cool water discharge slows the growth of two aquatic plants.

Modelling capability was limited by a number of factors, such as being dependent on theoretical data, found to be limited and varying between studies. Further development of this model set-up could improve, to at limited extent, the realism of the results presented. Regarding a completely realistic relationship, for this type of study site with high species abundance, modelling of individual species would not replace the need for field ecology surveys to assess cool water effects.

> *4. Can a model be developed to predict spatial temperature distribution and associated effect on macrophytes with higher -ΔTºC?*

To predict the effects from a cooler temperature difference, a -10 °C temperate difference model was developed with cooling during biological spring. This model resulted in severely reduced growth closest to the discharge point, especially compared to Scenario 3. This demonstrates that the model can be developed for prediction scenarios and even cooler water further slows the growth of the modelled aquatic plants. Further calibration and verification of Scenario 3 would be required to support the accuracy of using the model to predict effects.

6.1 RECOMMENDATIONS

Carrying out water quality sampling at the same of the day throughout the year would reduce the impact of diurnal variation on the data, this would improve the ability to attribute effects when assessing the data. Measuring water quality more frequently during cold water discharge would also benefit observing effects and drawing relationships.

The macrophyte model was a very interesting model to use, incorporating water temperature and water quality. However, higher frequency of ecology surveys would contribute more to understanding cool water effects on the aquatic ecosystem than modelling. This opinion takes into consideration the amount of input data required, availability of the data and the time to develop the model. Further, undertaking ecology surveys at the same time as water quality measurements would improve the likelihood of identifying relationships between water quality and the aquatic ecosystem.

It would be interesting to explore the potential of ATES influence on species composition in waterways and the capability to mitigate global warming and / or urban heat island effects on water temperature.

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7 APPENDICIES

APPENDIX I – SIT LOCATION AND LAYOUT MAP

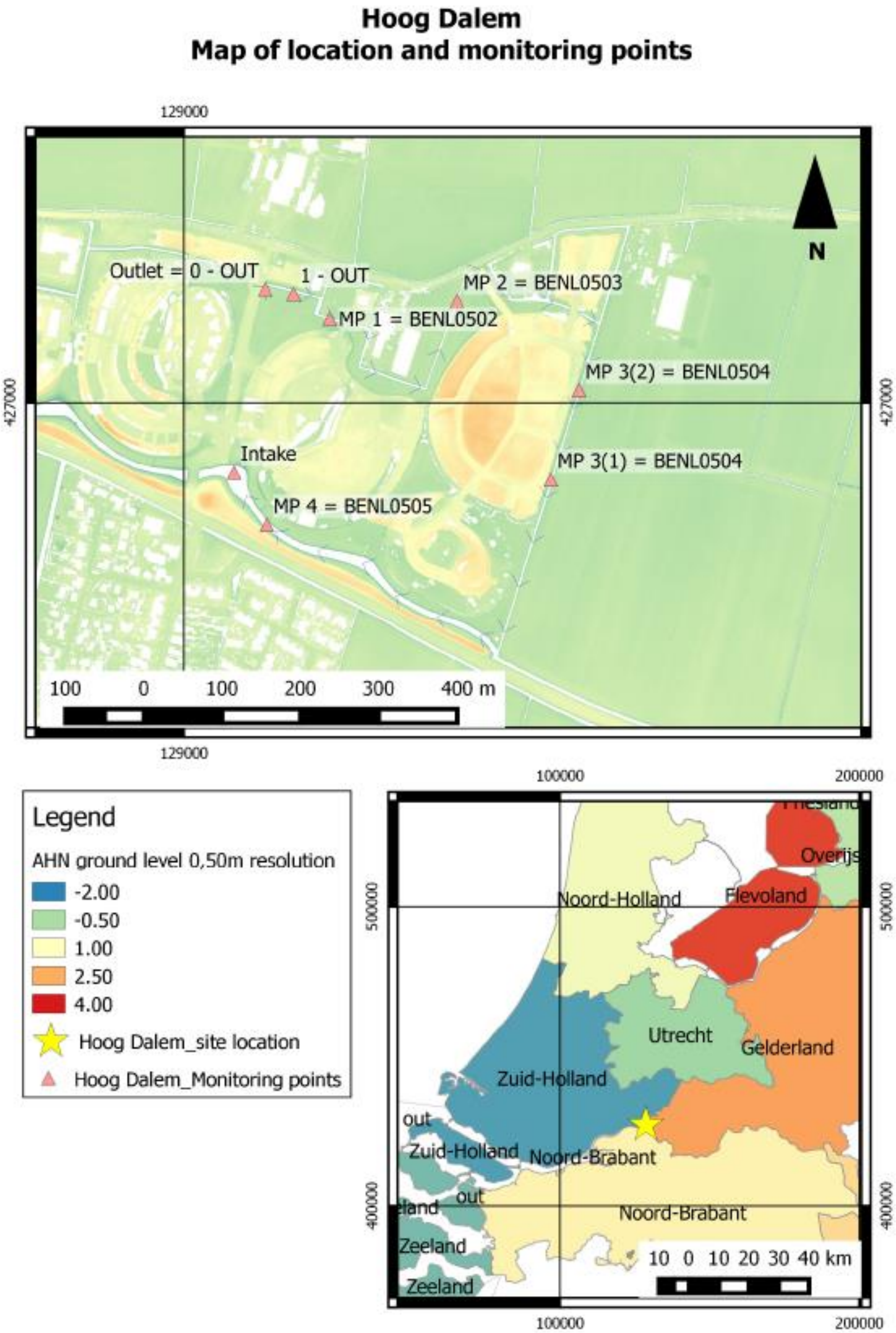
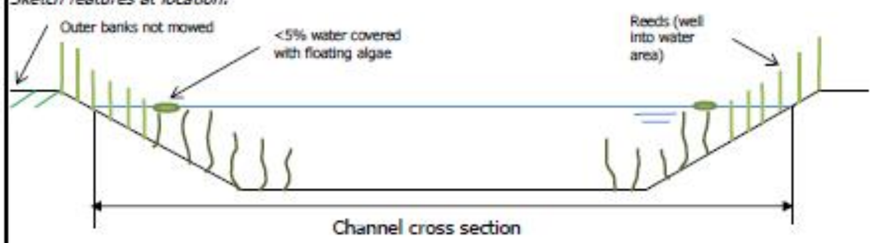


Figure 7.1Hoog Dalem site location and layout

Site:	Hoog Dalem	Date:	19-08-16
Location:	Discharge	Time start (hh:mm):	18:00
Weather conditions:	Warm day, light rain, cloudy		

Sketch features at location:



Describe surrounds

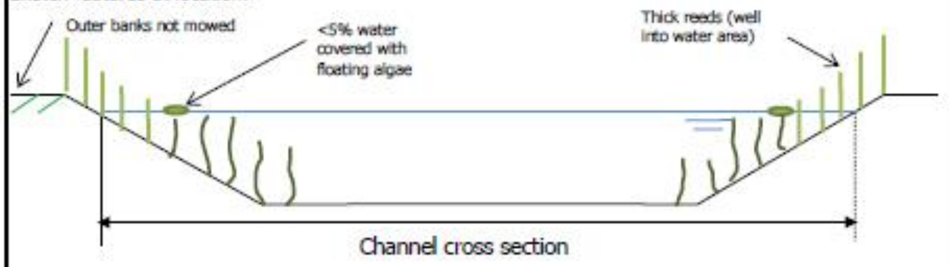
— Water appeared quite stagnant
— Flop not present
— Could feel cold water discharge
— Thick reeds on banks up to water line, less than at the intake
— Channel is narrower than intake, 504 and 505
— Channel is quite narrow compared to height of reeds (~2m) and shaded from the reeds

Aquatic vegetation		**Water observation**	
Rooted emergent	Some on banks	Odor	Normal
Rooted submergent	Some rooted submerged (possibly Elodea nuttallii)	Clarity (could substrate be seen)	Less algae, but water is very dark
Rooted floating	Some present	Water surface oils (slick, sheen, flecks, none)	No visible surface oils
Free floating			
Floating Algae	Minimal amount		
Attached Algae			
Dominant species present	Algae		

Substrate type: not visible at the monitoring sites.

Site:	Hoog Dalem	Date:	19-08-16
Location:	Point 502	Time start (hh:mm):	18:15
Weather conditions:	Warm day, light rain, cloudy		

Sketch features at location:



Describe surrounds

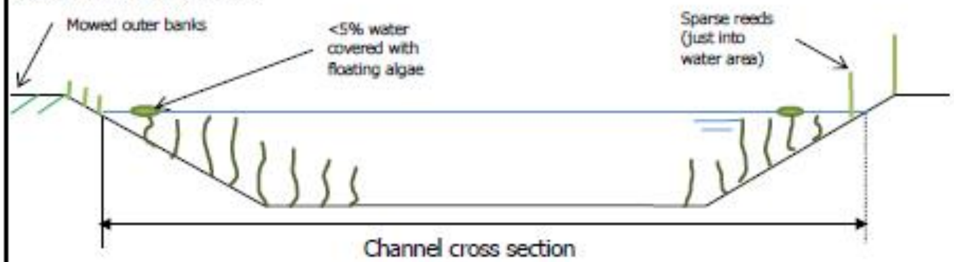
- Water appeared quite stagnant
- Thick reeds on banks up to water line, less than at the intake
- Channel is narrower than intake, 504 and 505
- Channel is quite narrow compared to height of reeds (~2m) and shaded from the reeds
- Lower trees located on the north side of the channel

Aquatic vegetation		Water observation	
Rooted emergent		Odor	Normal
Rooted submergent	Mostly rooted submerged (possibly Elodea nuttallii)	Clarity (could substrate be seen)	Less algae, but water is very dark
Rooted floating		Water surface oils (slick, sheen, flecks, none)	No visible surface oils
Free floating	Minimal amount		
Floating Algae			
Attached Algae	Minimal amount		
Dominant species present	Algae		

Substrate type: not visible at the monitoring sites.

Site:	Hoog Dalem	Date:	19-08-16
Location:	Point 503	Time start (hh:mm):	17:45
Weather conditions:	Warm day, light rain, cloudy		

Sketch features at location:



Describe surrounds

— Water appeared quite stagnant
— Constriction in channel upstream due to combination of a culvert and prominant growth of reeds upstream and downstream of culvert
— Few reeds on banks, just up to water line, less than at the intake
— Channel is narrower than intake, 504 and 505
— Water is quite dark, reduced visibility

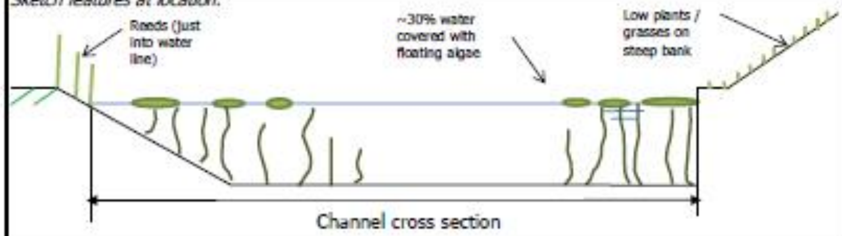


Aquatic vegetation		Water observation	
Rooted emergent		Odor	Normal
Rooted submergent	Mostly rooted submerged (possibly Elodea nuttallii)	Clarity (could substrate be seen)	Less algae, but much darker
Rooted floating		Water surface oils (slick, sheen, flecks, none)	No visible surface oils
Free floating	Minimal amount		
Floating Algae			
Attached Algae	Minimal amount		
Dominant species present	Algae		

Substrate type: not visible at the monitoring sites.

Site:	Hoog Dalem	Date:	19-08-16
Location:	Point 504	Time start (hh:mm):	17:30
Weather conditions:	Warm day, light rain, cloudy		

Sketch features at location:



Describe surrounds

- Wider waterway section
- Inner bank is verticle and does not have reeds present
- Many small fishes (2-3cm long) observed
- Water appeared quite stagnant
- Considerably less algae than at 505, imporved visual clarity downstream of 505
- Thick reeds on banks into water, not as much as the intake
- Area is 'more open' / straight section
- Upstream and downstream of the measuring point there is less algae cover
- 504 section widens compared to 505:

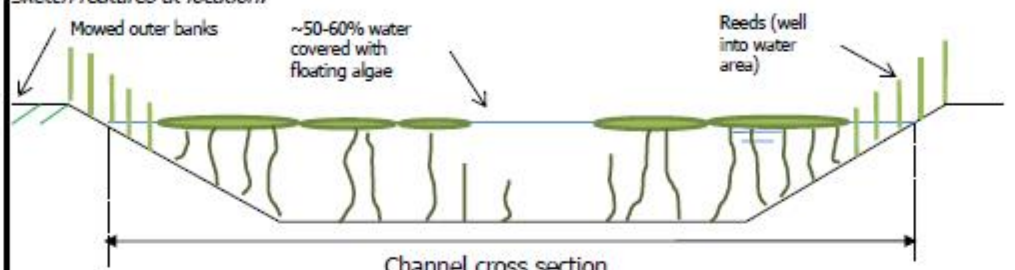
Aquatic vegetation		**Water observation**	
Rooted emergent	Close to banks	Odor	Manure smell
Rooted submergent	Lots (possibly Elodea nuttallii)	Clarity (could substrate be seen)	Clearer than other locations, not able to view substrate (~15m downstream observed sand)
Rooted floating	-	Water surface oils (slick, sheen, flecks, none)	No visible surface oils
Free floating	Minimal amount		
Floating Algae	Some floating		
Attached Algae	Mostly attached		
Dominant species present	Algae		

Substrate type: not visible at the monitoring sites.

Fieldsheet: Hoog Dalem channel observation

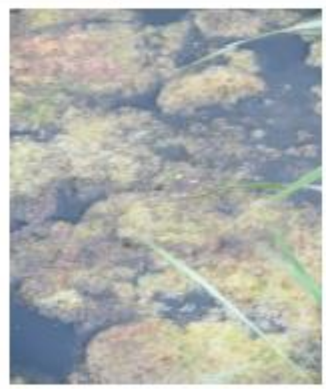
Site:	Hoog Dalem	Date:	19-08-16
Location:	Point 505	Time start (hh:mm):	17:15
Weather conditions:		Warm day, light rain, cloudy	

Sketch features at location:



Describe surrounds

- Water appeared quite stagnant
- Considerable amount of algae
- Thick reeds on banks into water, not as much as the intake
- Area is 'more open' / straight section
- Upstream and downstram of the measuring point there is less algae cover



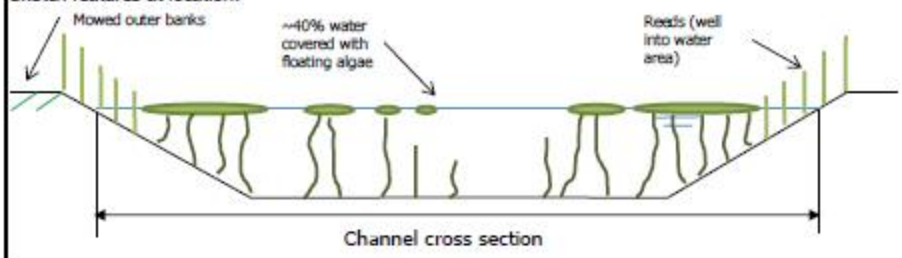
Aquatic vegetation		Water observation	
Rooted emergent		Odor	Strong manure smell
Rooted submergent	Could not see	Clarity (could substrate be seen)	Mostly covered in algae
Rooted floating	Could not see	Water surface oils (slick, sheen, flecks, none)	No visible surface oils
Free floating	Some towards centre waterway		
Floating Algae	Considerable amount floating		
Attached Algae			
Dominant species present	Algae		

Substrate type: not visible at the monitoring sites.

Fieldsheet: Hoog Dalem channel observation

Site:	Hoog Dalem	Date:	19-08-16
Location:	Intake	Time start (hh:mm):	17:00
Weather conditions:	Warm day, light rain, cloudy		

Sketch features at location:



Describe surrounds

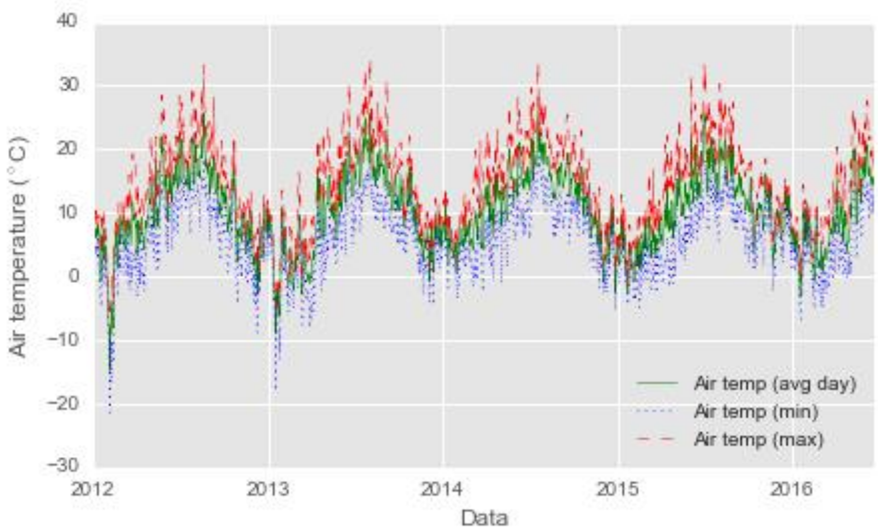
— Water appeared quite stagnant
— Considerable amount of algae
— Thick reeds on banks well into Water area

Aquatic vegetation		**Water observation**	
Rooted emergent		Odor	Normal -> no prominent odour
Rooted submergent	Present / under algae	Clarity (could substrate be seen)	Slightly turbid, could not see substrate
Rooted floating		Water surface oils (slick, sheen, flecks, none)	No visible surface oils
Free floating	Some towards centre waterway		
Floating Algae	Considerable amount floating		
Attached Algae	Mostly attached to water plants		
Dominant species present	Mostly algae		
Substrate type: not visible at the monitoring sites.			

APPENDIX III – AIR TEMPRATURE

At Hoog Dalem, data has been collected during 2012, 2013, 2015 and on-going for 2016. To give context to the years where data was collected, an overview of historic air temperature in The Netherlands has been carried out. The air temperature data was sourced from the Royal Dutch Meteorological Institute (KNMI), link: https://www.knmi.nl/kennis-en-datacentrum/achtergrond/centraal-nederland-temperatuur-cnt, accessed 12/08/2016. The temperature data is in a monthly time interval for the duration 1906 to 2016 (not complete). Daily air temperature at Herwijnen, also from KNMI, has been used to support the study, including for interpreting diver depths based on pressure.

The monthly air temperature is the mean of De Bilt, Winterswijk/Hupsel, Oudenbosch/Gilze-Rijen, Gemert/Volkel, Deelen, Eindhoven. This data set is considered applicable to Hoog Dalem given the site is located within the measuring stations used to develop the data set, Oudenbosch and De Bilt. The air temperature has been assessed based on year and month.



MONTHLY TEMPERATURE DISTRIBUTION

The median monthly air temperature was assessed to observe how the summer months, during cool water discharge, compare with the historic average summer temperatures. The next graph presents a box-plot of monthly air temperature based on 1906-2015, with monthly temperature for 2012, 2013, 2014 and 2015. As can be observed, most of the cold water discharges during summer months are located near or above historic median monthly temperature.

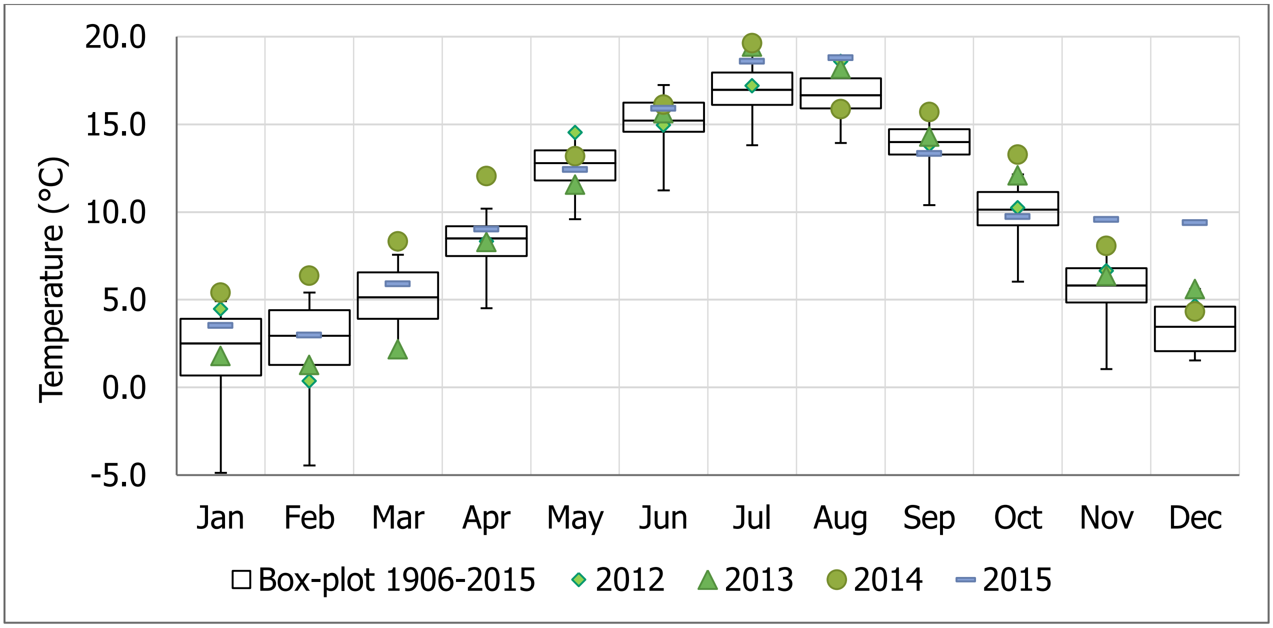


Figure 7.2Box Plot - Average Monthly Temperature 1906 – 2015

The below table presents average monthly air temperature for the years 2012, 2013 and 2015.

Table 7.1 Air temperature (°C) Hoog Dalem measurement year (2012, 2013, 2015)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2012	4,5	0,4	8,2	8,3	14,5	15,0	17,2	18,6	13,8	10,2	6,6	4,7
2013	1,8	1,3	2,2	8,3	11,6	15,6	19,4	18,2	14,3	12,1	6,3	5,6
2015	3,5	3,0	5,9	9,0	12,4	15,9	18,6	18,8	13,3	9,7	9,6	9,4

The next graph presents the deviation of the Hoog Dalem measurement year temperature from the mean of monthly average (1906-2015). July and August mean air temperatures were approximately 2°C warmer than the mean. While the June temperatures are closer to the mean and May and September show more variation about the mean.

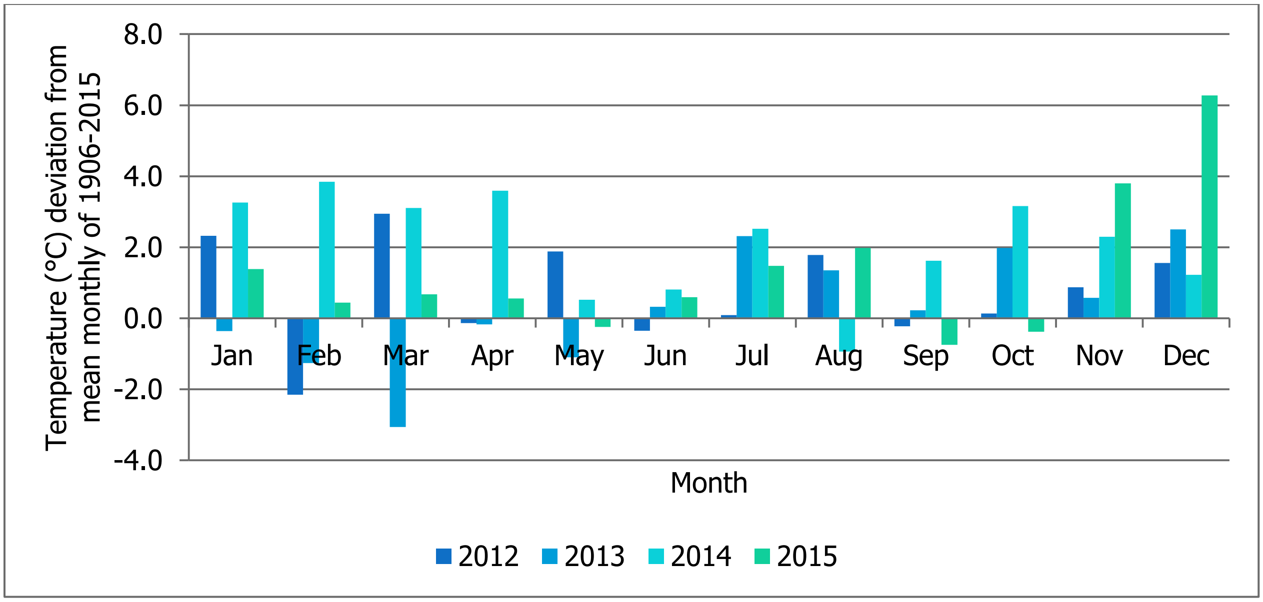


Figure 7.3Hoog Dalem measurement year temperature deviation from median of monthly average (1906-2015)

Years that experienced the warmest average monthly temperatures were 1997, 2003, 2006 and 2008, Table 7.2.

Table 7.2 Warmest monthly air temperature (°C)

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	-1,5	6,2	7,9	7,6	12,8	15,9	17,3	**20,4**	14,0	9,5	6,3	4,6
2003	2,2	1,6	7,4	9,9	13,5	**18,4**	18,9	19,5	14,4	7,3	7,9	3,8
2006	1,0	2,4	3,8	8,7	14,4	16,9	**22,6**	16,0	**17,8**	13,7	8,9	6,1
2008	6,1	4,9	5,7	8,6	**15,6**	16,4	17,9	17,3	13,4	9,7	6,5	2,1

ANNUAL TEMPERATURE DISTRIBUTION

Annual air temperature was assessed to observe how the years, during cool water discharge, compare with the historic average annual temperatures. It was observed, consistent with the monthly summer temperatures, that the annual average of the measurement years is higher than the historic average. Further, the average temperature for 2012 was similar to the historic average and 2014 was found to have the warmest annual average air temperature.

APPENDIX IV – ECOLOGY OBSERVATION DATA

MACROPHYTE SURVEYS

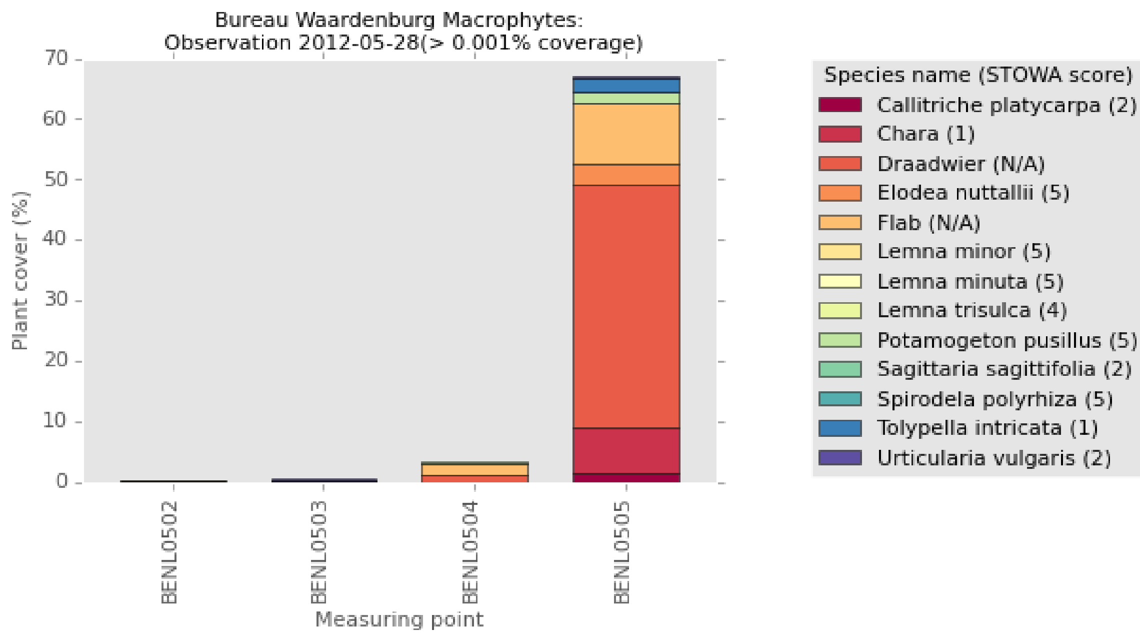


Figure 7.4Ecology – BwB – macrophyte observations – 28 May 2012

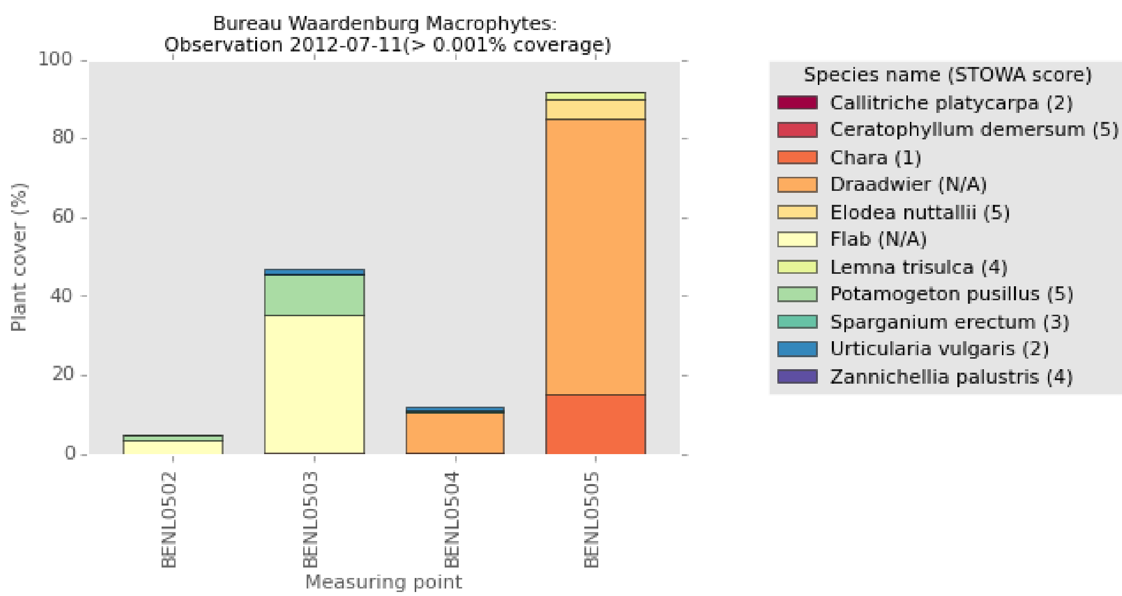


Figure 7.5Ecology – BwB – macrophyte observations – 11 July 2012

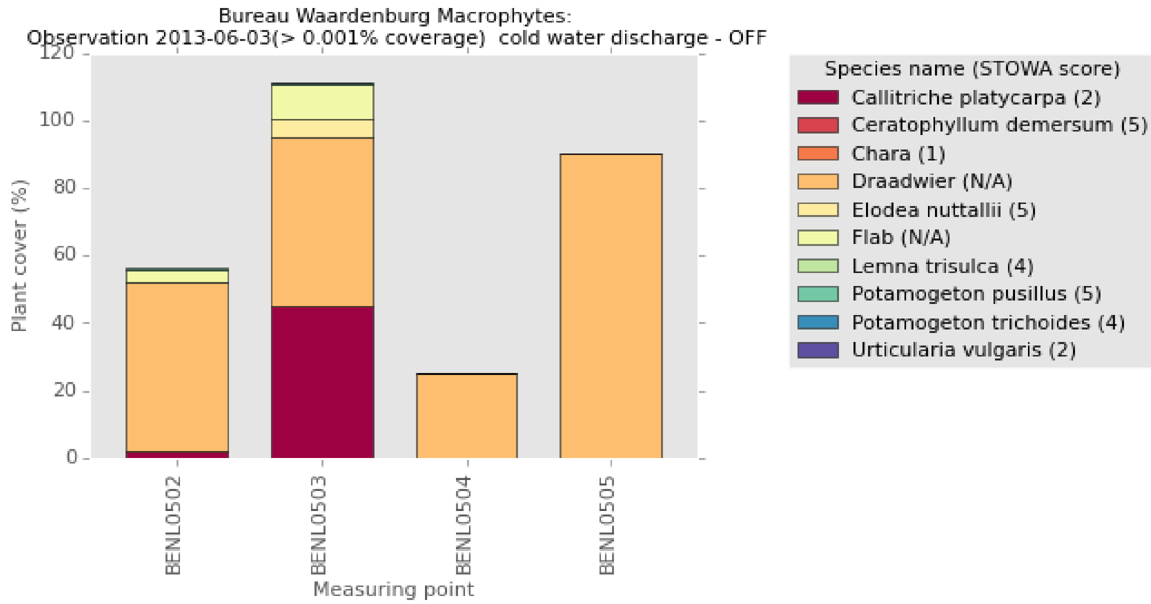


Figure 7.6Ecology – BwB – macrophyte observations – 3 June 2013

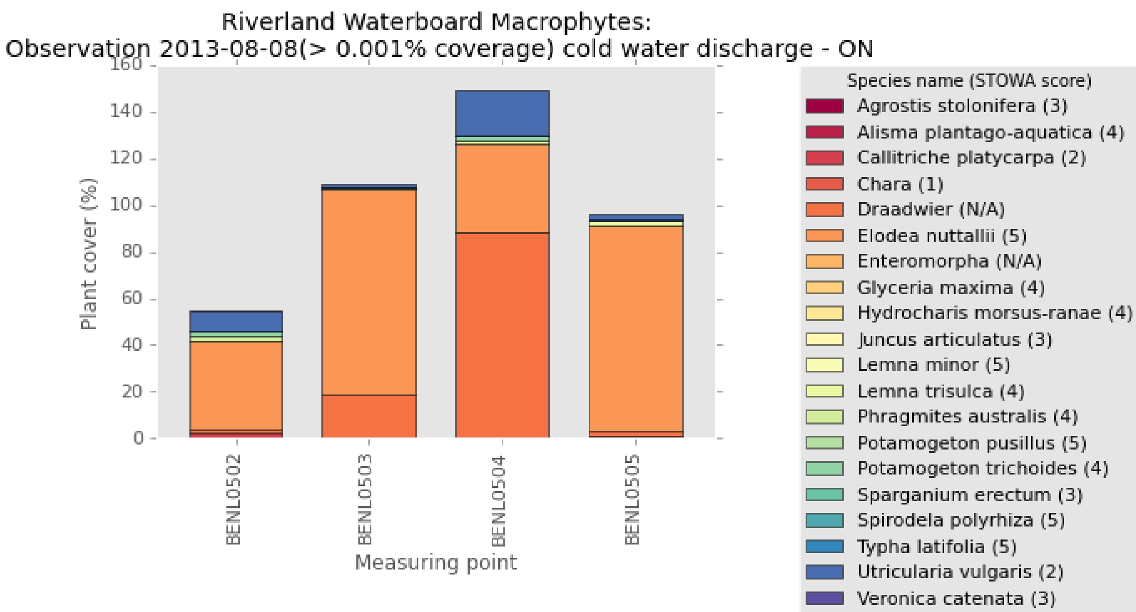


Figure 7.7Ecology – WSRL – macrophyte observations – 8 August 2013

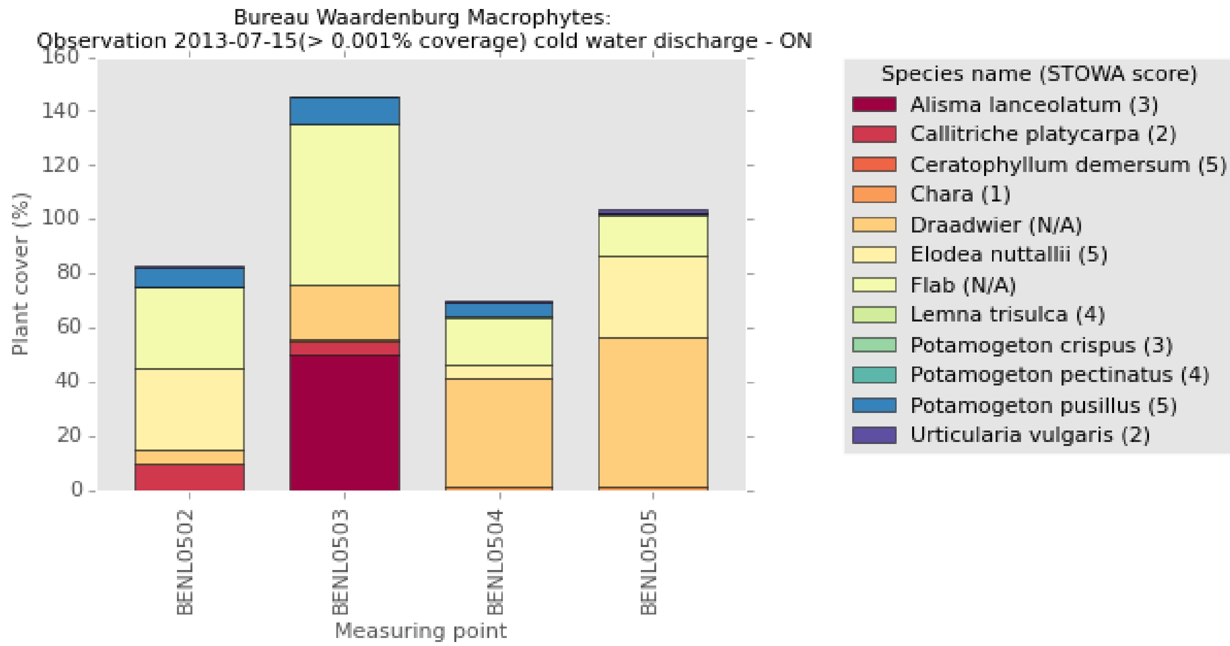


Figure 7.8Ecology – BwB – macrophyte observations – 15 July 2013

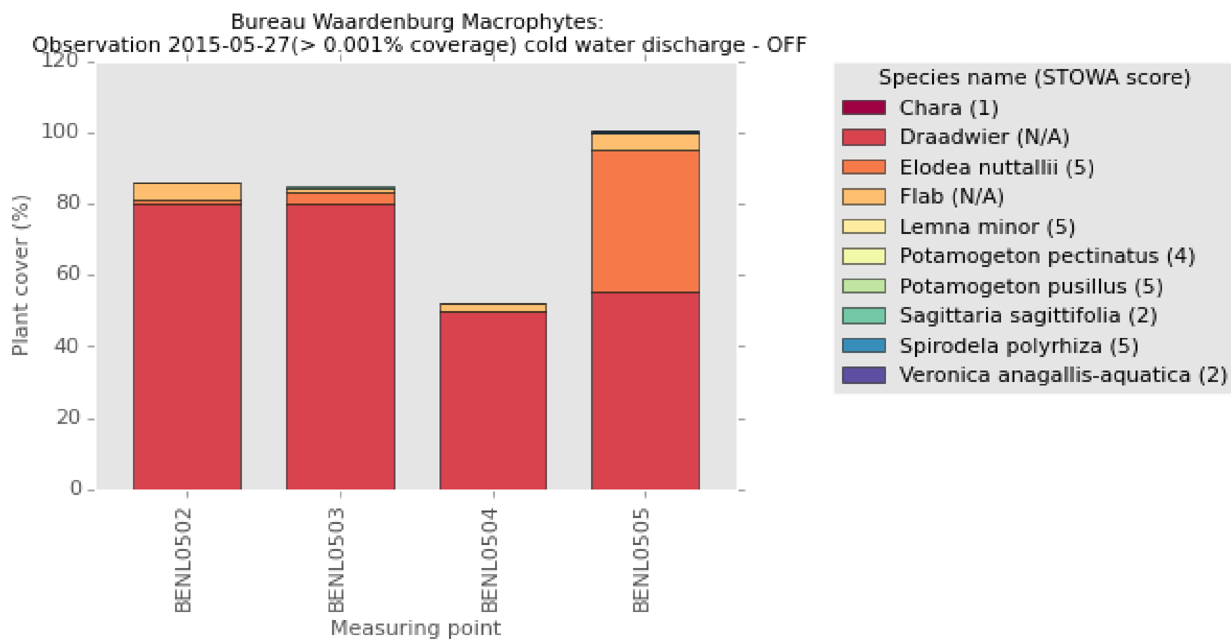


Figure 7.9Ecology – BwB – macrophyte observations – 27 May 2015

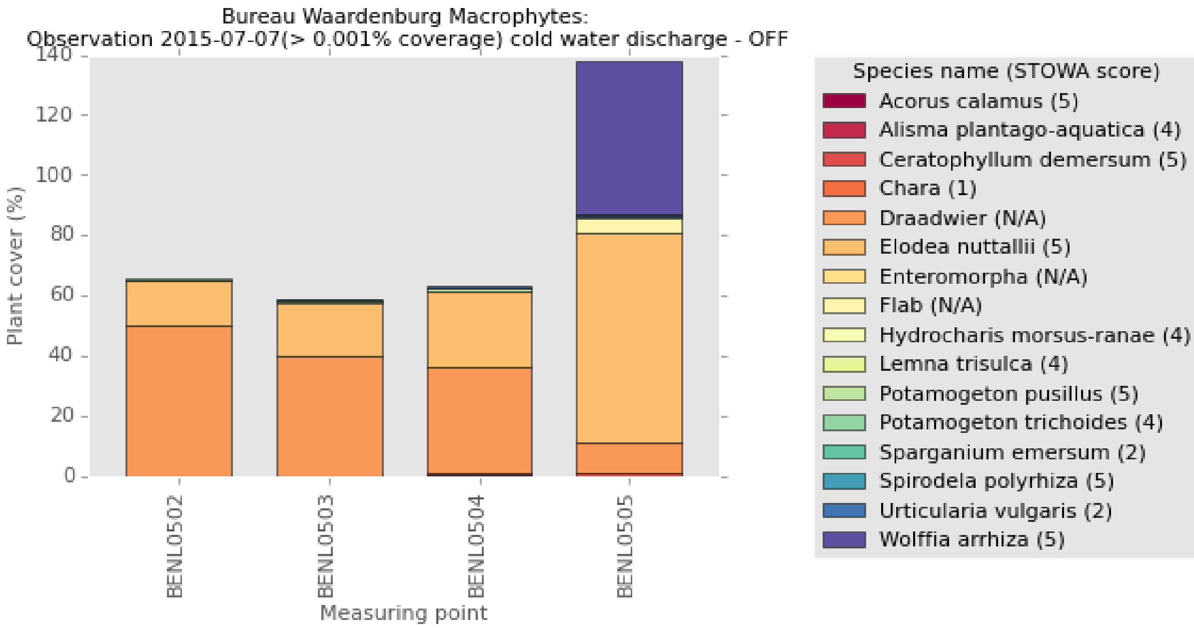


Figure 7.10 Ecology – BwB – macrophyte observations – 7 July 2015

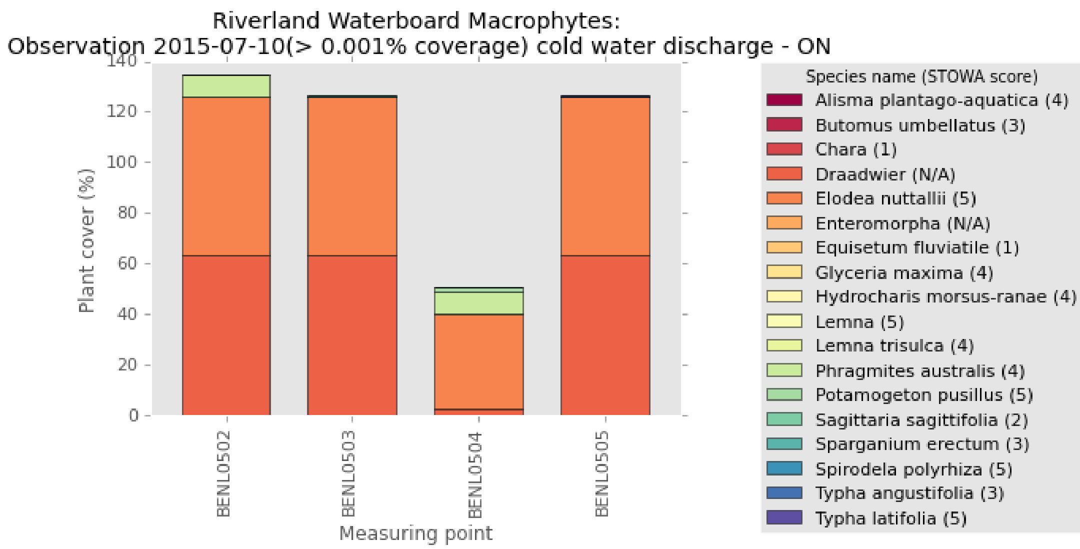


Figure 7.11 Ecology – WSRL – macrophyte observations – 10 July 2015

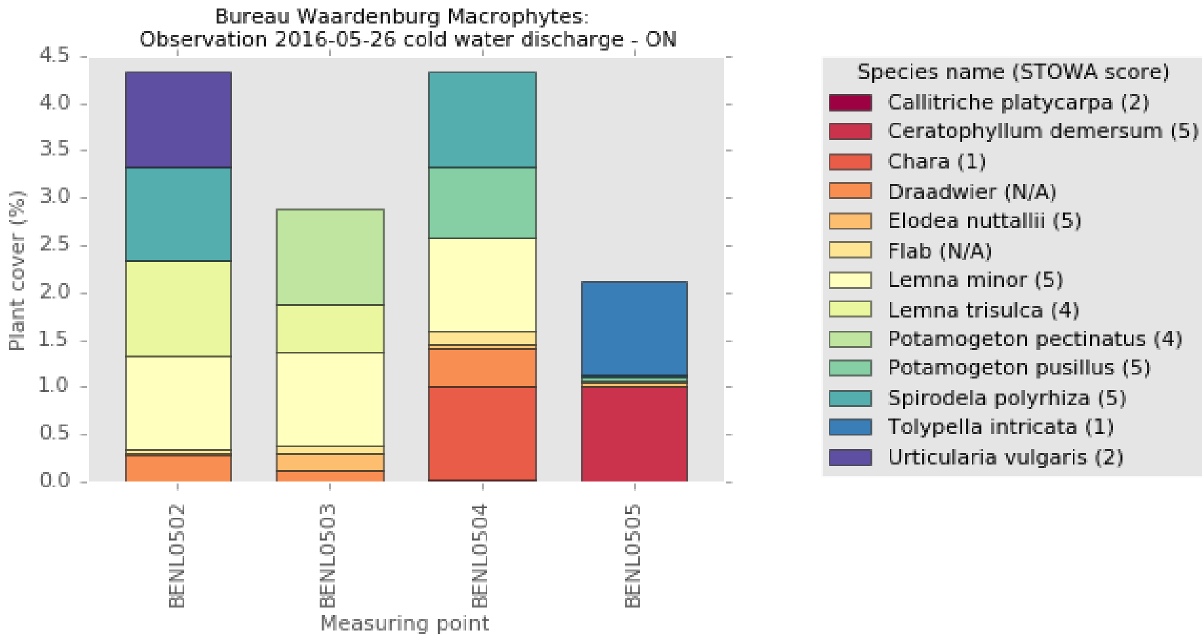


Figure 7.12 Ecology – BwB – macrophyte observations – 26 May 2016

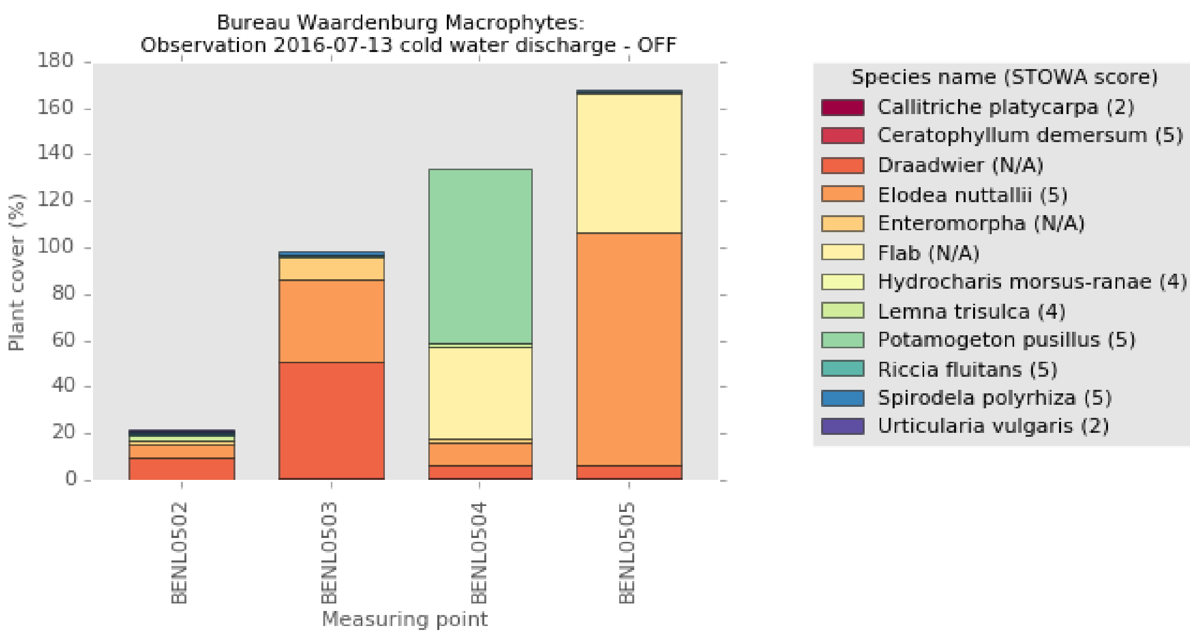


Figure 7.13 Ecology – BwB – macrophyte observations – 13 July 2016

MACROFAUNA

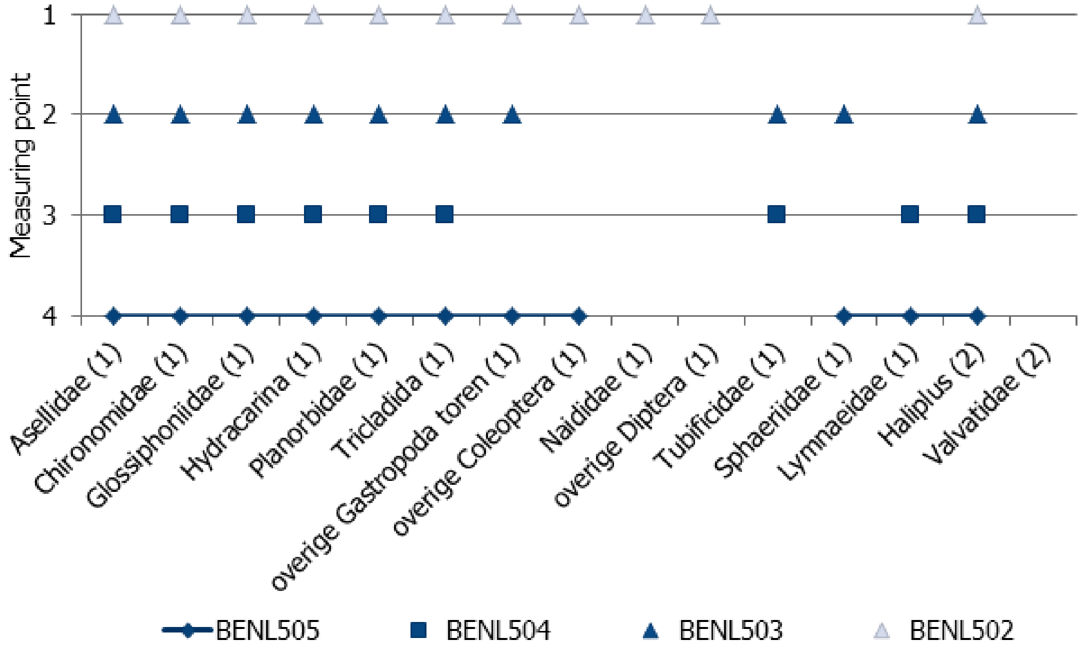


Figure 7.14 Ecology – macrofauna observations – 15 July 2015 (part a)

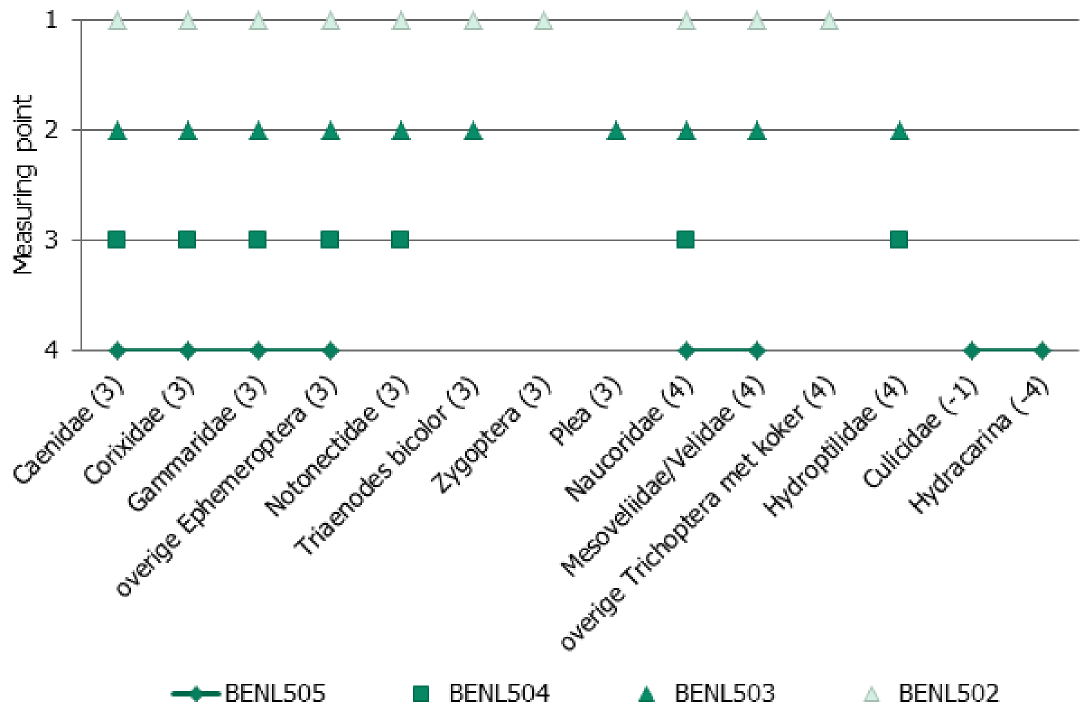


Figure 7.15 Ecology – macrofauna observations – 15 July 2015 (part b)

Table 7.3 M1A type fish species preferred water temperature range for life stages (Buijse, 2016)

Fish type	Life stage	Temperature (°C)					
		>5 – 10	>10 - 15	>15 - 20	>20 - 25	>25 - 30	>30
Bitter roach	**egg/larvae**			✓			
	juvenile	✓	✓	✓			
	Adult	✓	✓	✓			
Three-spined stickleback	**egg/larvae**			✓			
	juvenile						
	Adult	✓	✓	✓	✓		
Giebel	**egg/larvae**			✓	✓		
	juvenile			✓	✓	✓	
	Adult	✓	✓	✓	✓	✓	✓
Small loach	**egg/larvae**				✓		
	juvenile		✓				
	adult	✓	✓	✓	✓	✓	✓
Crucian carp	**egg/larvae**			✓	✓		
	juvenile			✓	✓	✓	
	adult	✓	✓	✓	✓	✓	✓
Rudd	**egg/larvae**			✓	✓		
	juvenile			✓	✓	✓	
	adult	✓	✓	✓	✓	✓	
Pike	**egg/larvae**	✓	✓				
	juvenile			✓			
	adult	✓	✓	✓	✓	✓	
Nine-spined stickleback	**egg/larvae**			✓			
	juvenile						
	adult	✓	✓	✓	✓	✓	
Smee	**egg/larvae**			✓	✓		
	juvenile						
	adult	✓	✓	✓	✓	✓	✓
Tench	**egg/larvae**				✓		
	juvenile				✓	✓	
	adult	✓	✓	✓	✓	✓	
Big loach	**egg/larvae**		✓				
	juvenile	✓	✓	✓			
	adult	✓	✓	✓	✓		

APPENDIX V – WATER QUALITY DATA OVERVIEW

TABLE OF CONTENTS

FIELD MEASUREMENT RESULTS 20

RELATIONSHIPS BETWEEN TEMPERATURE 21

TEMPERATURE 26

OXYGEN 28

TURBIDITY 29

CONDUCTIVTIY 31

PH 32

YEARLY BI-MONTHLY WATER QUALITY RESULTS 34

INVESTIGATE RELATIONSHIPS 34

COMBINED TIME SERIES GRAPHS 36

A. WATER TEMPERATURE 40

B. VELOCITY 42

C. NON-METALLIC INORGANICS 43

D. DISSOLVED OXYGEN AND ORGANIC MATTER 44

E. OPTICAL PROPERTIES 48

F. NUTRIENTS 51

G. BIOMASS 58

H. SALINITY 60

I. ACIDITY 62

J. IRON 64

FIELD MEASUREMENT RESULTS

This section describes the field data. In order to observe the results from the field campaigns, the graphs presented for each measured parameter measured include:

- Scatter matrix
- Box plot
- Profile plot illustrating spatial variation for varying depth profiles has been included

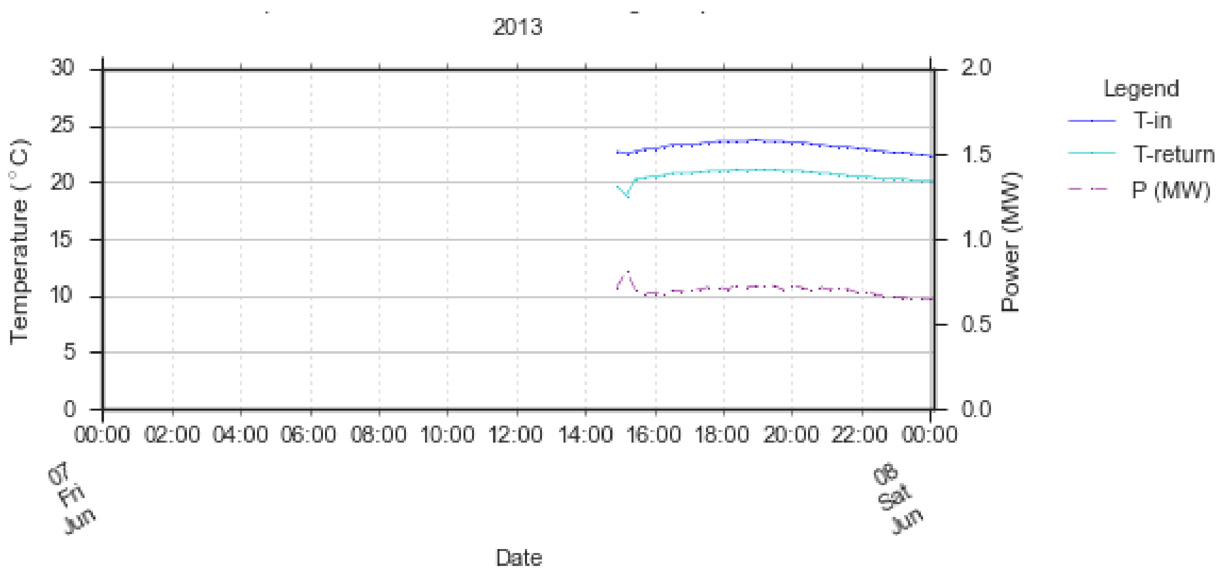


Figure 7.16 Operational water temperature during field campaign A

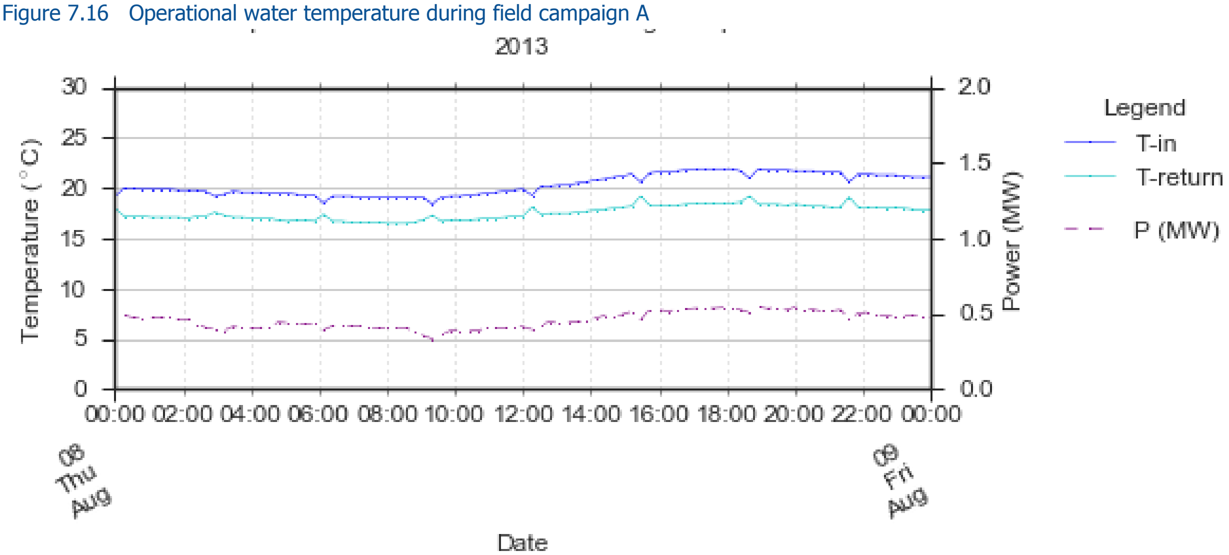


Figure 7.17 Operational water temperature during field campaign B

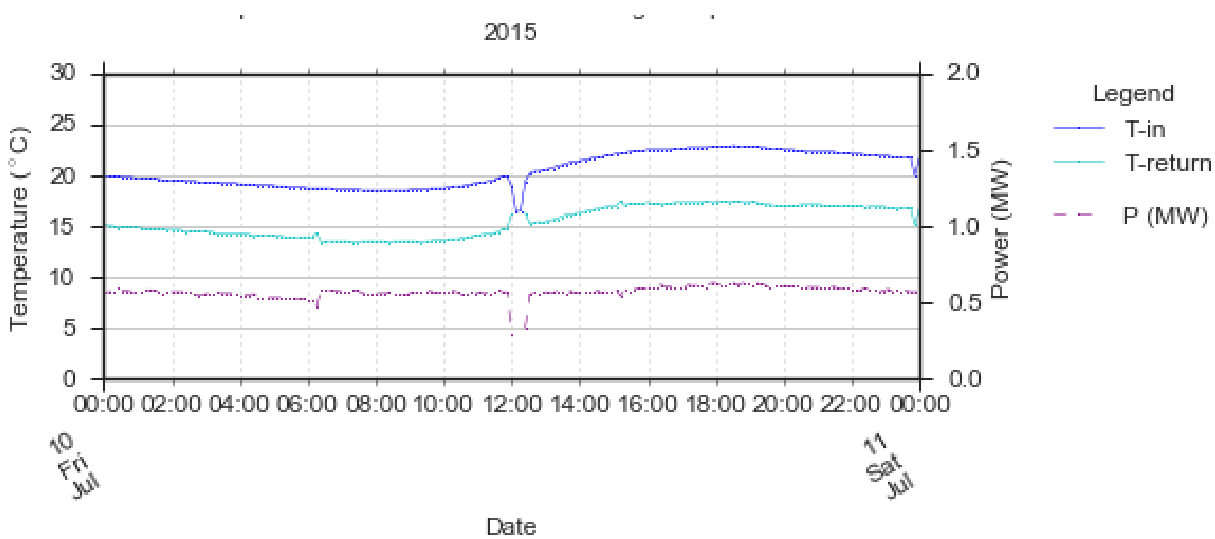


Figure 7.18 Operational water temperature during field campaign C

RELATIONSHIPS BETWEEN TEMPERATURE

To observe if there is a relationship between oxygen and temperature, the following section presents several scatter matrix plots with the correlation coefficient[22] annotated on each plot, based on the data collected during the three field campaigns, excluding the observations prior to 14:00 hours during Campaign A.

Since field campaigns were not undertaken in periods where cold water discharge has not been present for a longer period of time prior to the campaign, it is not possible compare if this effect at this specific location is due to the effect of cold water discharge. The data collected throughout the year has been taken closer to the water surface, around 0.3m. Therefore, these scatter matrix show that for the laboratory data collected, there should be a reasonable observable relationship present.

The next scatter matrix presents the results for each of the six measurements points, for Campaigns A, B and C, at depths 0.1,0.3 and 0.7m for the parameters; water temperature, pH, DO and oxygen saturation. The median water temperature during campaigns was between 22-24°C. The correlation strength for the parameters to temperature is fair, in the range of 0.6-0.7.

[22] Correlation coefficient definition: "The value of correlation coefficient ranges between -1 and +1. If the correlation coefficient is larger than zero, two variables are positively correlated. In this case the variable y tends to increase as x increases on a scatter plot. If the correlation coefficient is smaller than zero, two variables are said to be negatively correlated. In this case the variable y tends to decrease as x increases on a scatter plot. The correlation coefficient measures of how close the cloud of points lies to a straight line on a scatter plot. When the correlation coefficient equals -1 or +1, the scatter plot of points (x,y) will be a straight line with negative or positive slope. In that case the variables are completely dependent. The variables x and y are statistically uncorrelated if the correlation coefficient is zero." (Luxemburg & Coenders, 2015)

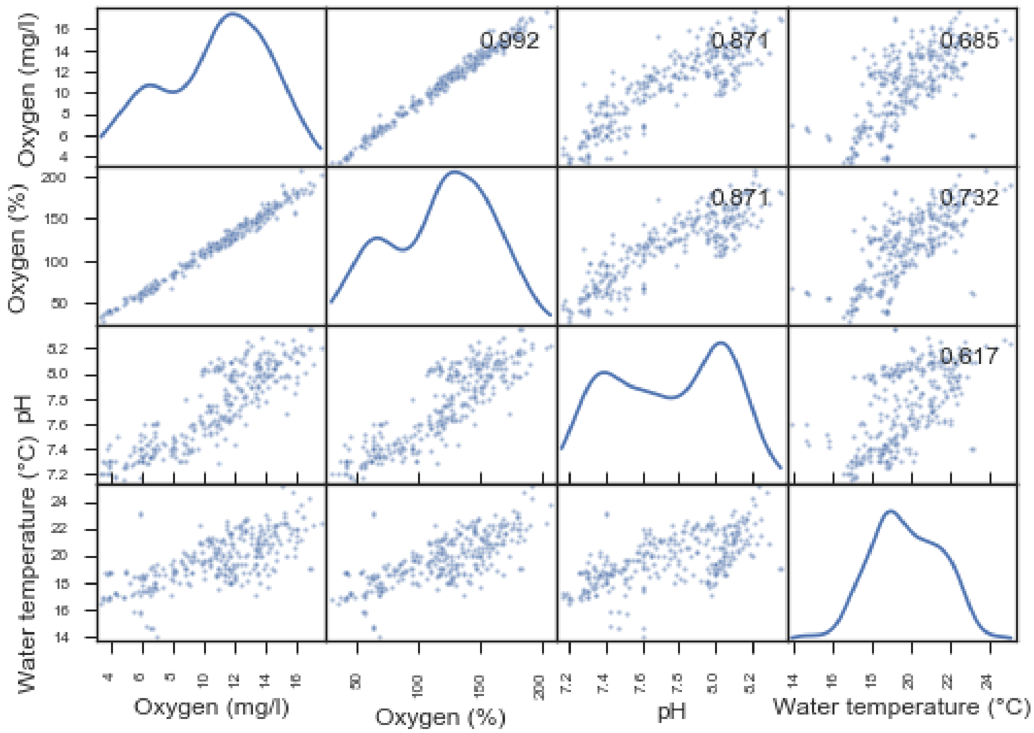


Figure 7.19 Scatter matrix with correlation coefficient – field observations for all measuring points for depths 0.1m, 0.3m and 0.7m

Based on the scatter matrix for all observation points, there appears to be a positive relationship, as temperature increases, DO, oxygen saturation and pH increase. It is expected that DO concentration decreases as water temperature increases. However, since the observations were made throughout single day(s), the diurnal variation of oxygen appears to be dominant.

To gain more insight into the relationships and effect of cold water discharge, the focus of the next two sections is to compare point BENL0502 (close to cold water discharge) with point BENL0505 (furthest form cold water discharge) at the 0.1m, 0.3m and 0.7m depth. For the days observed the cold water discharge operation performance was quite consistent, as previously discussed and therefore observing only the results at BENL0502 would not be sufficient to understand if the effects on relationships are due to cold water discharge or other causes. An option to compare if cold water discharge has an influence on the water quality observations is to compare the relationships observed at the location closest and furthest from cold water discharge (BENL0505), since field campaigns were not undertaken when there was no cold water discharge.

The ratio of oxygen saturation and DO remained fairly constant throughout the field campaigns and therefore is not provided on the following matrix scatter plots.

BENL0502

At BENL0502 DO concentration is strongly, positively correlated (0.85) to water temperature at 0.1m depth, the data is presented in the next three graphs. The correlation between water temperature and DO weakens with depth to 0.53 at 0.7m depth.

Cold water discharge alters temperature and flow in the channel, flow has the potential to mobilise material suspended in the water column. The next three plots show the relationship between turbidity and water temperature to be a very weak and negative relationship, as temperature increases, turbidity decreases, conversely as turbidity increases, temperature decreases. Since turbidity is an indicator of the optical quality of the water, it makes sense that the influence of turbidity strengthens deeper in the water profile, the effect of light extinction due to suspended material is higher deeper in the water column. Overall the turbidity was very low during field campaigns, hence it makes sense that there is a weak relationship with turbidity since it has a weak influence on the system, lower turbidity has less light extinction.

The relationship between turbidity and DO showed no relationship near the surface of the water with the relationship strength increasing lower in the water column. Lower in the water column turbidity increased, DO concentrations increased, it would be expected that as turbidity increases, DO would also decrease. However, since the turbidity value is very low and the relationship is weak than it is likely due to other factors.

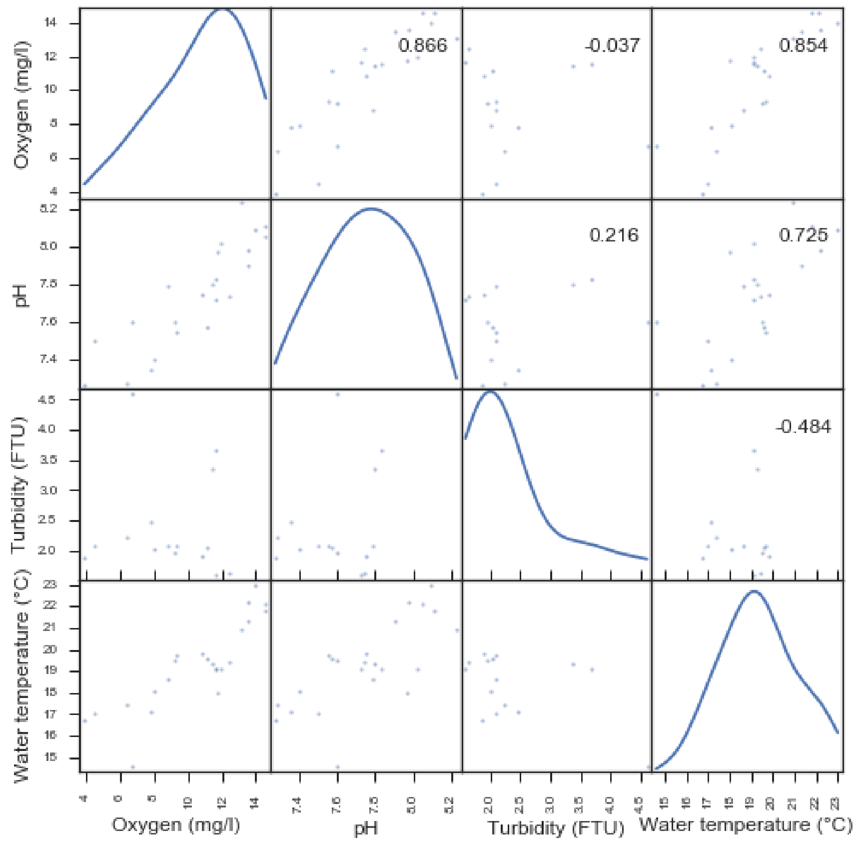


Figure 7.20 Scatter matrix – BENL0502 for depth 0.1m

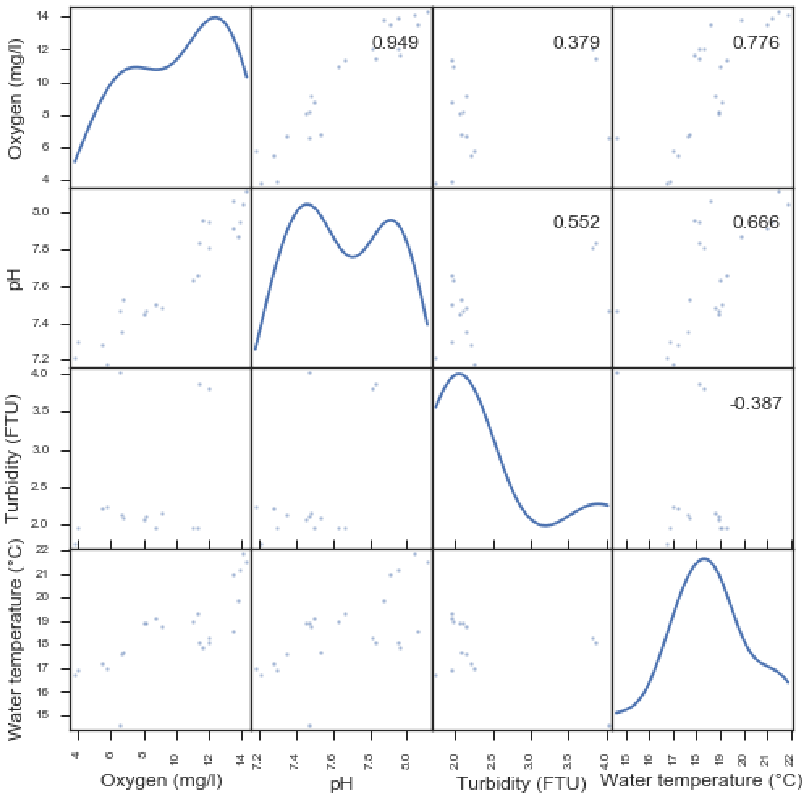


Figure 7.21 Scatter matrix – BENL0502 for depth 0.3m

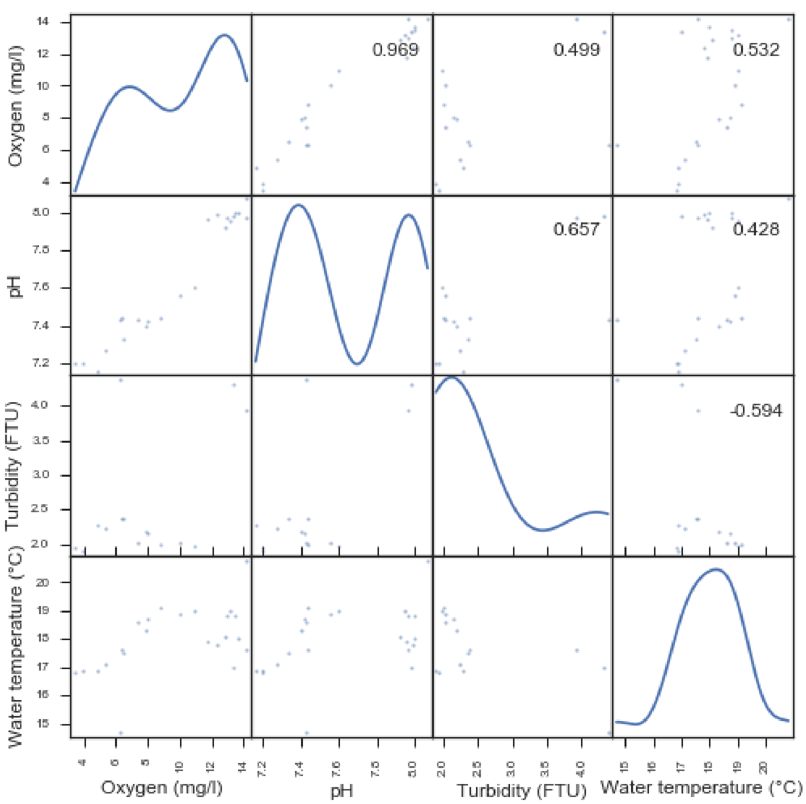


Figure 7.22 Scatter matrix – BENL0502 for depth 0.7m

BENL0505

At BENL0505 DO concentration correlation to water temperature is weaker than at BENL0502. Furthermore, the correlation from shallow to deep experiences less variability than what was observed at BENL0502. The correlation between oxygen concentration and temperature varies from approximately 0.7 at 0.1m to 0.75 at 0.7m depth.

The next three plots show the relationship between turbidity and water temperature at BENL0505 to be a very weak, similar to BENL0502 and a positive relationship, opposite to BENL0502. This means, as temperature increases, turbidity increases, conversely as turbidity increases, temperature increases. This shows that closer to BENL0502, there is a strong difference in turbidity during cold water discharge, observed during field campaigns.

The relationship between turbidity and DO showed effectively no relationship near the surface of the water with the relationship strength increasing lower in the water column. The relationship between turbidity and DO concentration at 0.7m depth was 0.75 at BENL0505 and 0.5 at BENL0502. Lower in the water column turbidity increased, DO concentrations increased, it would be expected that as turbidity increases, DO would decrease due to effects such as light extinction. Similar to BENL0502, the turbidity value at BENL0502 is very low and the relationship is weak.

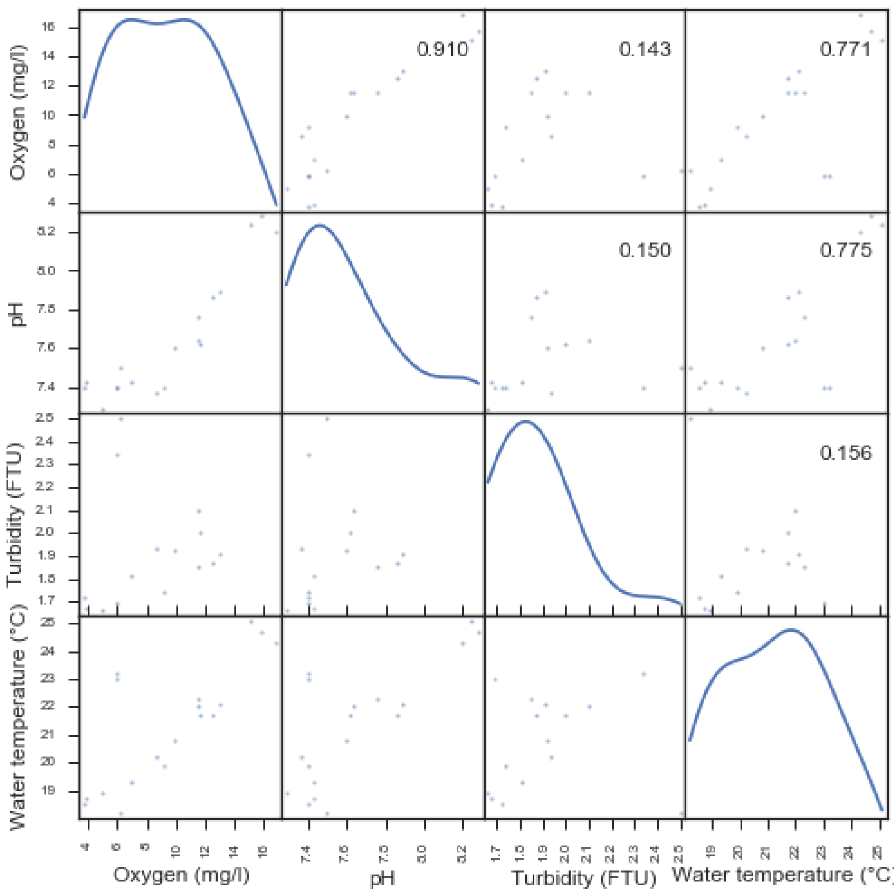


Figure 7.23 Scatter matrix – BENL0505 for depths 0.1m

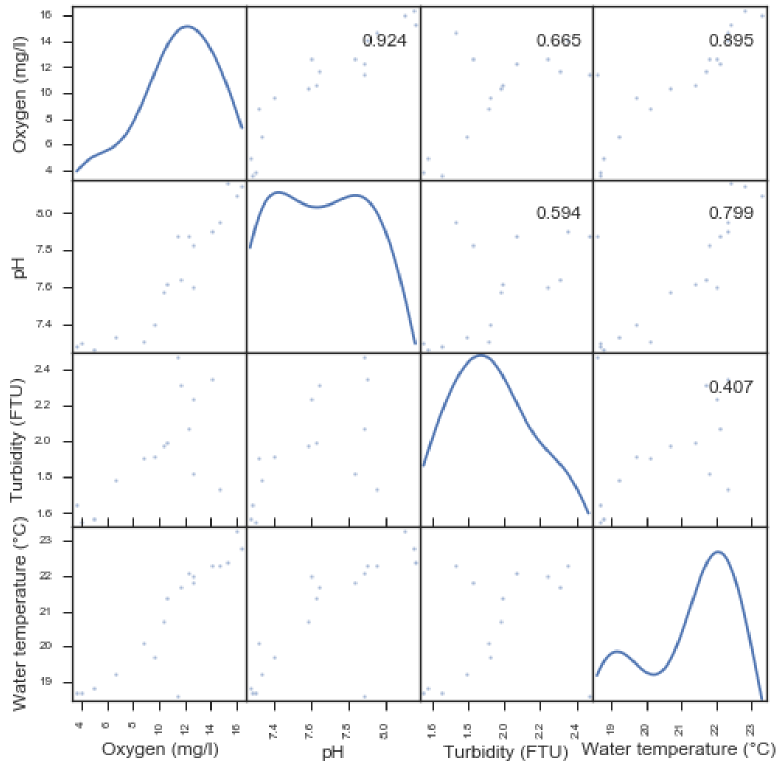


Figure 7.24 Scatter matrix – BENL0505 for depths 0.3m

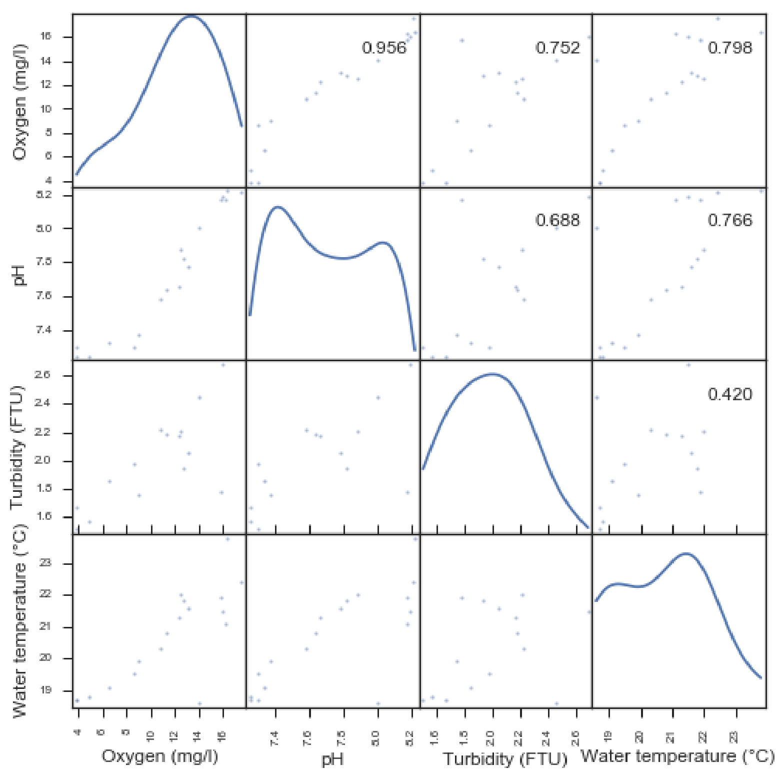


Figure 7.25 Scatter matrix – BENL0505 for depths 0.7m

TEMPERATURE

During cold water discharge, median temperature increased along the channel by approximately 3°C, as can be observed in the next graph. This increase in mean temperature during cold water discharge, showed that the field measurements presented a similar trend as the laboratory measurements. Note, measuring point "1 – OUT" appears to have a different trend than the other measuring points, observations at this point were only recorded during Campaign A, therefore there are much fewer observation results at "0-OUT" and "1-OUT" than for BENL0502 to BENL0505.

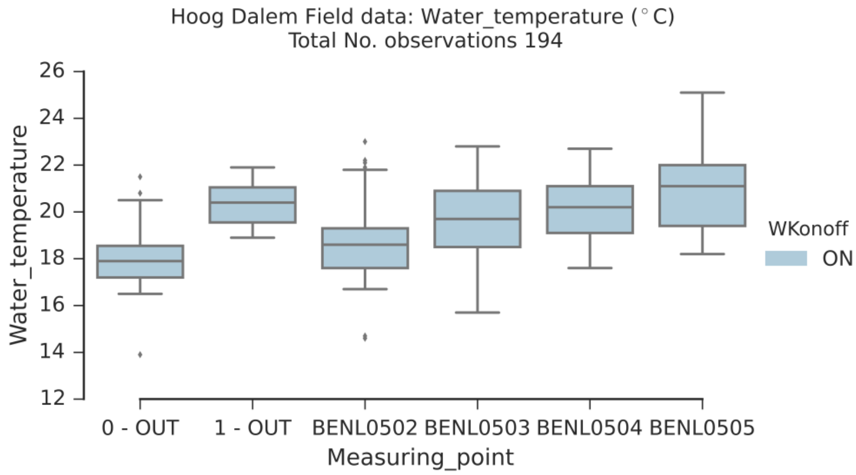


Figure 7.26 Box plot – field data – water temperature

When analysing field campaign measured water quality it should be taken into consideration that the air temperature at the time of measurements was relatively consistent, as shown in the below table.

Table 7.4 Air temperature during field campaigns (KNMI, station 356 Herwijnen)

Date			**Air temperature (°C)**		
			Avg.	**Min**	**Max**
2013	Aug	8	16.5	10.3	22.2
2013	Jun	7	17.9	10.1	25.3
2015	Jul	10	16.8	7.1	23.1

OXYGEN

To illustrate spatial variation in oxygen, along the channel, the following graphs show the results from the three different campaigns as one box plot. There is a broader spread in field DO results due to diurnal variation:

1. Laboratory data time for observations 7:30 to 15:00 at a depth near surface 20-30cm (not specifically recorded)
2. Field campaign were recorded from time 5:45 to 20:10 and field campaigns measured at profiles 10 cm (3.37-17mg/l), 30 cm (3.63-17mg/l), 70cm (3.45-17mg/l)

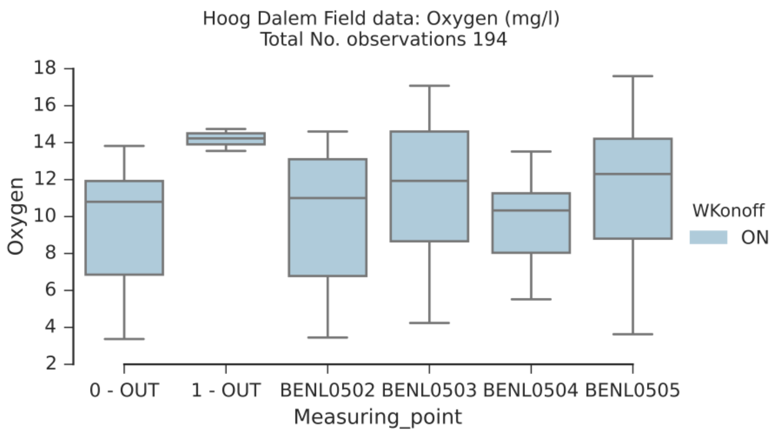


Figure 7.27 Box plot – field data – oxygen

To illustrate the change in DO due to diurnal variation, the following two graphs show the results for three different depths at BENL0502 and BENL0505 for the 2015 field campaign.

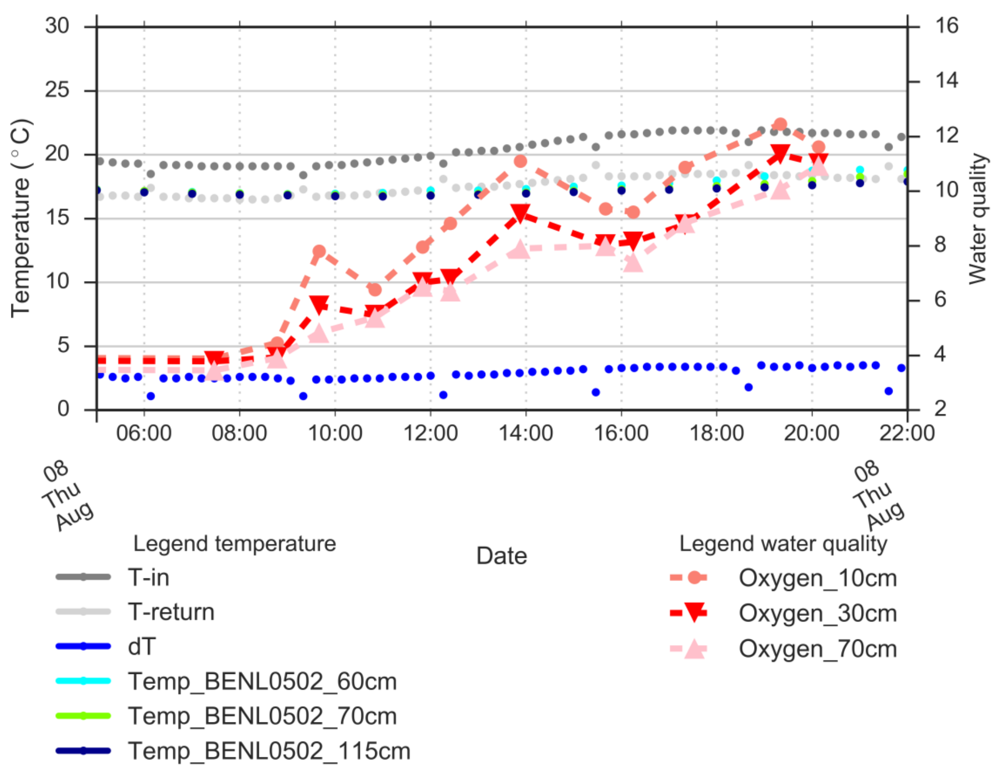


Figure 7.28 Time series – field data – DO diurnal variation BENL0502

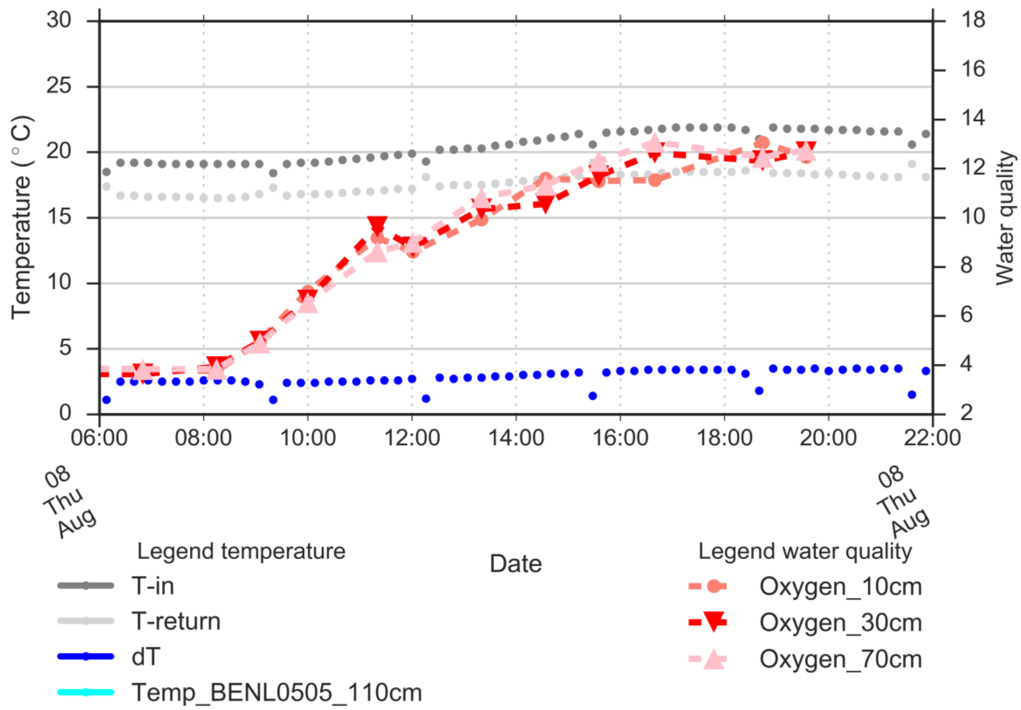


Figure 7.29 Time series – field data – DO diurnal variation BENL0505

TURBIDITY

The following graph shows the turbidity results for the three different depths.

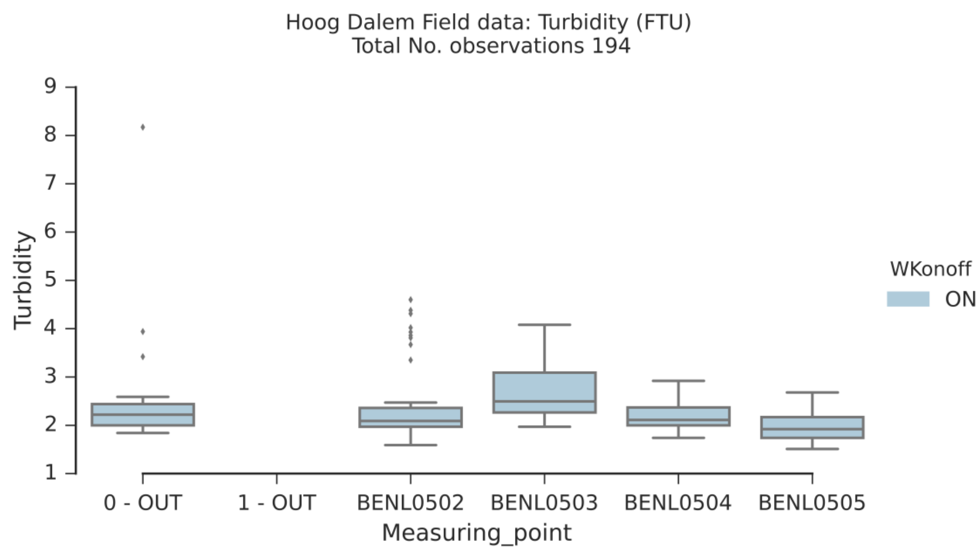


Figure 7.30 Box plot – field data – turbidity

To illustrate spatial variation in turbidity, along the channel, the following graphs show turbidity results for three different depths. At each depth there appears to be a trend that turbidity reduces with distance from BENL0502.

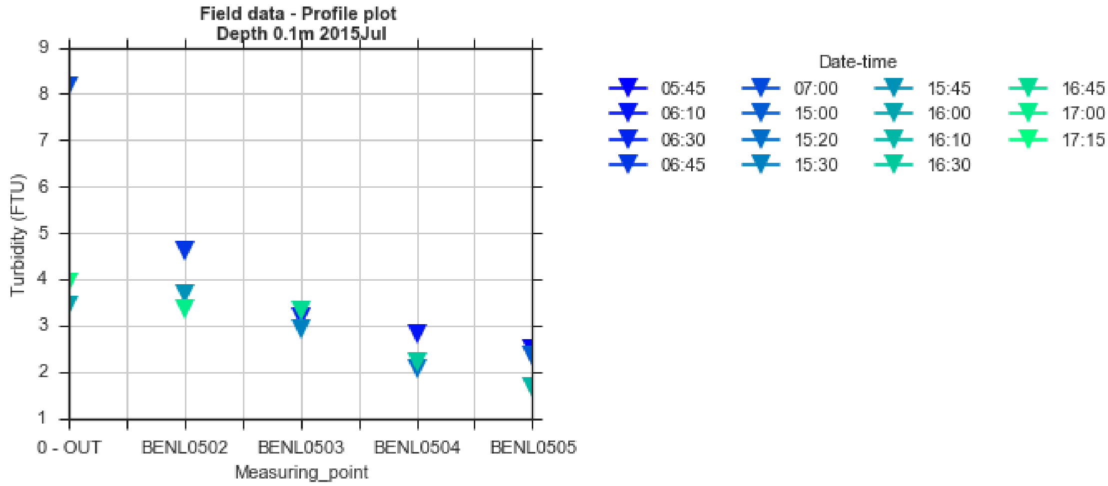


Figure 7.31 Turbidity Vs. location – 2015 field campaign – 0.1m from surface

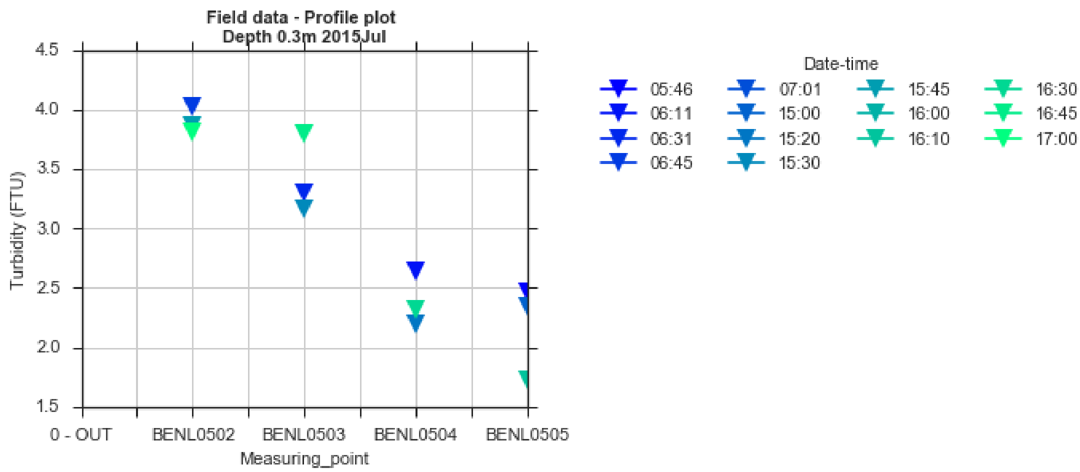


Figure 7.32 Turbidity Vs. location – 2015 field campaign – 0.3m from surface

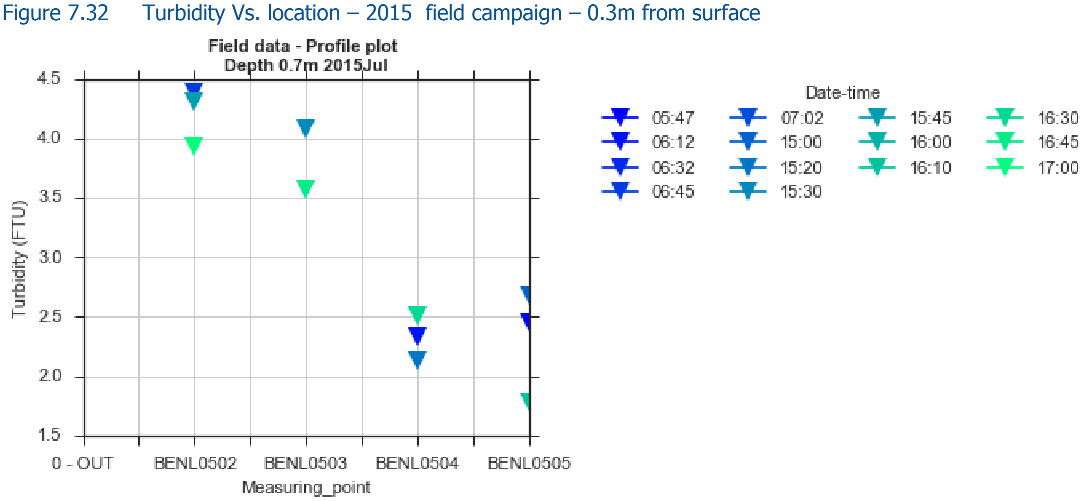


Figure 7.33 Turbidity Vs. location – 2015 field campaign – 0.7m from surface

CONDUCTIVTIY

The following graph shows the EC results for the three different depths, it is likely that different measuring equipment was used for the different campaigns.

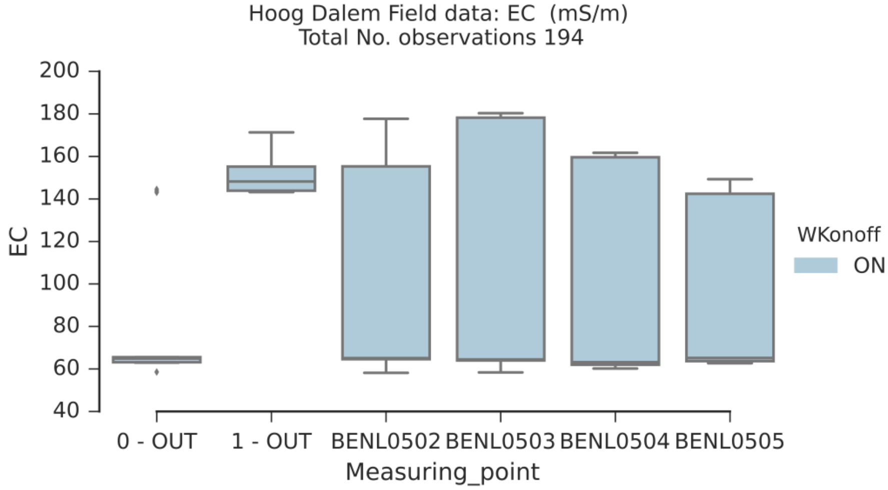


Figure 7.34 Box plot – field data – EC

To illustrate spatial variation in EC, along the channel, the following graphs show EC results for three different depths during 2015 observations.

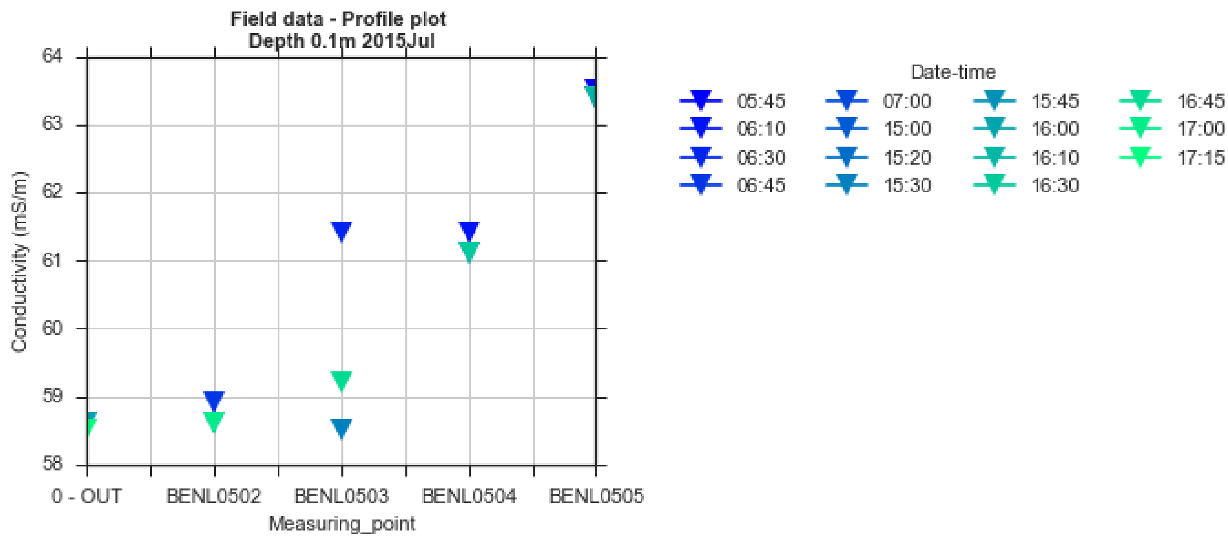


Figure 7.35 EC Vs. location – 2015 field campaign – 0.1m from surface

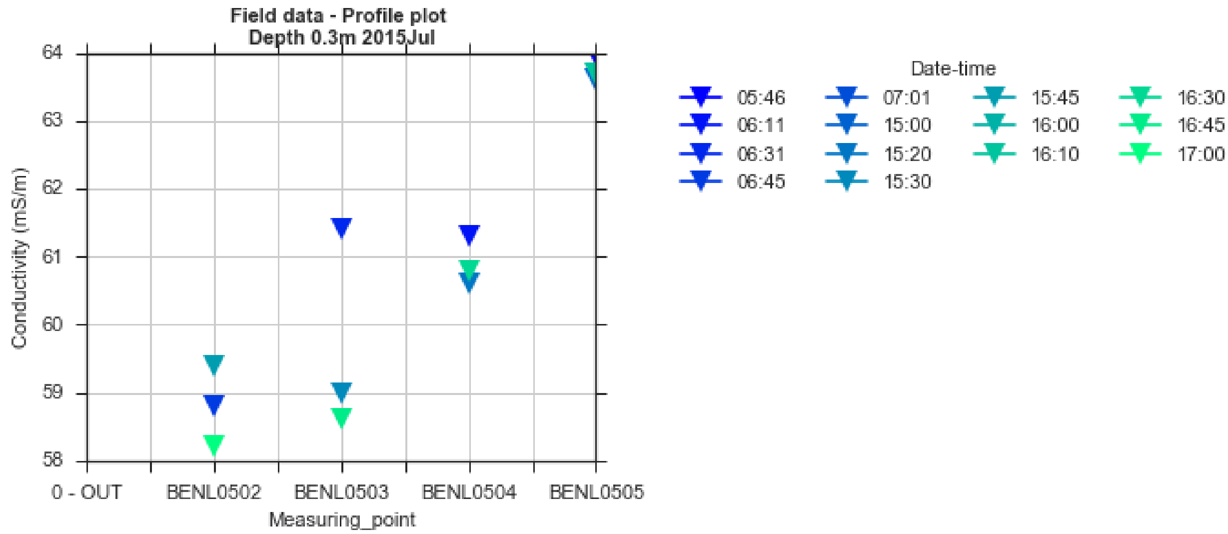


Figure 7.36 EC Vs. location – 2015 field campaign – 0.3m from surface

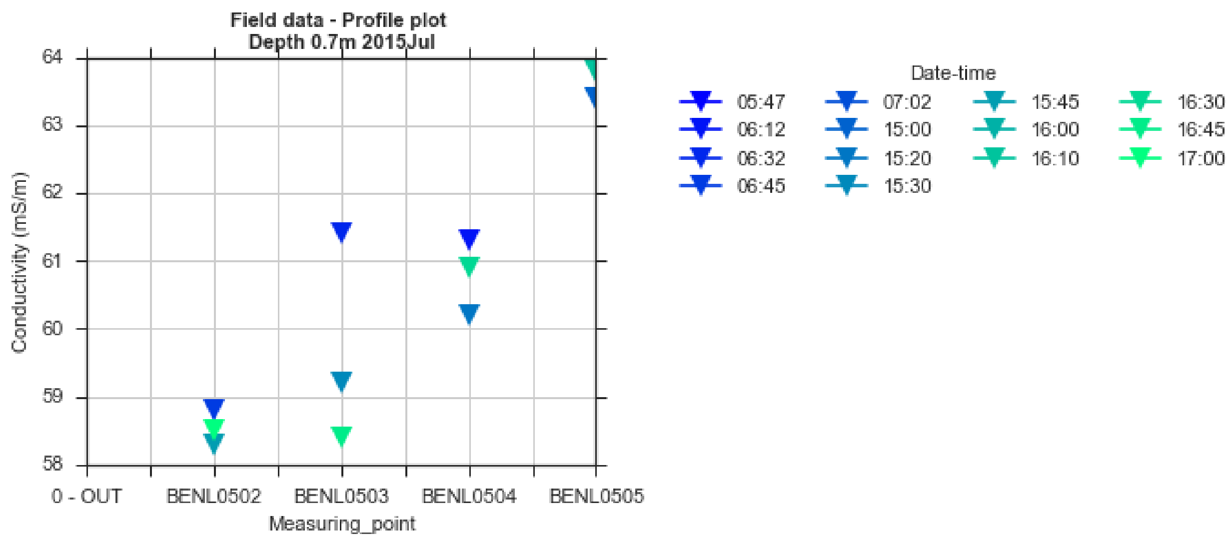


Figure 7.37 EC Vs. location – 2015 field campaign – 0.7m from surface

PH

The following graph shows the pH results for the three different depths.

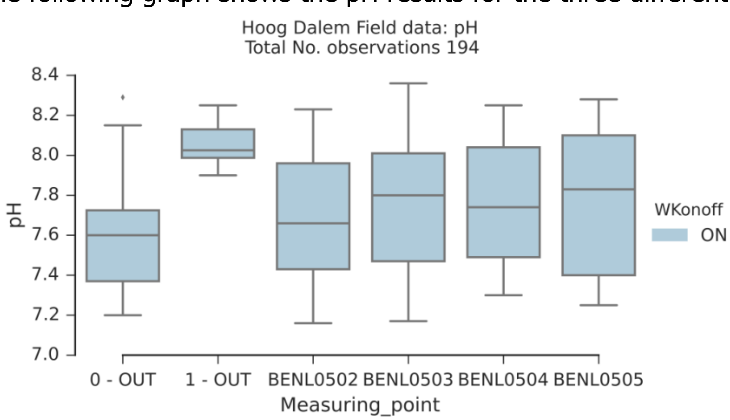


Figure 7.38 Box plot – field data – pH

To illustrate spatial variation in pH, along the channel, the following graphs show pH results for three different depths. Based on the graphs it is difficult to see a strong relationship.

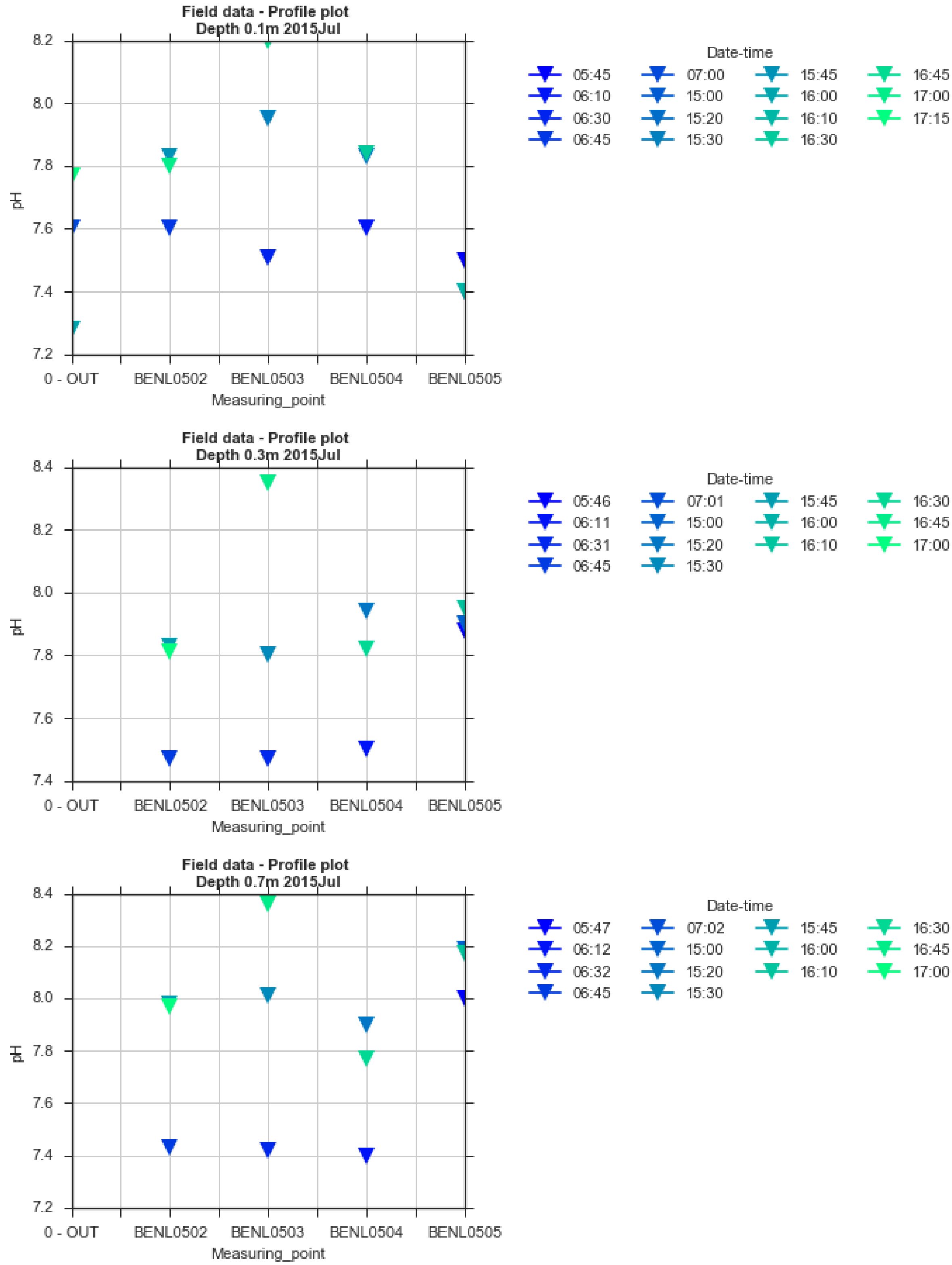


Figure 7.39 pH Vs. location – spatial variation – field data

YEARLY BI-MONTHLY WATER QUALITY RESULTS

To present the results from the measurements undertaken throughout the year, two types of graphs have been prepared for each parameter:

1. Box plots separated by cold water discharge on or off for each measuring point
2. Variation throughout the year for each measuring point

The box plots were selected to view the range and skewness of the data. The time series plots for each parameter present the variation throughout the year at each measuring point, with periods of cold water discharge shaded blue on each graph. The following sections summarise observations for each parameter.

INVESTIGATE RELATIONSHIPS

To enhance understanding of the relationships between water quality parameters at each measuring point, scatter matrix for each measuring point was prepared, an overview graph is shown below and two separate graphs are provided after. Overall, there is a high variation in data points, with low confidence in most of the trend lines.

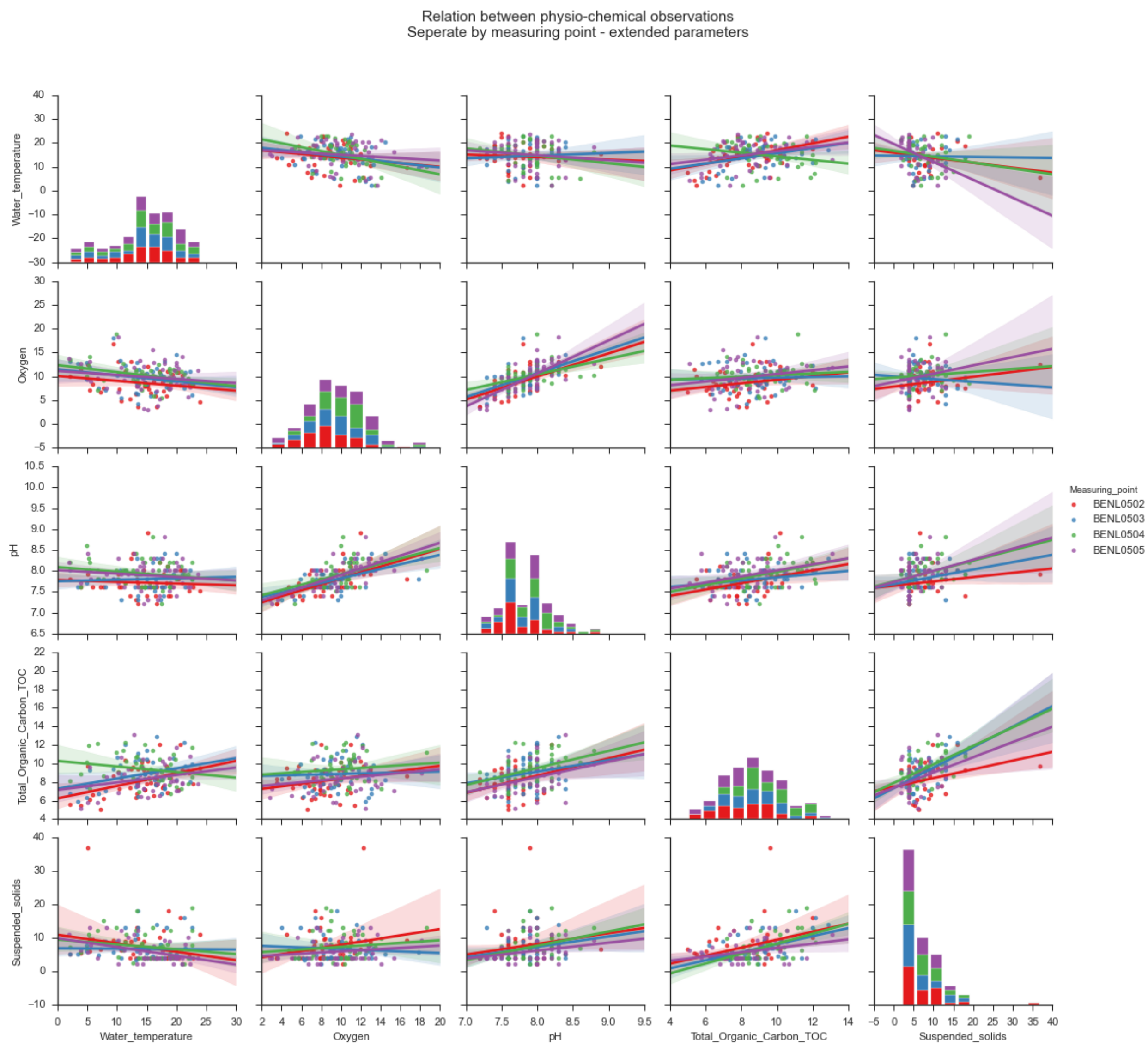


Figure 7.40 Scatter matrix – laboratory data along x-axis (water temperature, oxygen, pH, TOC and SS)

Relationship between temperature, DO (mg/l) and pH, see next tow graphs, was similar to the scatter matrix presented for the field campaigns. The DO concentration decreases with increasing water temperature. This shows that the diurnal influence was less dominant in the laboratory data than the field campaigns.

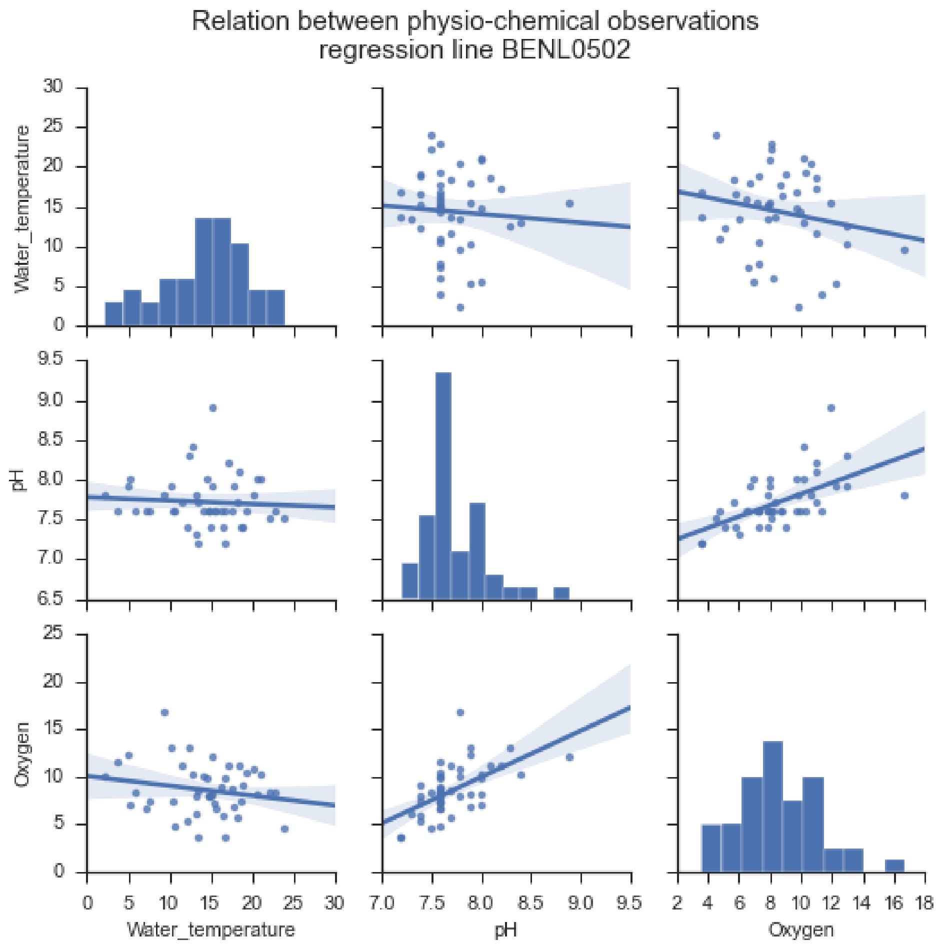


Figure 7.41 Scatter matrix – BENL0502

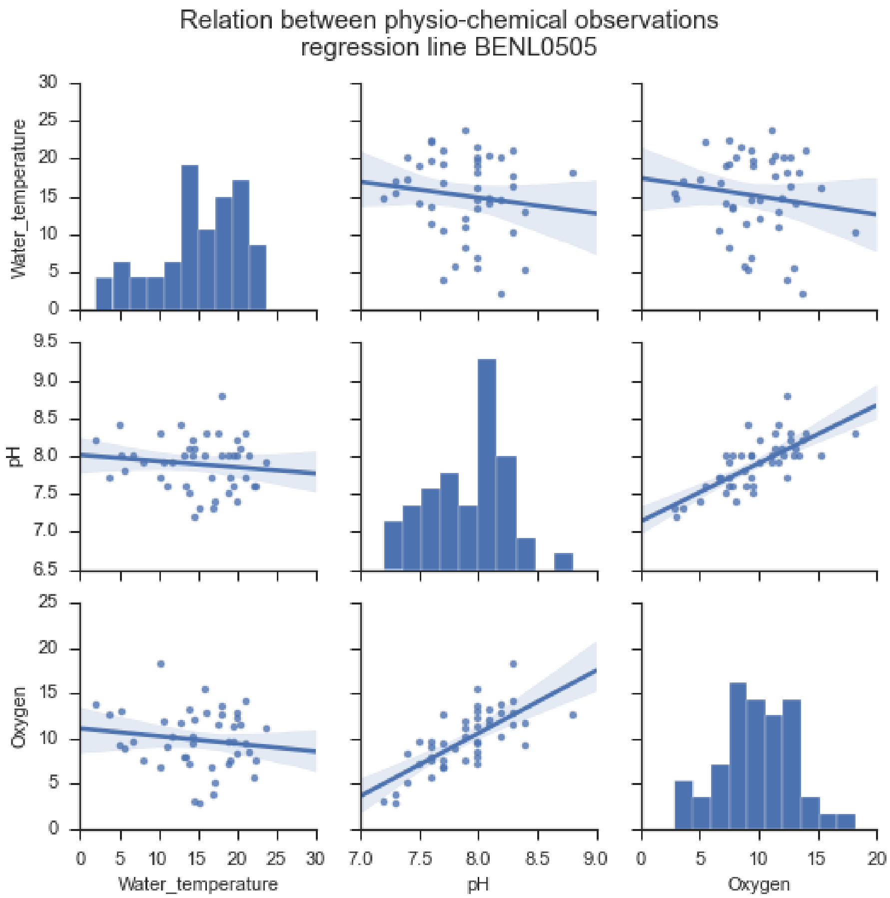


Figure 7.42 Scatter matrix – BENL0505

COMBINED TIME SERIES GRAPHS

The following section presents combined time series graphs that provide an overview for each year and each measuring point:

4. Operation cold water discharge (Eneco data)
5. In-stream water temperature observations (measured water temperature)
6. Water quality (laboratory data):
    - Oxygen saturation
    - Chl-a concentration
    - Duckweed cover

2013

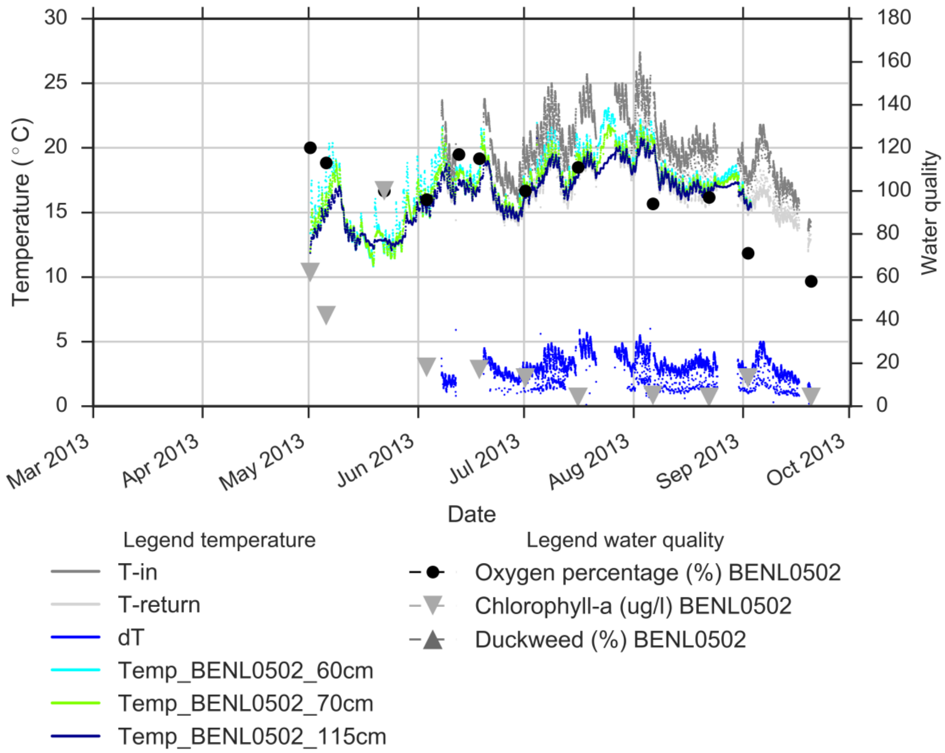


Figure 7.43 Combined effects – 2013 - BENL0502

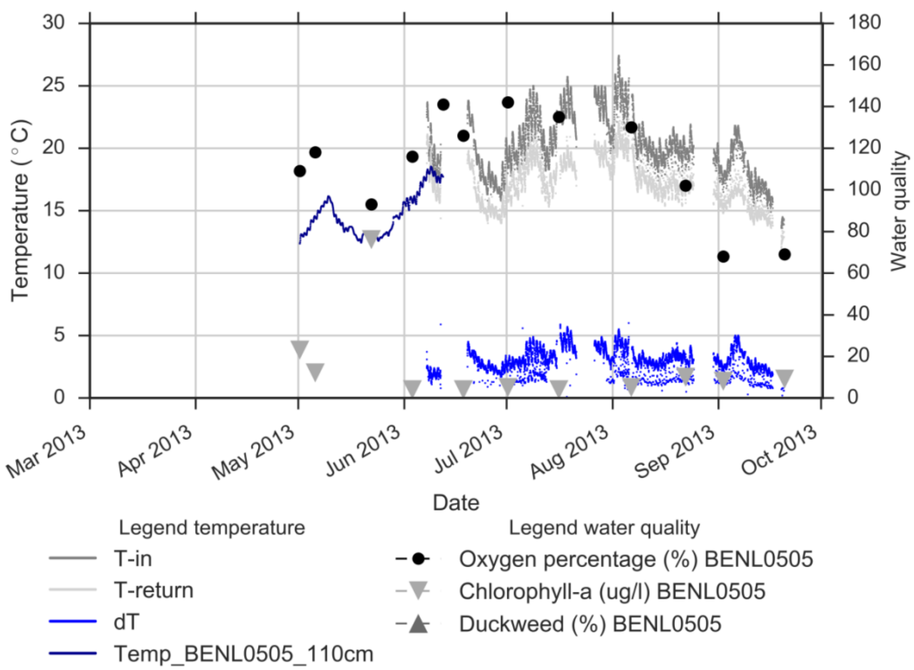


Figure 7.44 Combined effects – 2013 - BENL0505

2015

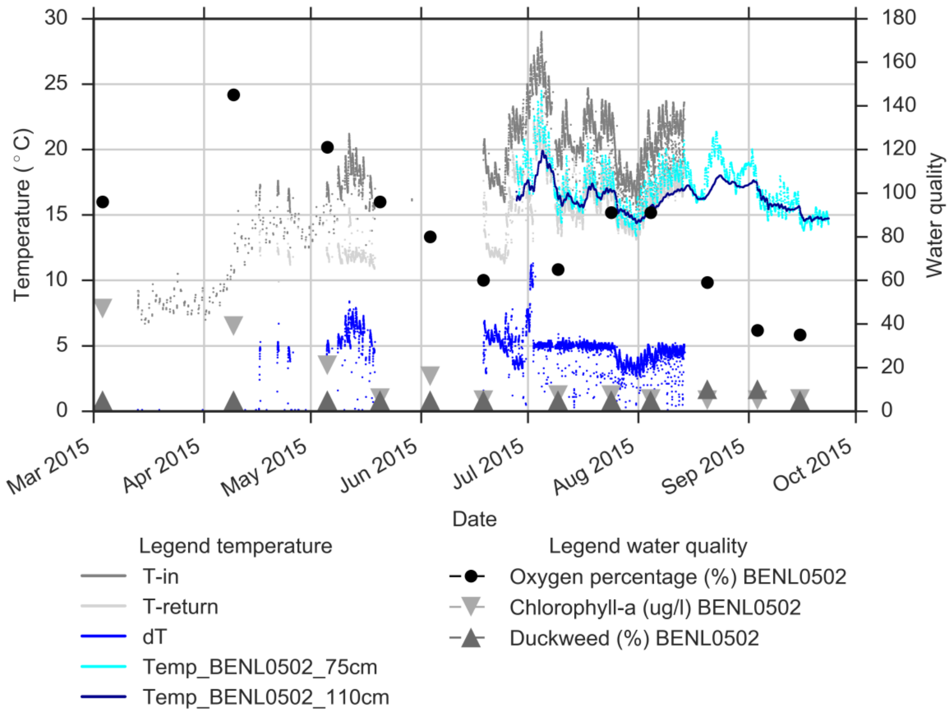


Figure 7.45 Combined effects – 2015 - BENL0502

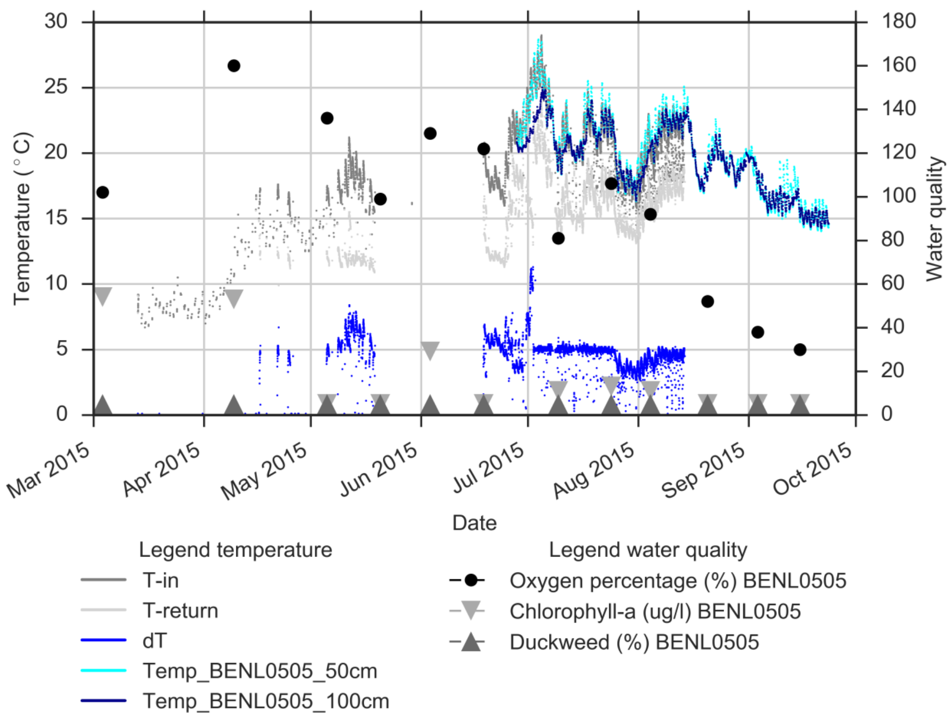


Figure 7.46 Combined effects – 2015 - BENL0505

2016

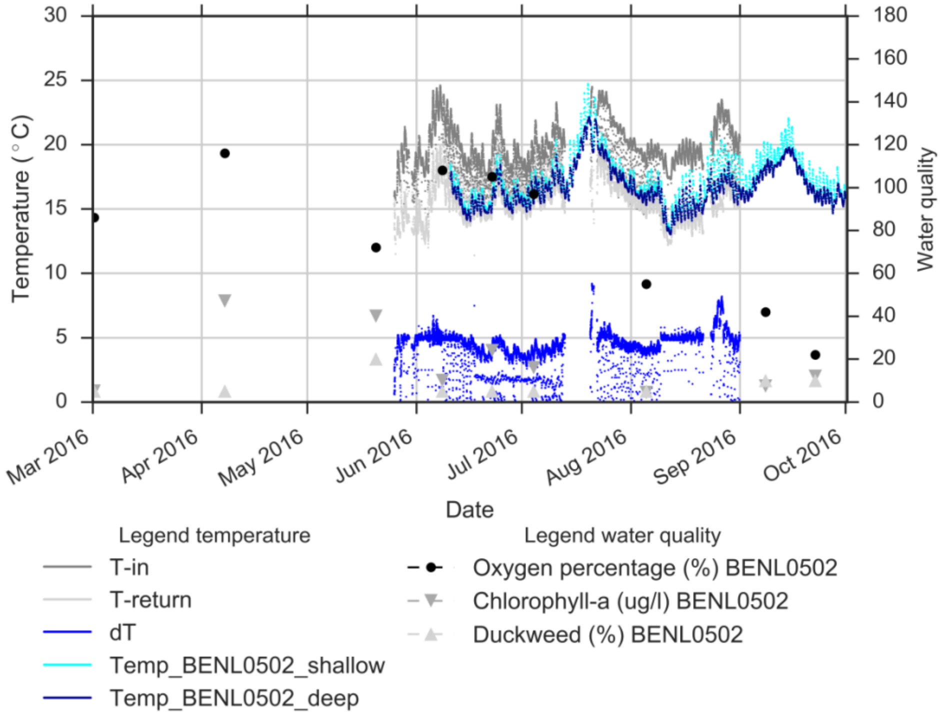


Figure 7.47 Combined effects – 2016 - BENL0502

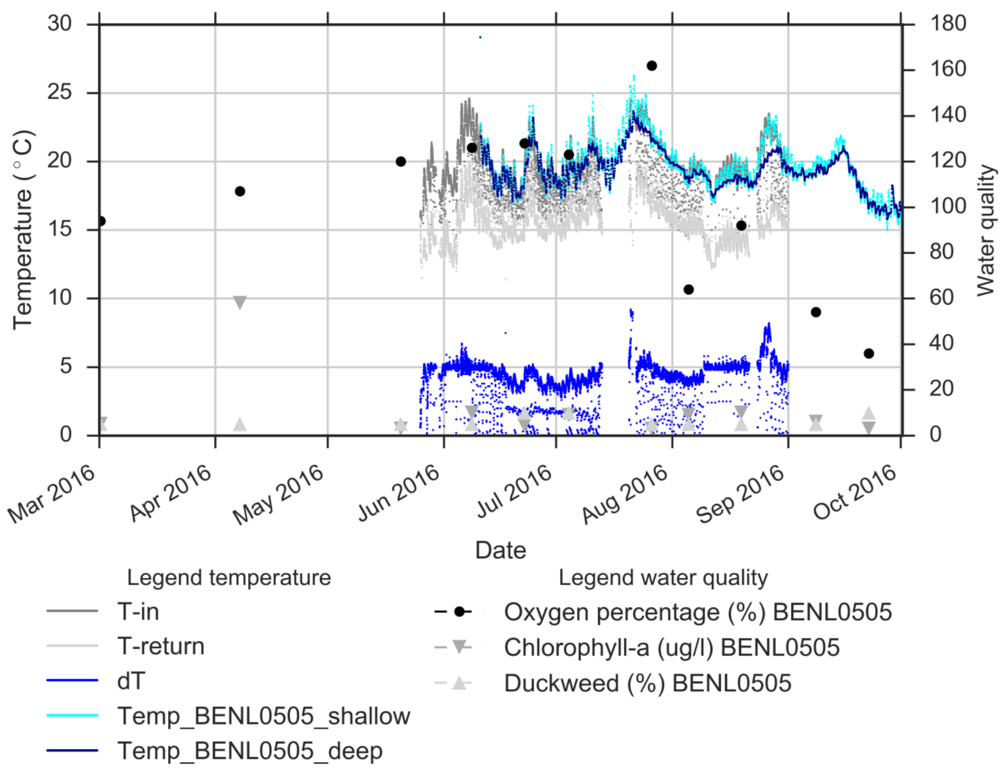


Figure 7.48 Combined effects – 2016 - BENL0505

A. WATER TEMPERATURE

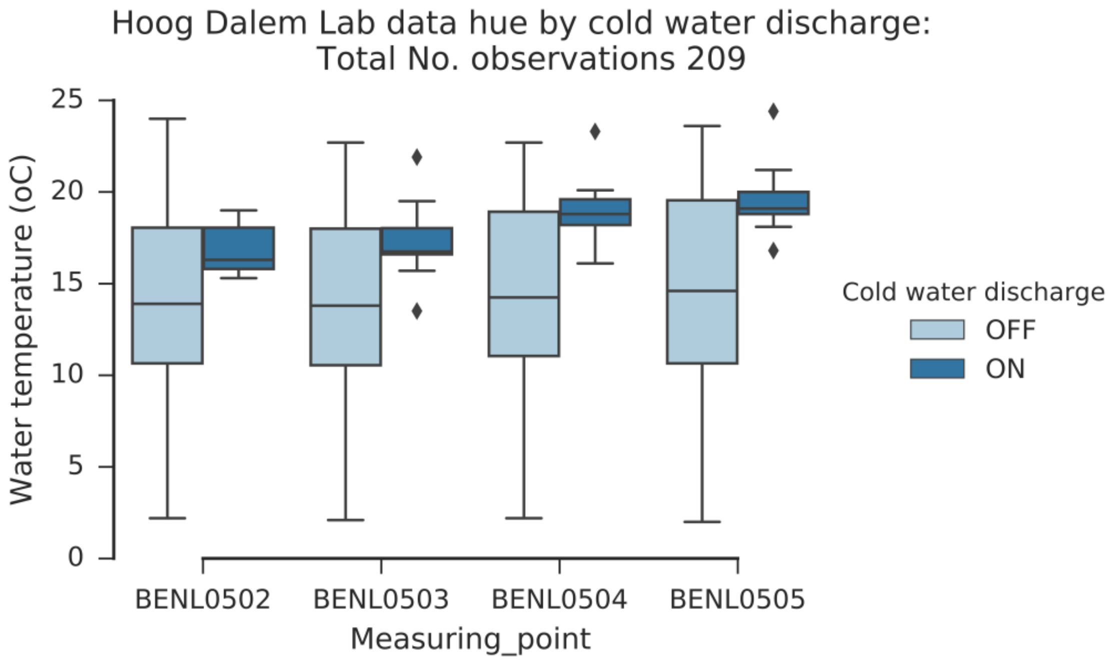


Figure 7.49 Box plot – ON / OFF – laboratory data – water temperature

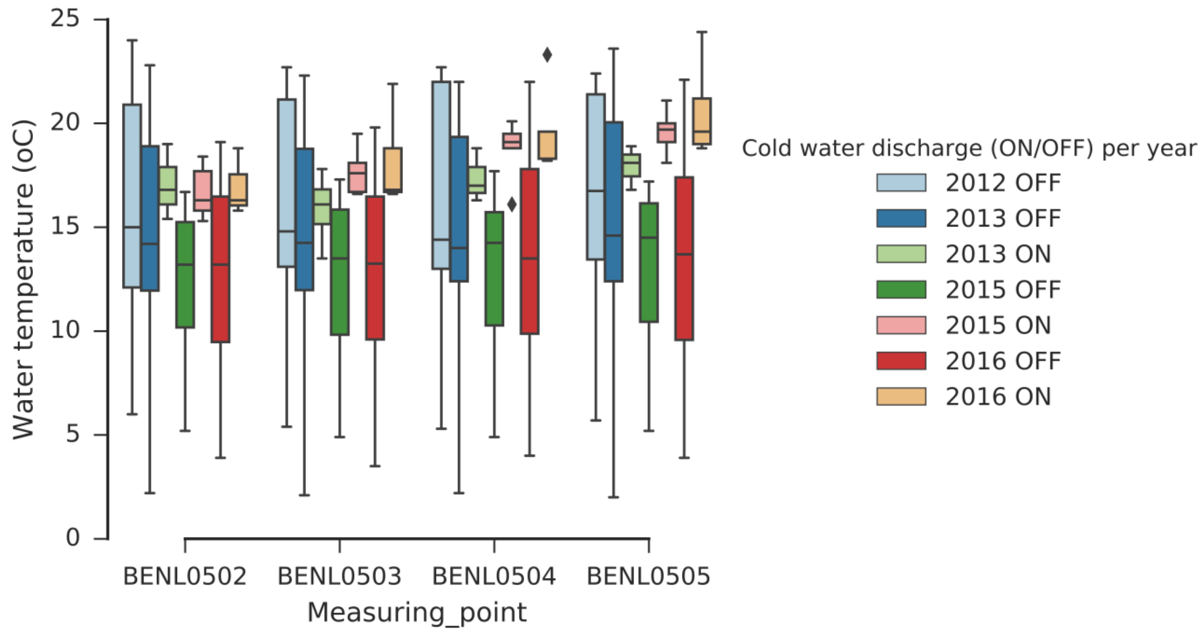


Figure 7.50 Box plot – each year ON / OFF – laboratory data – water temperature

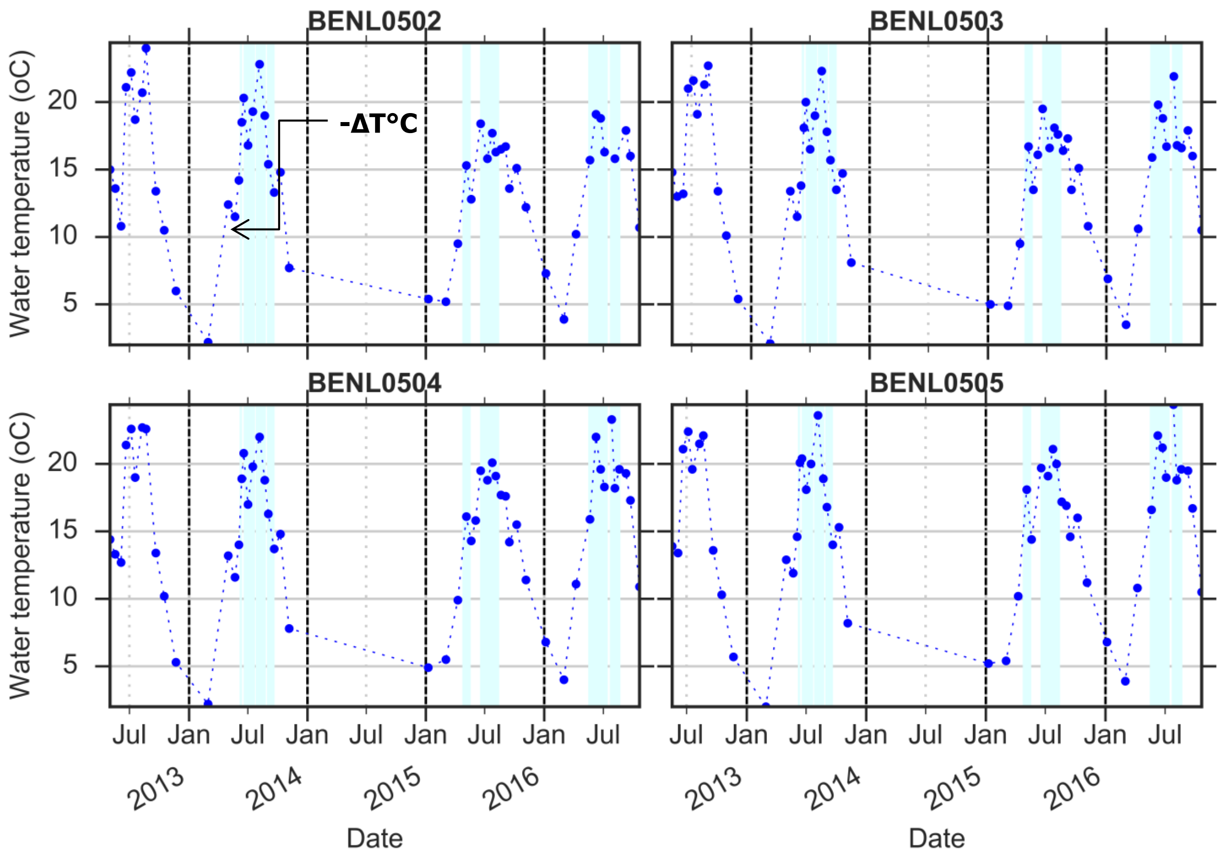


Figure 7.51 Time series plot – laboratory data – water temperature

B. VELOCITY

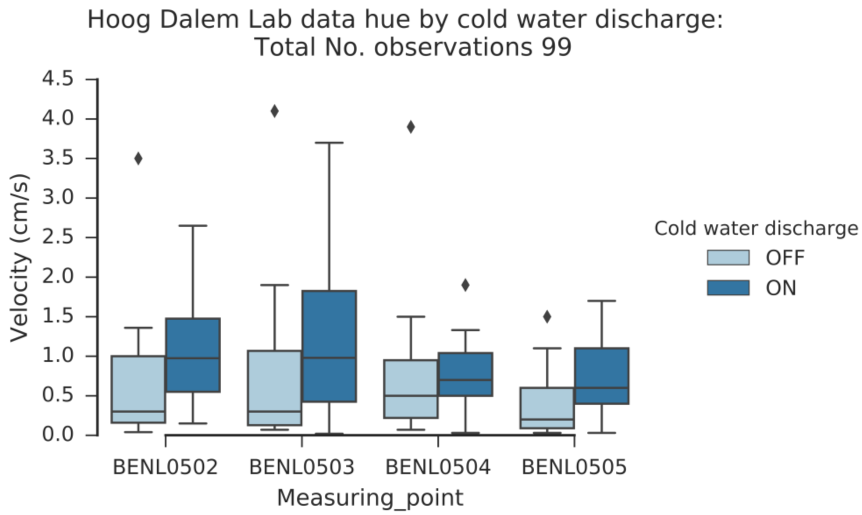


Figure 7.52 Box plot – laboratory data – velocity

The next graph shows that velocity was most consistently measured in 2015 and 2016.

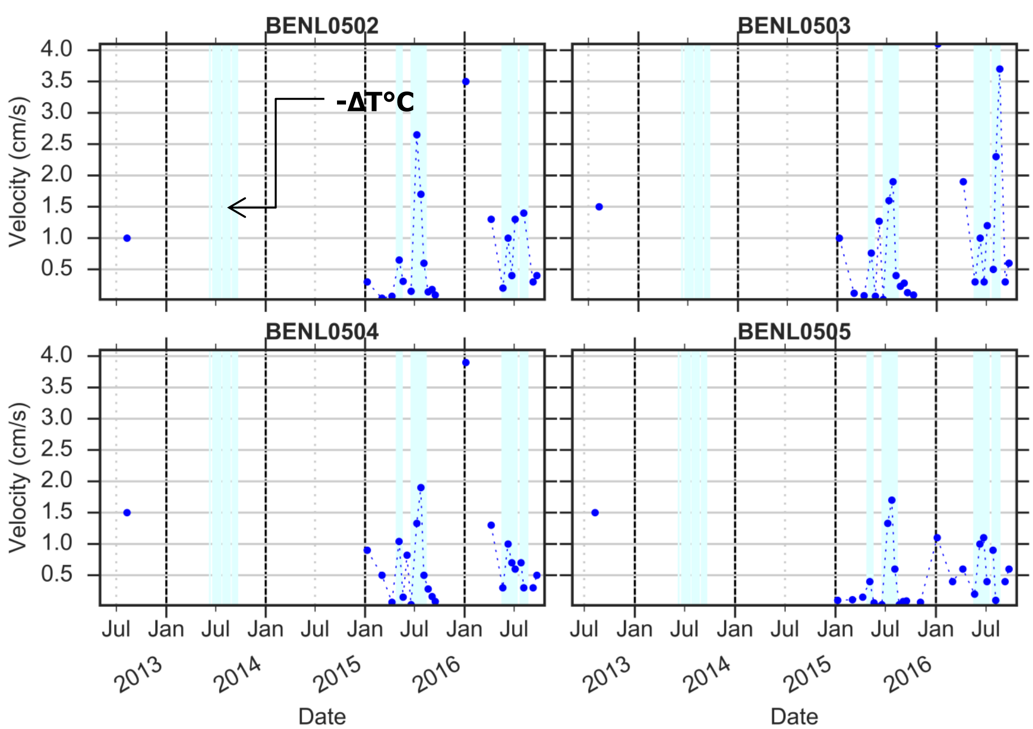


Figure 7.53 Time series plot – laboratory data – velocity

C. NON-METALLIC INORGANICS

A) SULPHATE

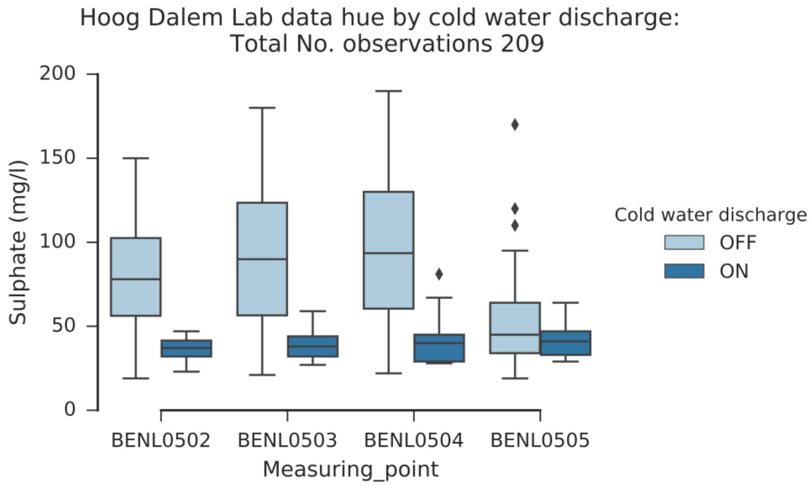


Figure 7.54 Box plot – laboratory data – sulphate

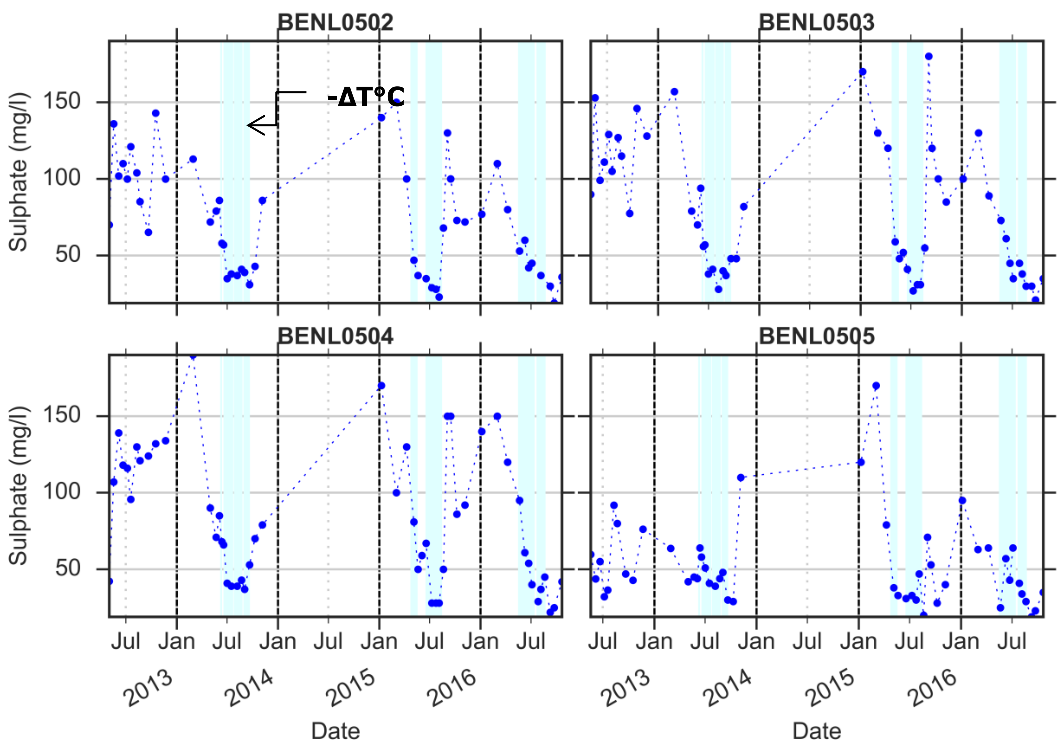


Figure 7.55 Time series plot – laboratory data – sulphate

D. DISSOLVED OXYGEN AND ORGANIC MATTER

A) DISSOLVED OXYGEN

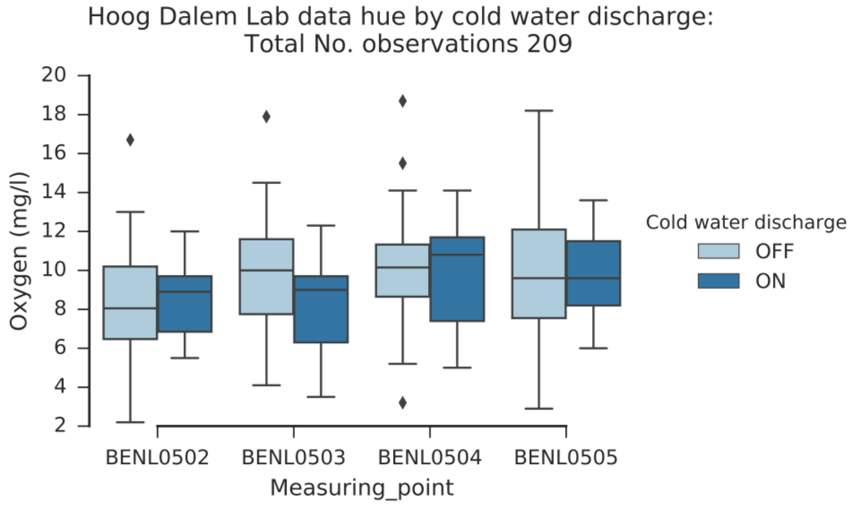


Figure 7.56 Box plot – laboratory data – oxygen

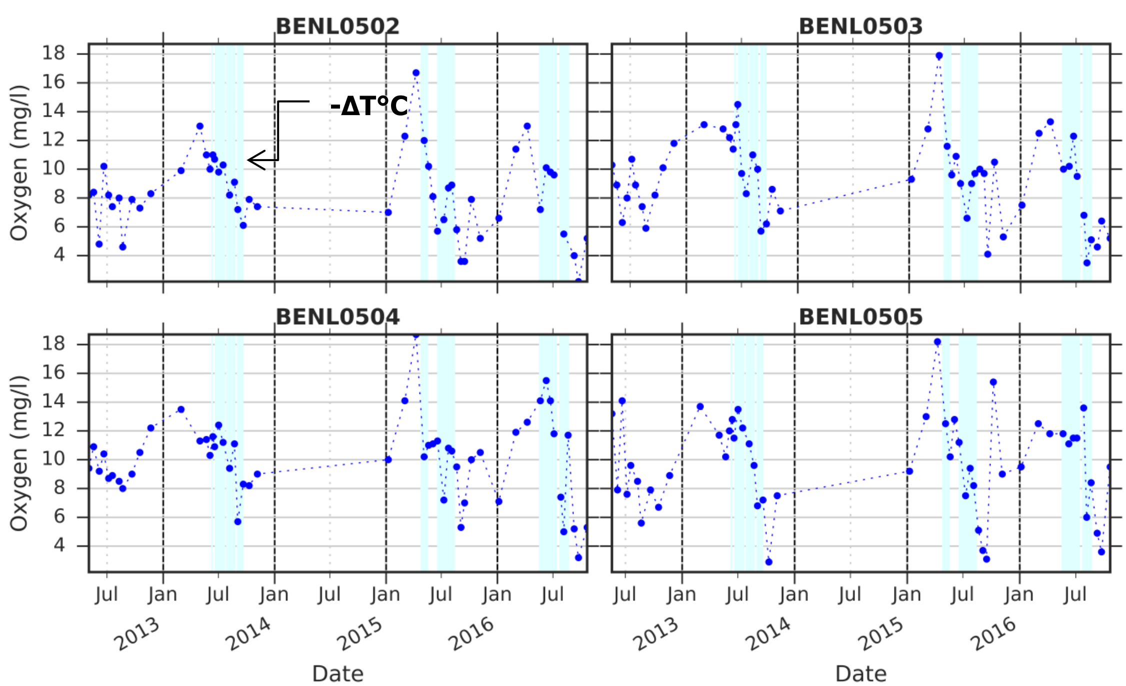


Figure 7.57 Time series plot – laboratory data – oxygen

A) OXYGEN SATURATION

The trend in oxygen saturation, presented in the next two graphs was similar to DO as previously discussed.

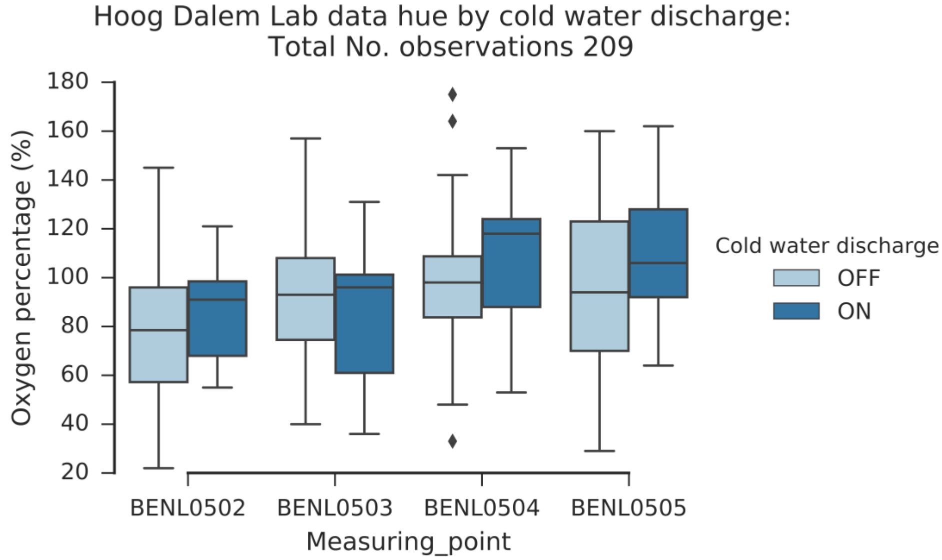


Figure 7.58 Box plot – laboratory data – oxygen (%)

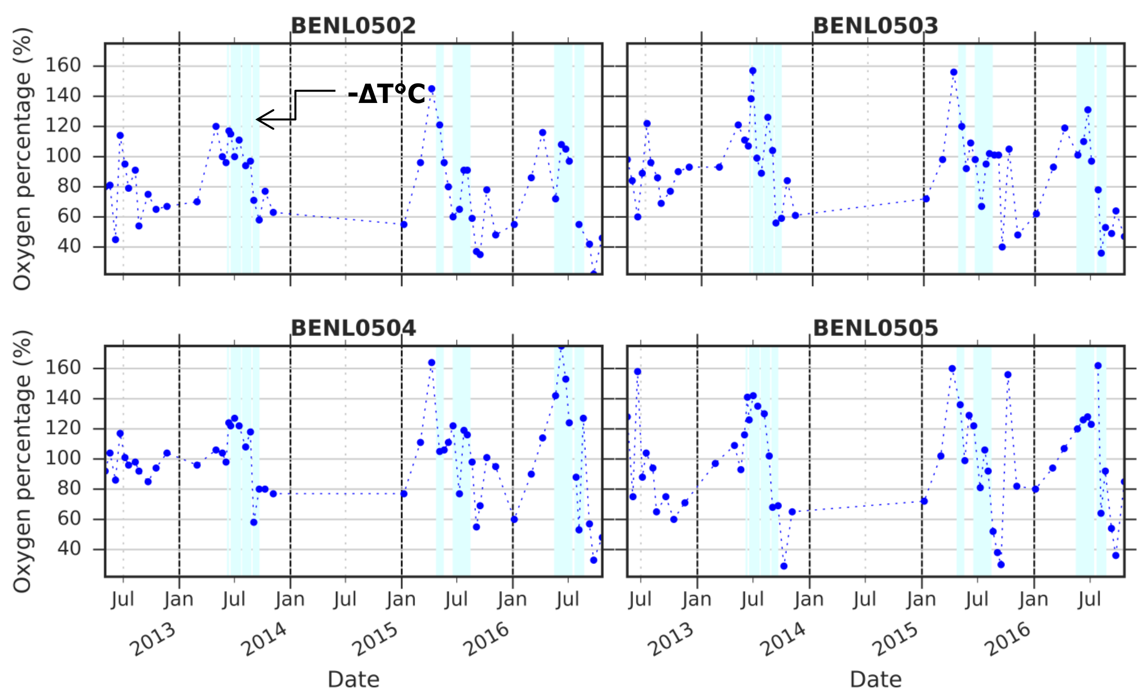


Figure 7.59 Time series plot – laboratory data – oxygen (%)

B) DISSOLVED ORGANIC CARBON

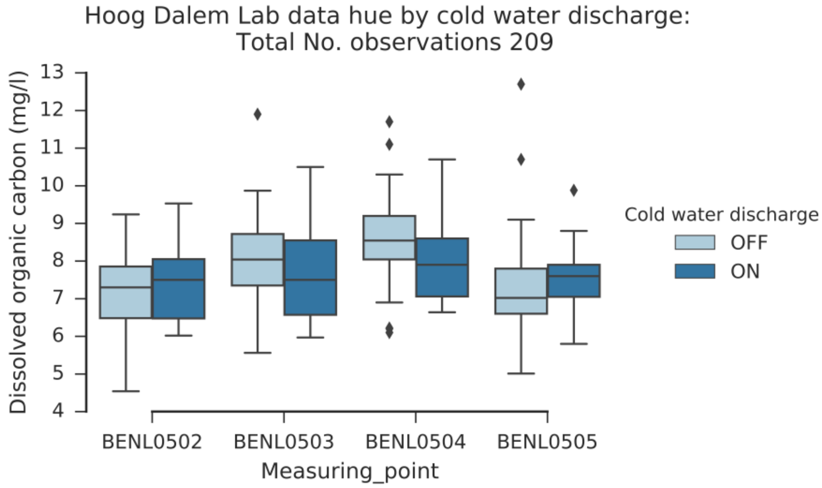


Figure 7.60 Box plot – laboratory data – DOC

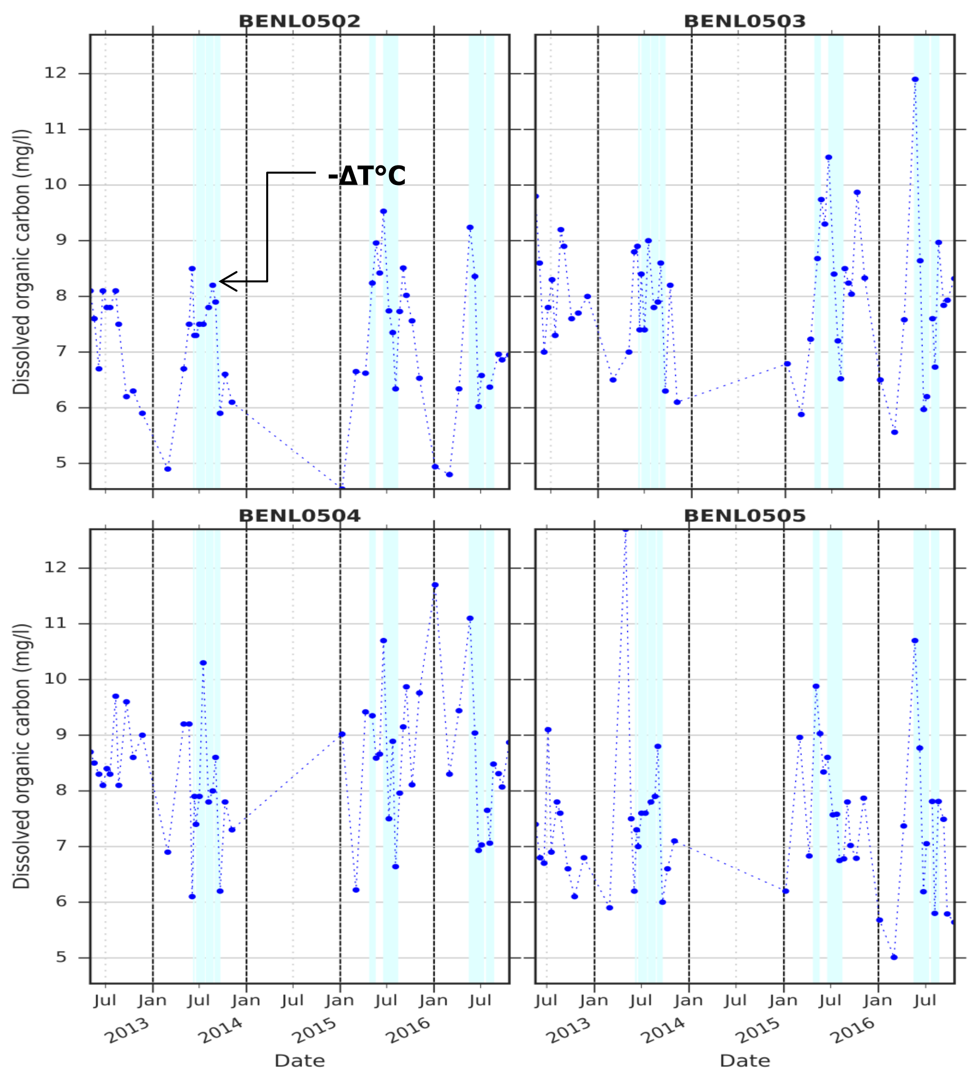


Figure 7.61 Time series plot – laboratory data – DOC

C) TOTAL ORGANIC CARBON

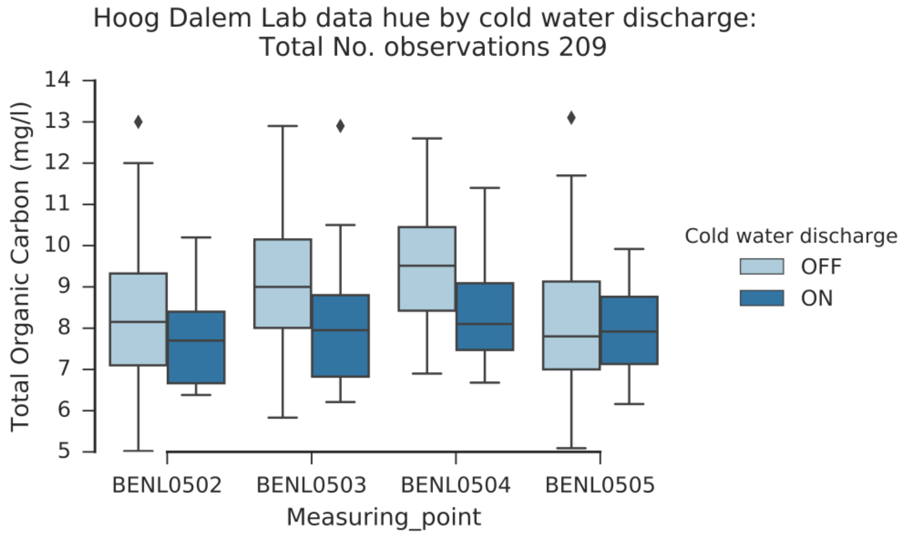


Figure 7.62 Box plot – laboratory data – TOC

TOC was rarely below 6mg/l and experienced peak concentrations along the channel up to 13mg/l, as presented in the next graph. The two highest peaks occurred during May.

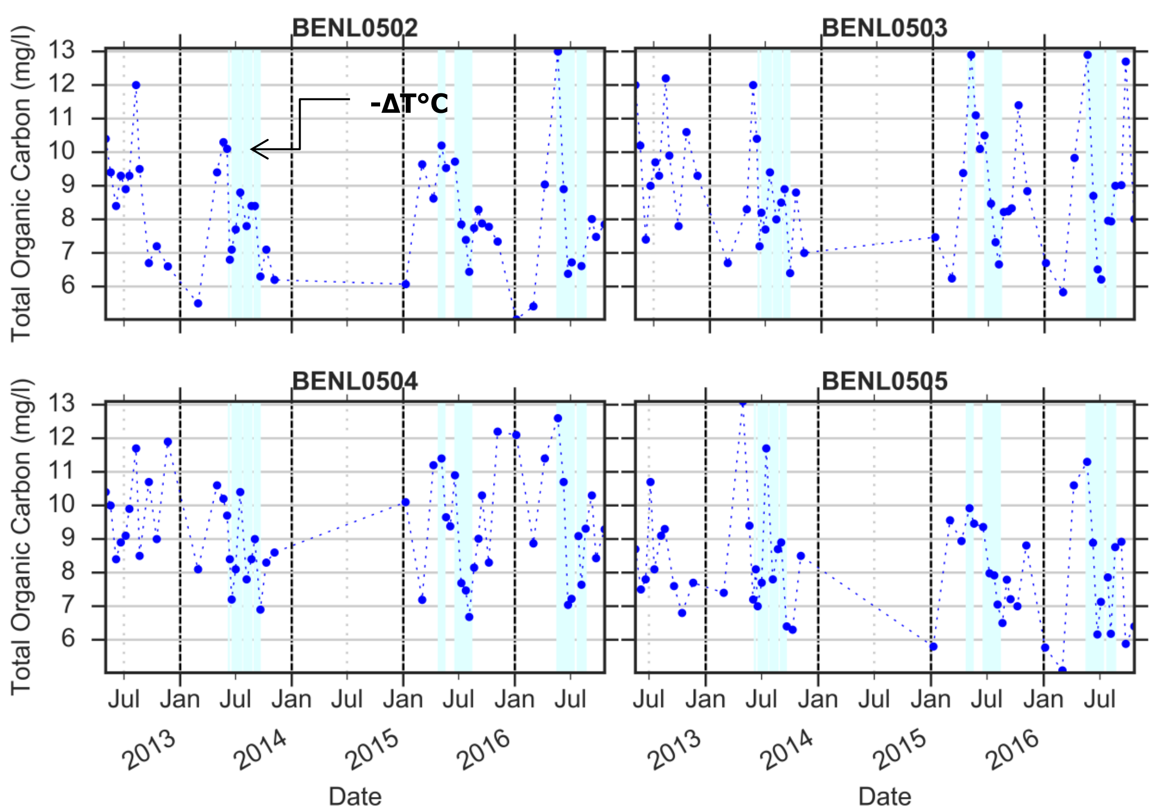


Figure 7.63 Time series plot – laboratory data – TOC

E. OPTICAL PROPERTIES

A) TOTAL SUSPENDED SOLIDS

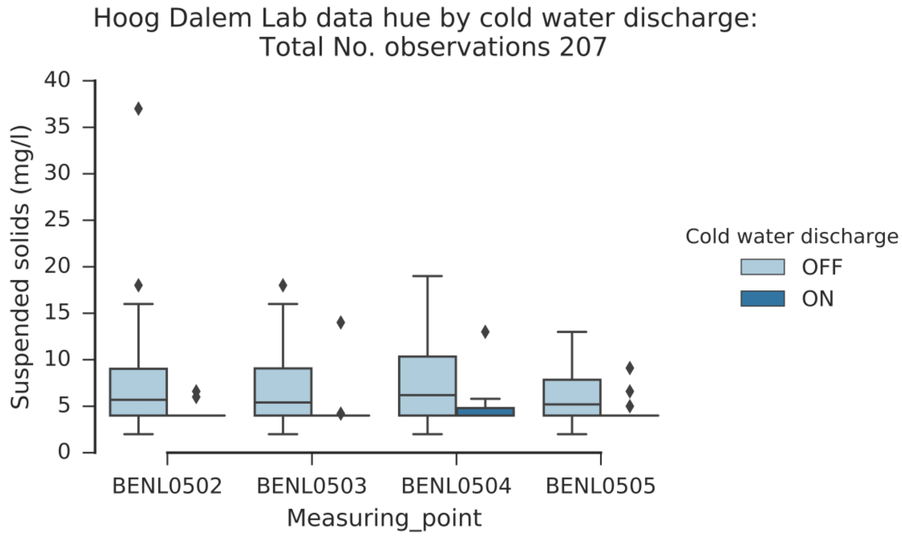


Figure 7.64 Box plot – laboratory data – SS

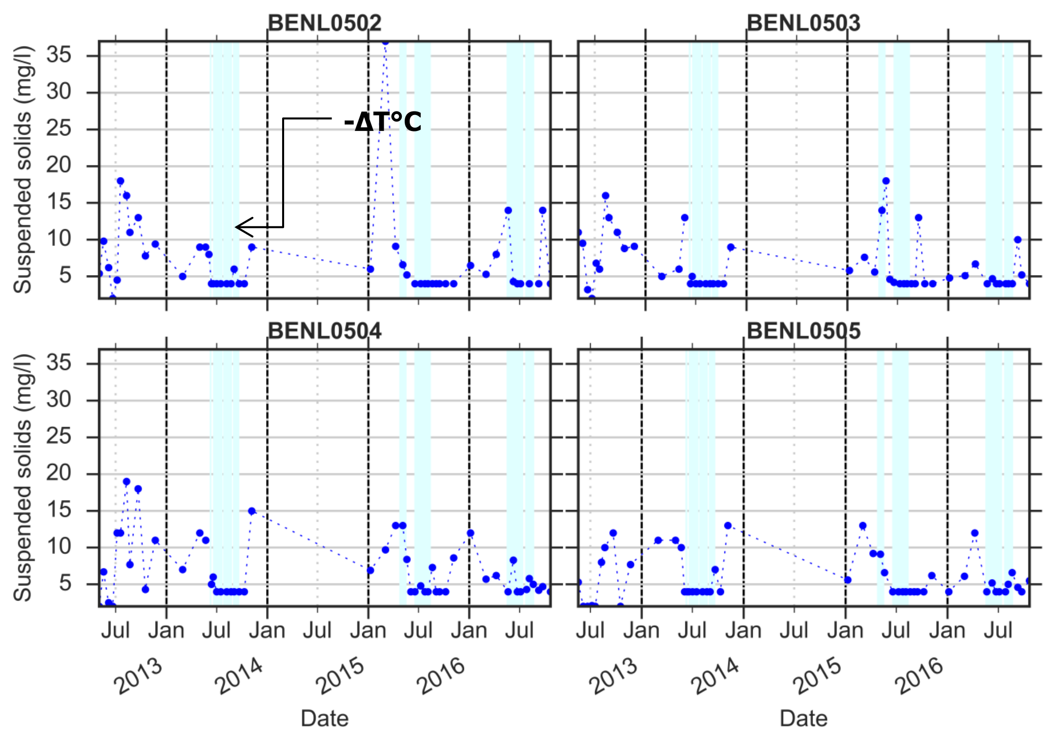


Figure 7.65 Time series plot – laboratory data – SS

B) TURBIDITY

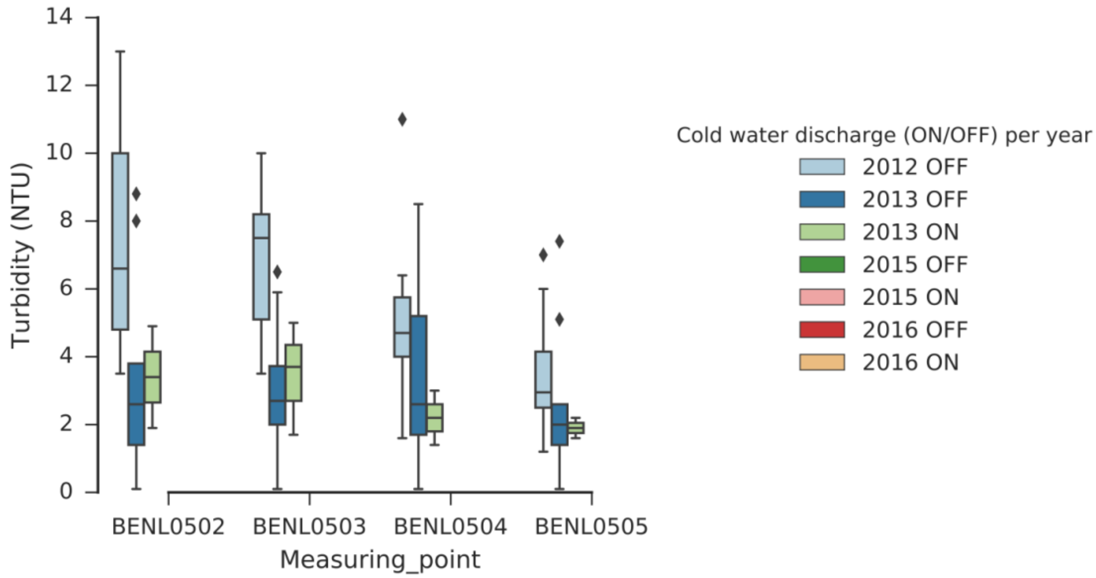


Figure 7.66 Box plot – laboratory data – turbidity

Turbidity observations are presented in the next graph, measurements after 2013 were not undertaken.

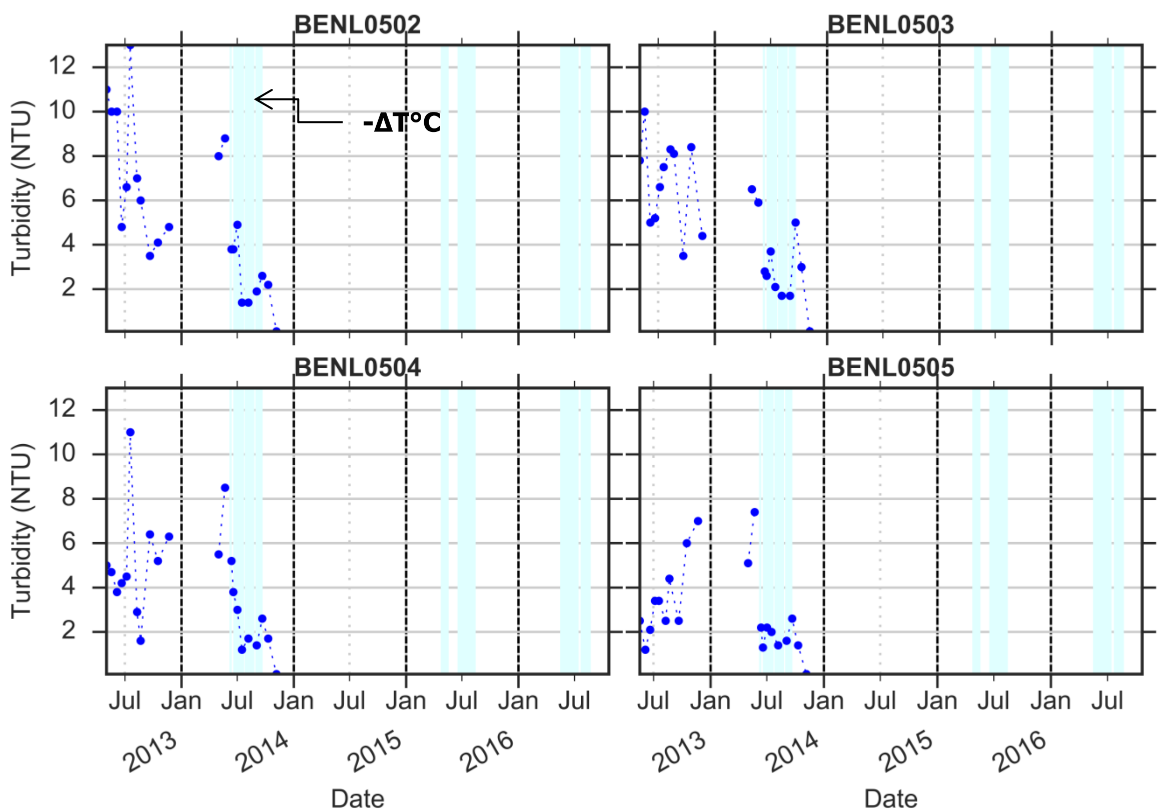


Figure 7.67 Time series plot – laboratory data – turbidity

C) SECCHI DEPTH

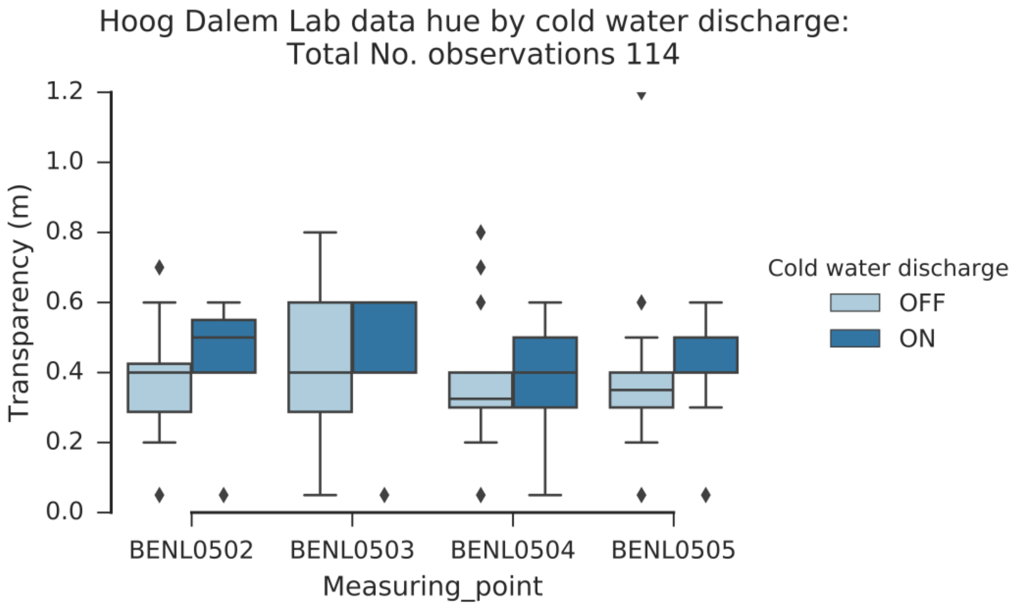


Figure 7.68 Box plot – laboratory data – SD

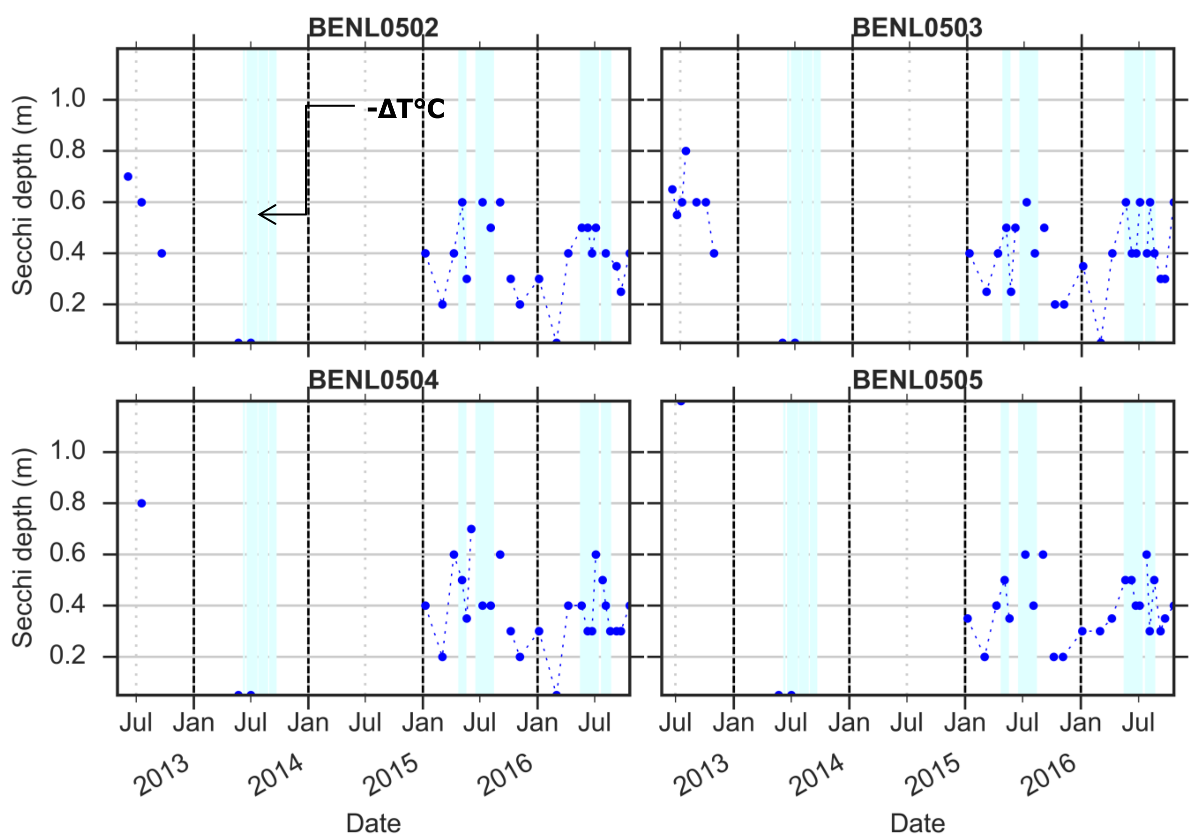


Figure 7.69 Time series plot – laboratory data – SD

F. NUTRIENTS

A) TOTAL PHOSPHORUS

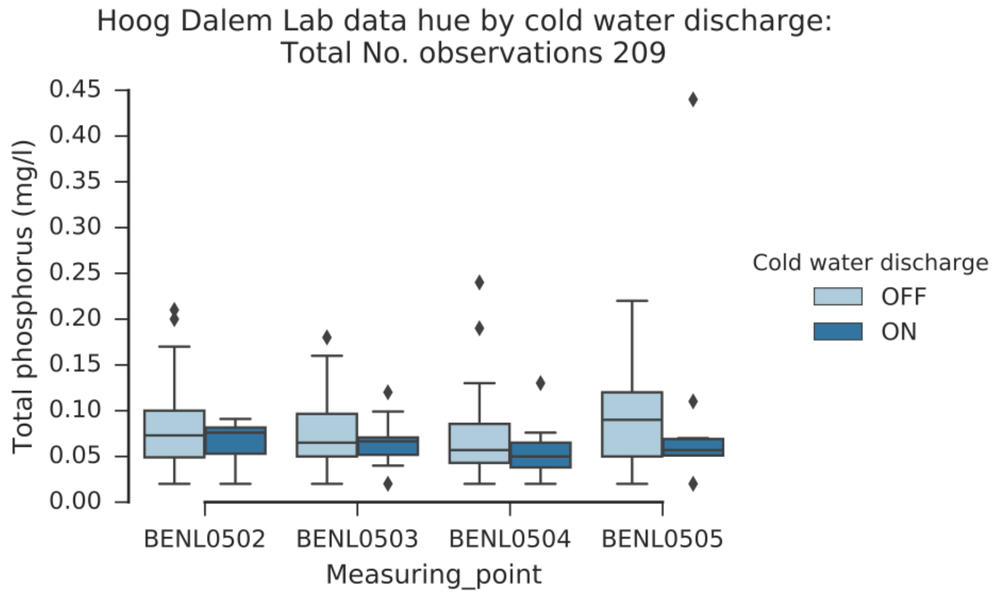


Figure 7.70 Box plot – laboratory data – TP

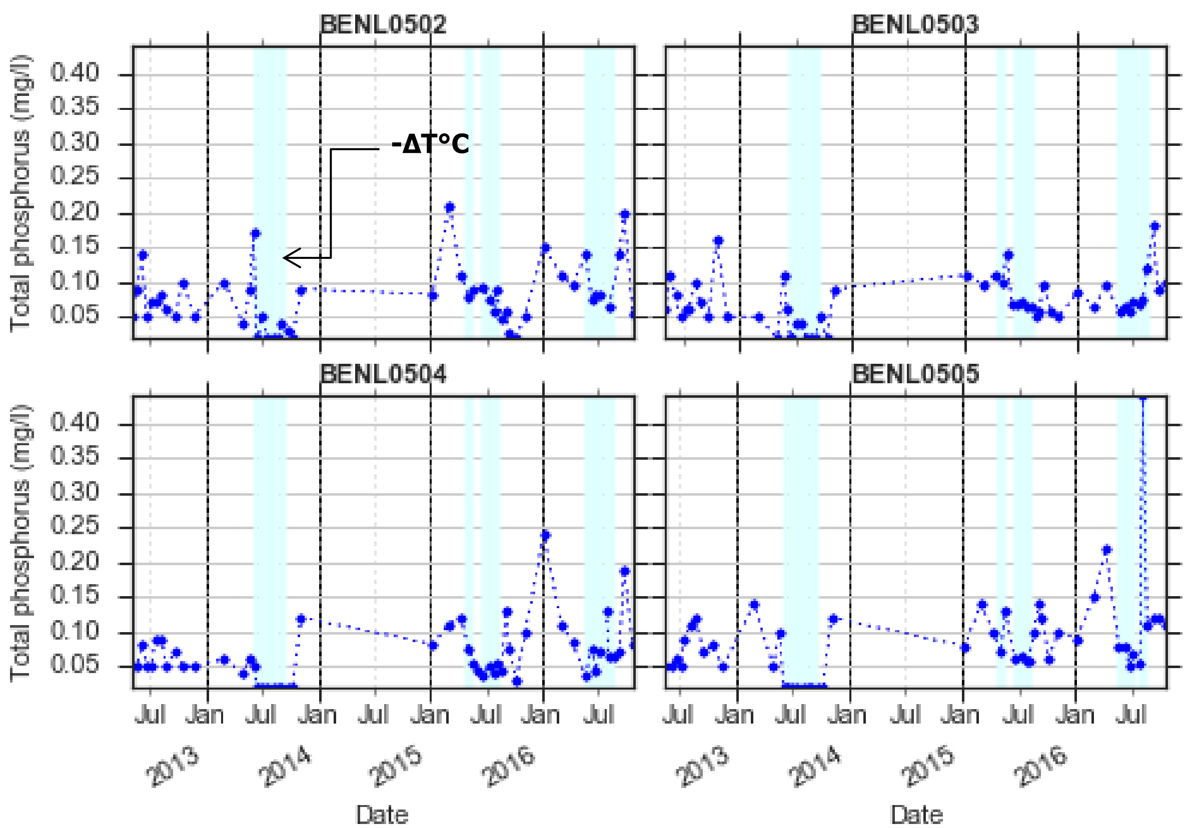


Figure 7.71 Time series plot – laboratory data – TP

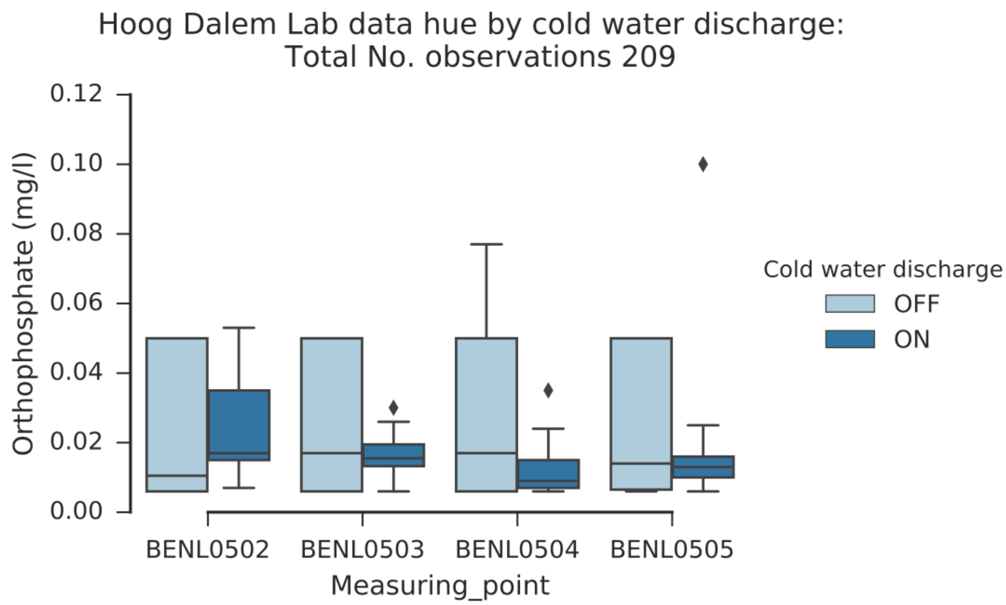


Figure 7.72 Box plot – laboratory data – orthophosphate

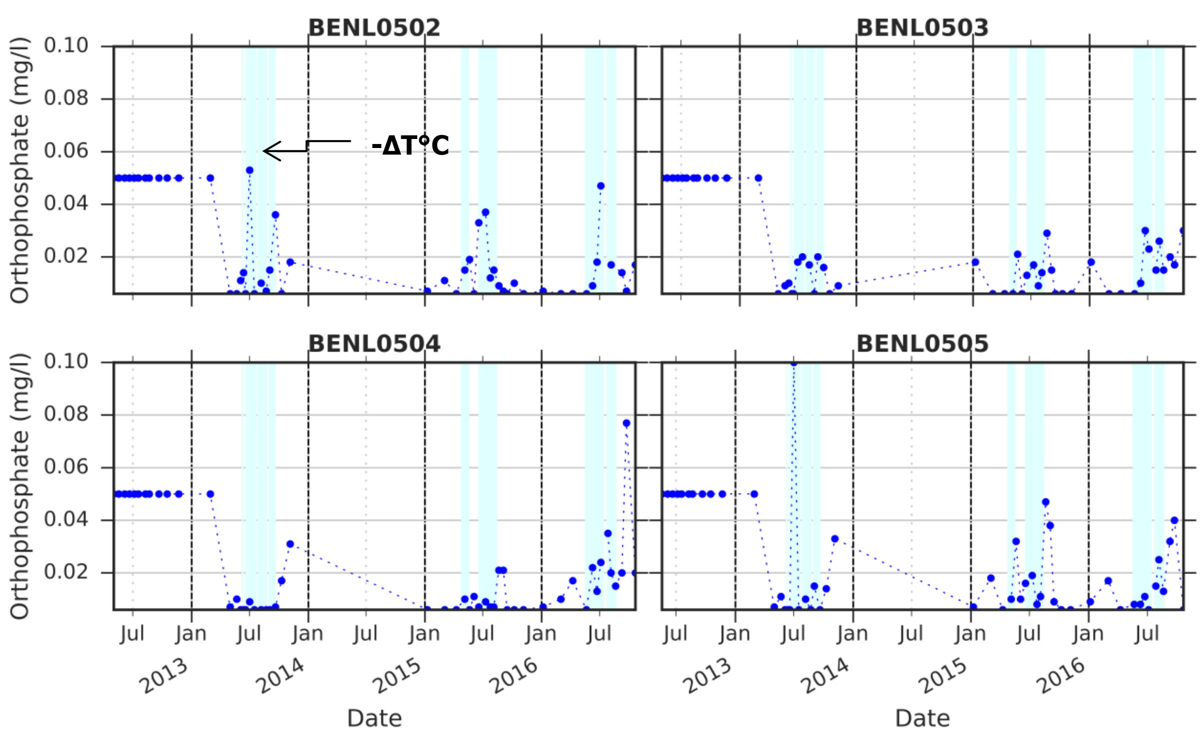


Figure 7.73 Time series plot – laboratory data – orthophosphate

B) TOTAL NITROGEN

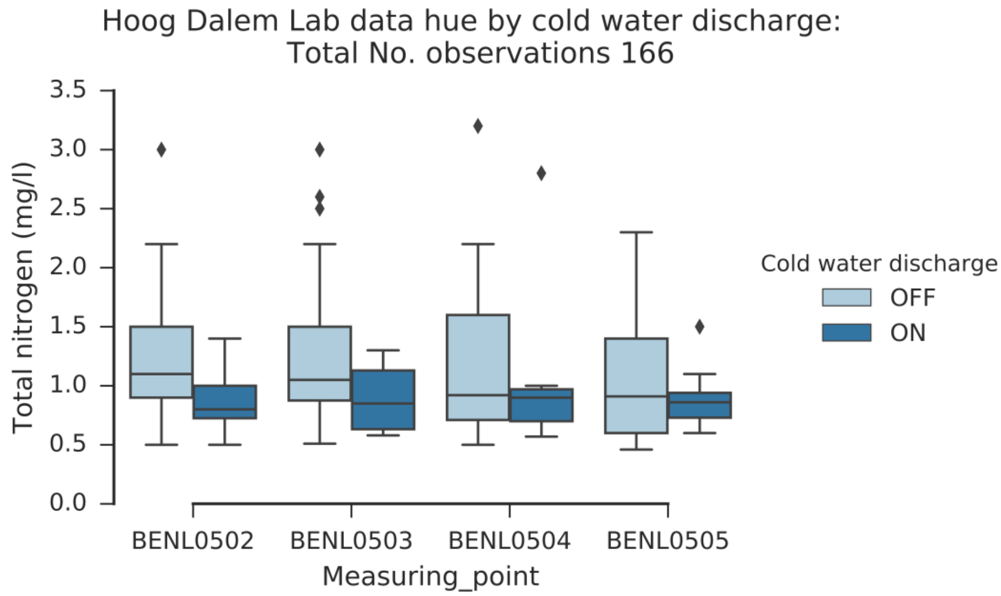


Figure 7.74 Box plot – laboratory data – TN

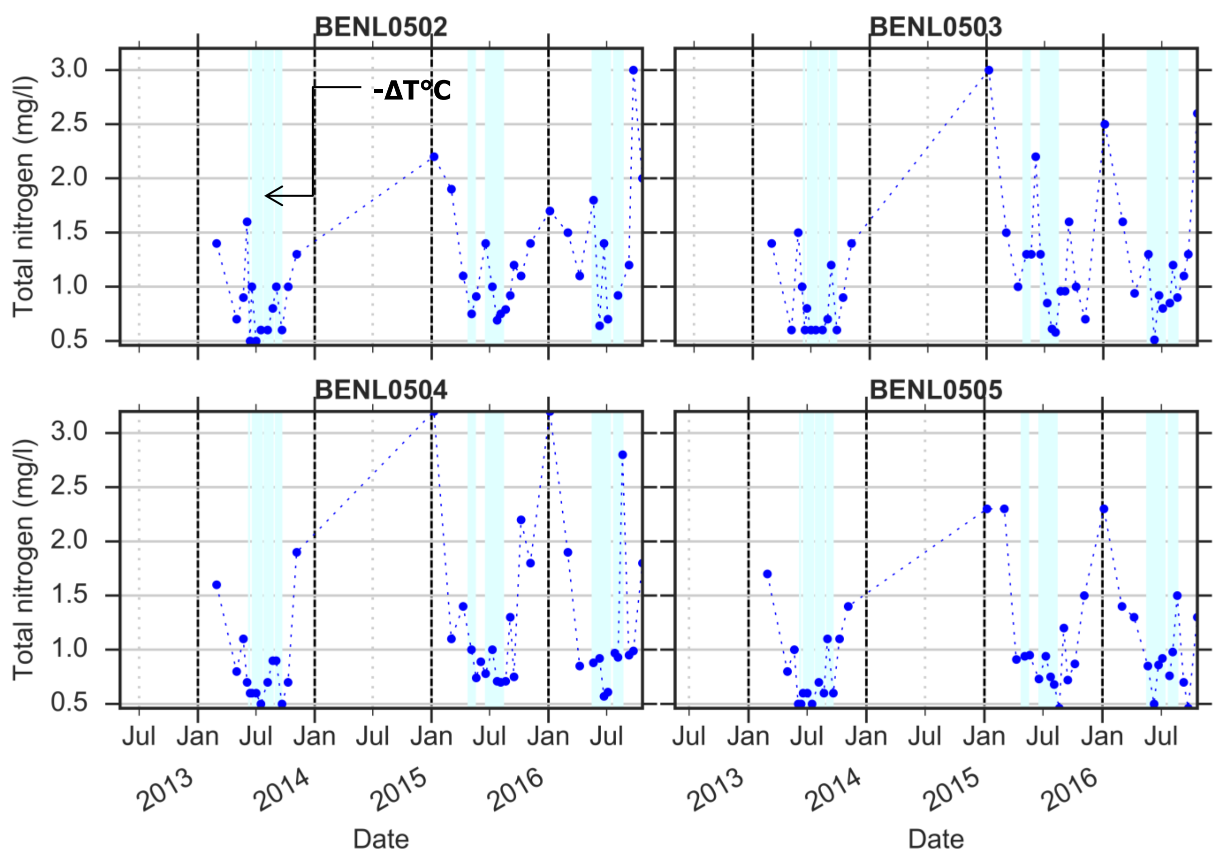


Figure 7.75 Time series plot – laboratory data – TN

C) AMMONIUM

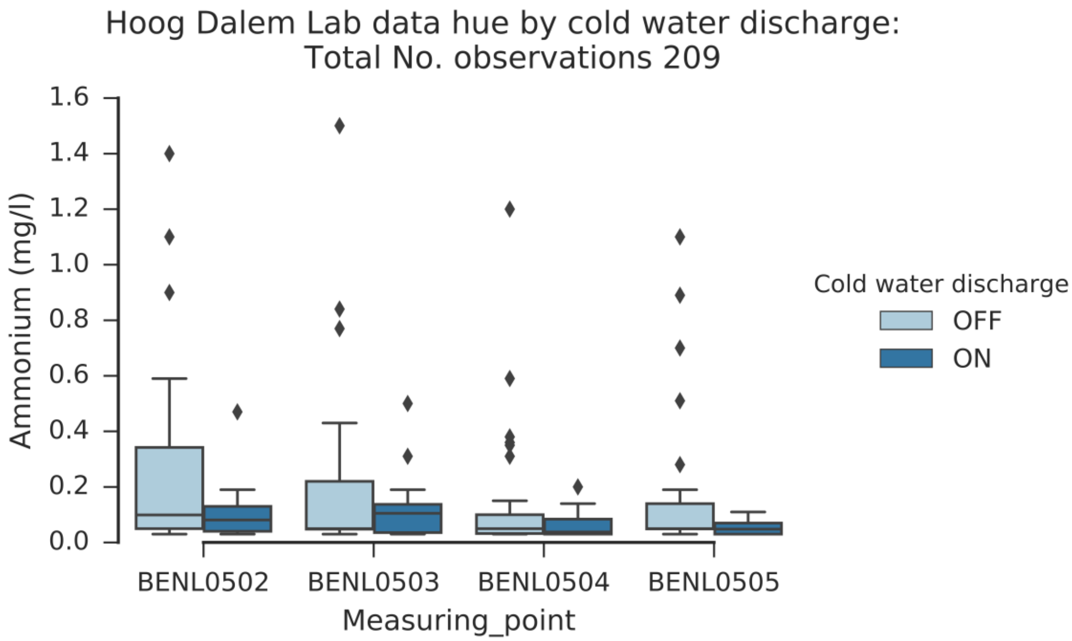


Figure 7.76 Box plot – laboratory data – ammonium

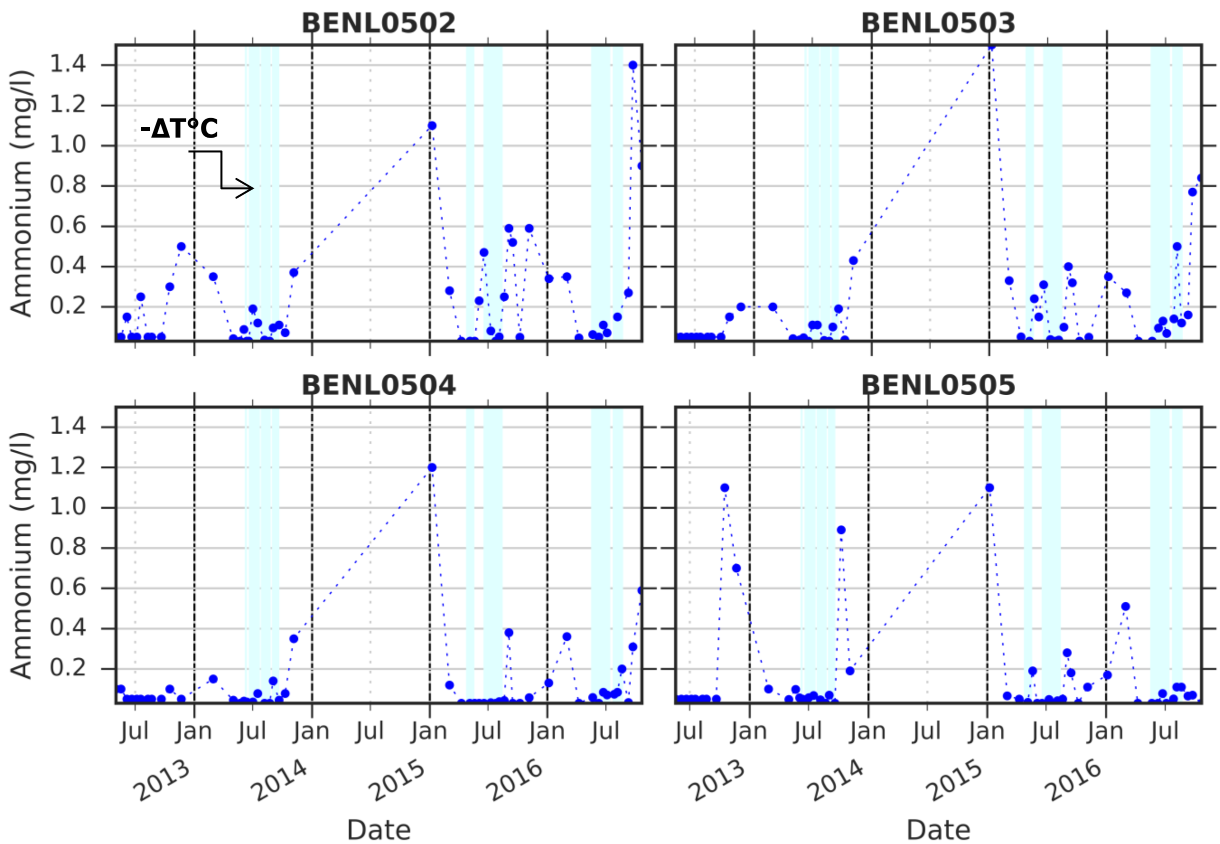


Figure 7.77 Time series plot – laboratory data – ammonium

D) TOTAL KJELDAHL NITROGEN

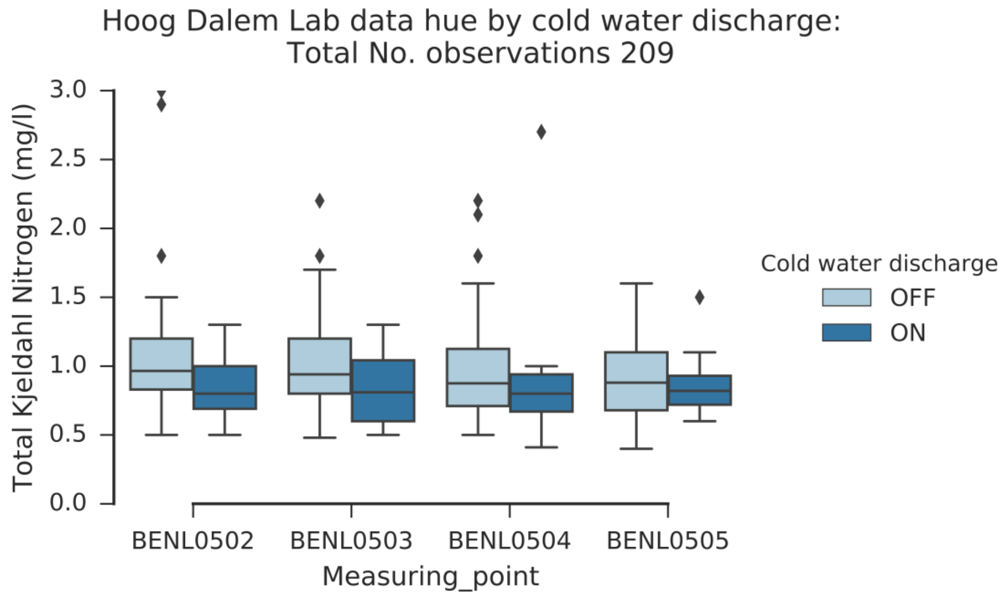


Figure 7.78 Box plot – laboratory data – TKN

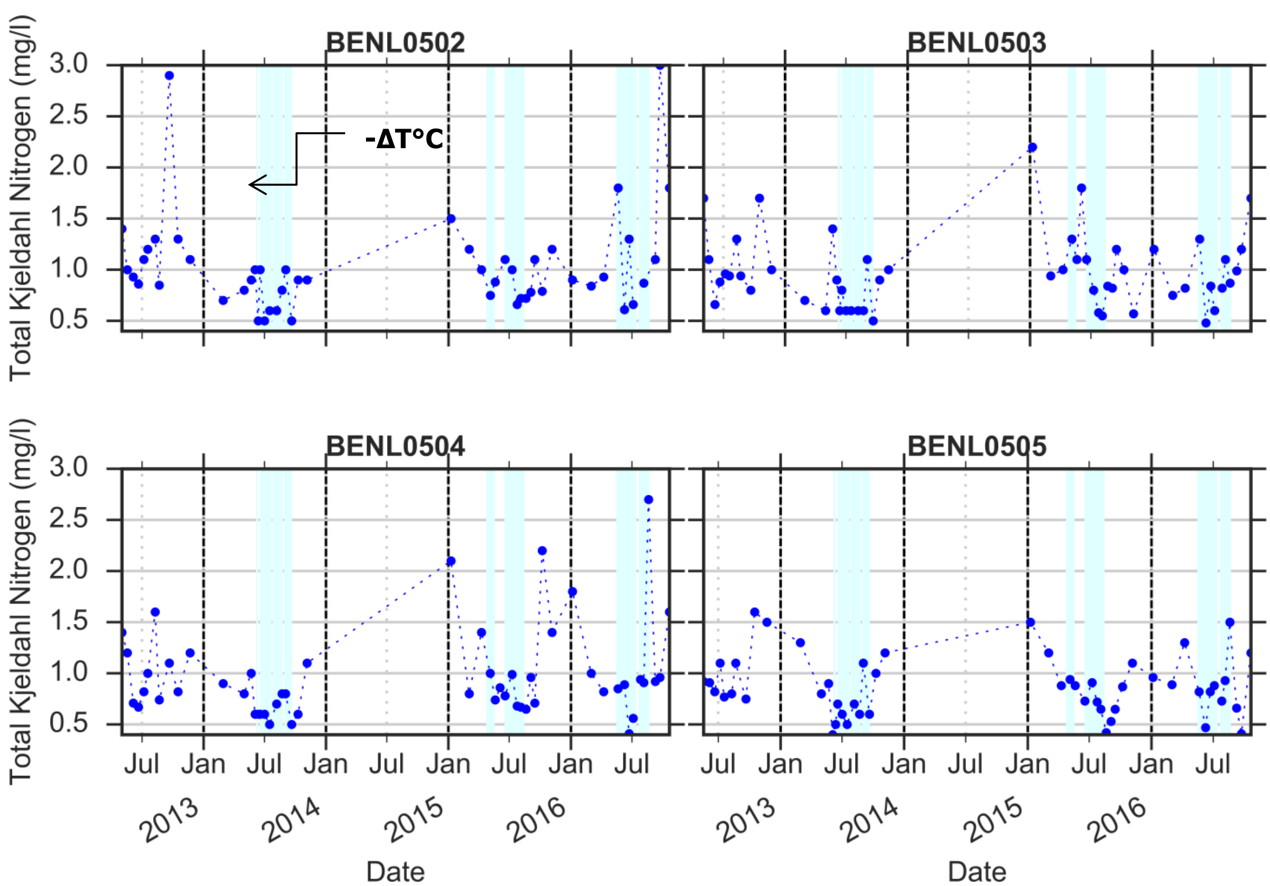


Figure 7.79 Time series plot – laboratory data - TKN

E) NITRATE

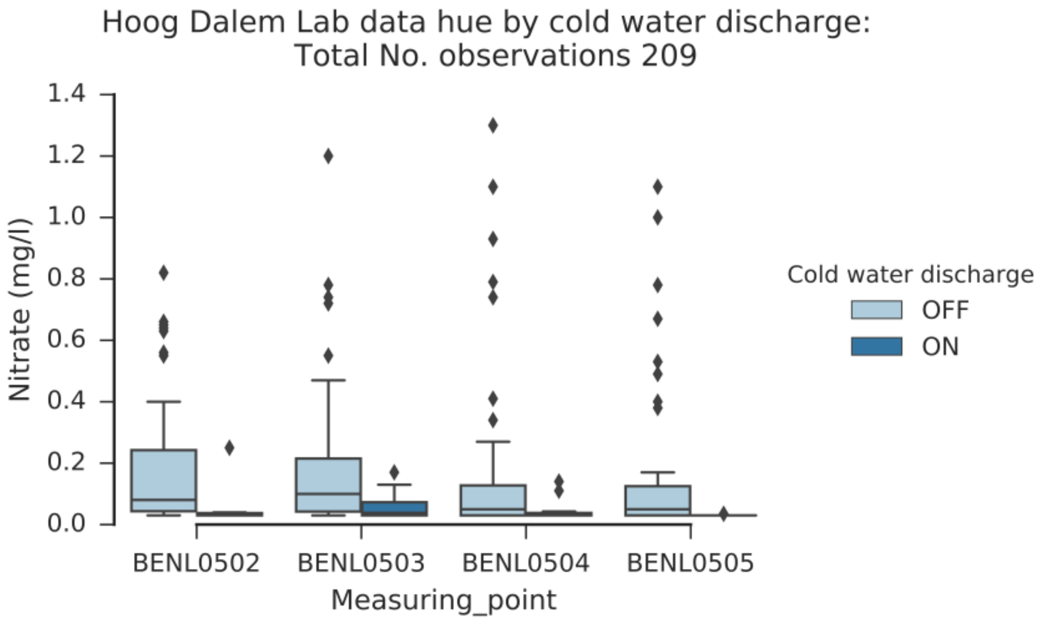


Figure 7.80 Box plot – laboratory data – nitrate

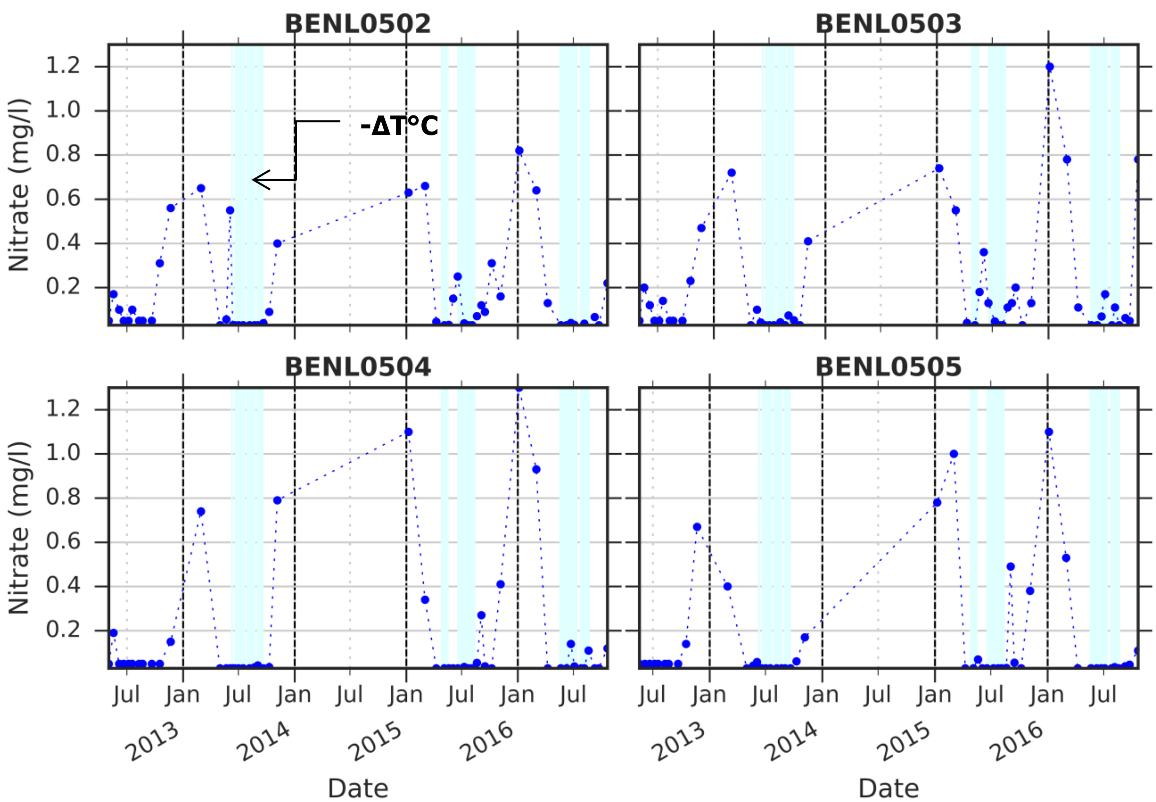


Figure 7.81 Time series plot – laboratory data – nitrate

F) NITRITE

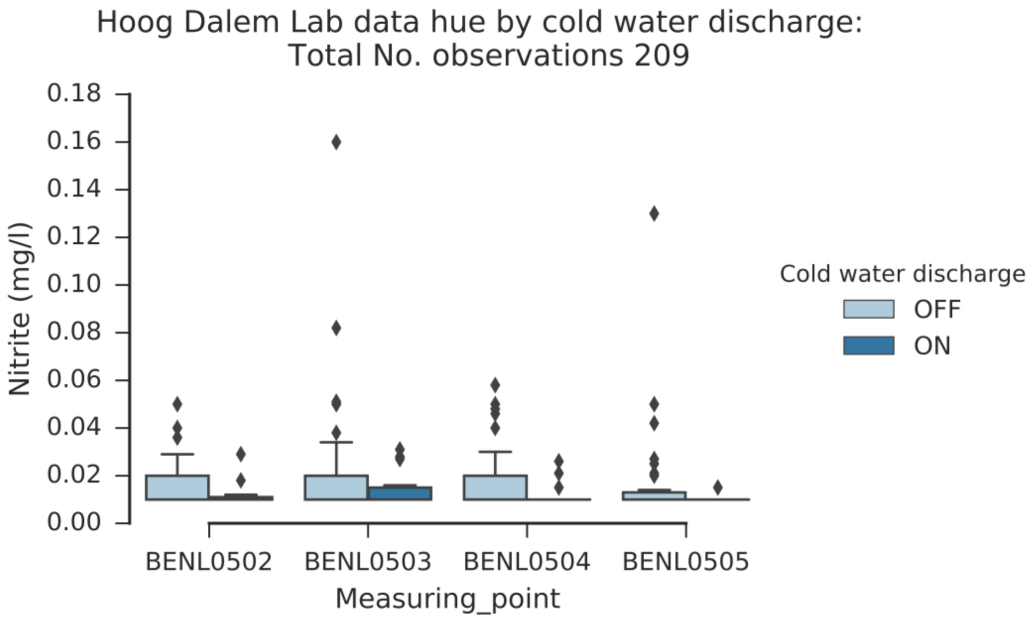


Figure 7.82 Box plot – laboratory data – nitrite

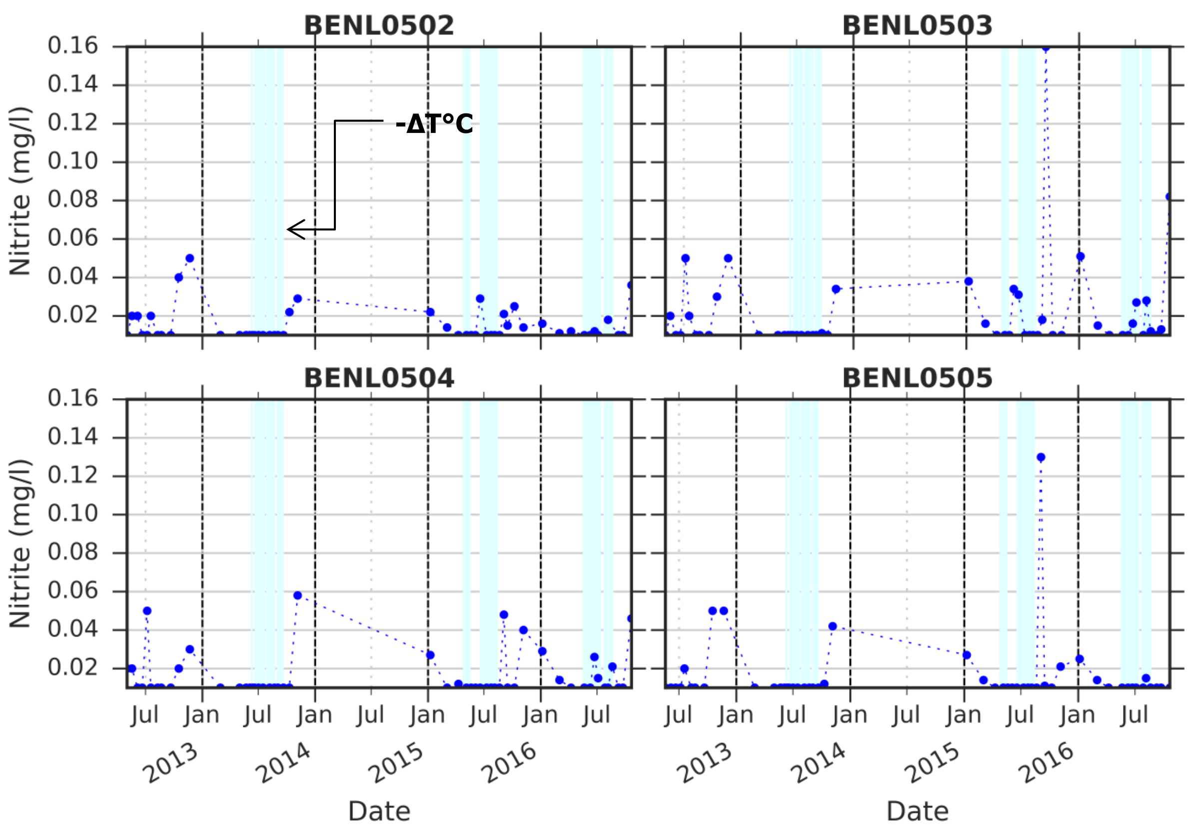


Figure 7.83 Time series plot – laboratory data – nitrite

G. BIOMASS

A) CHLOROPHYLL-A

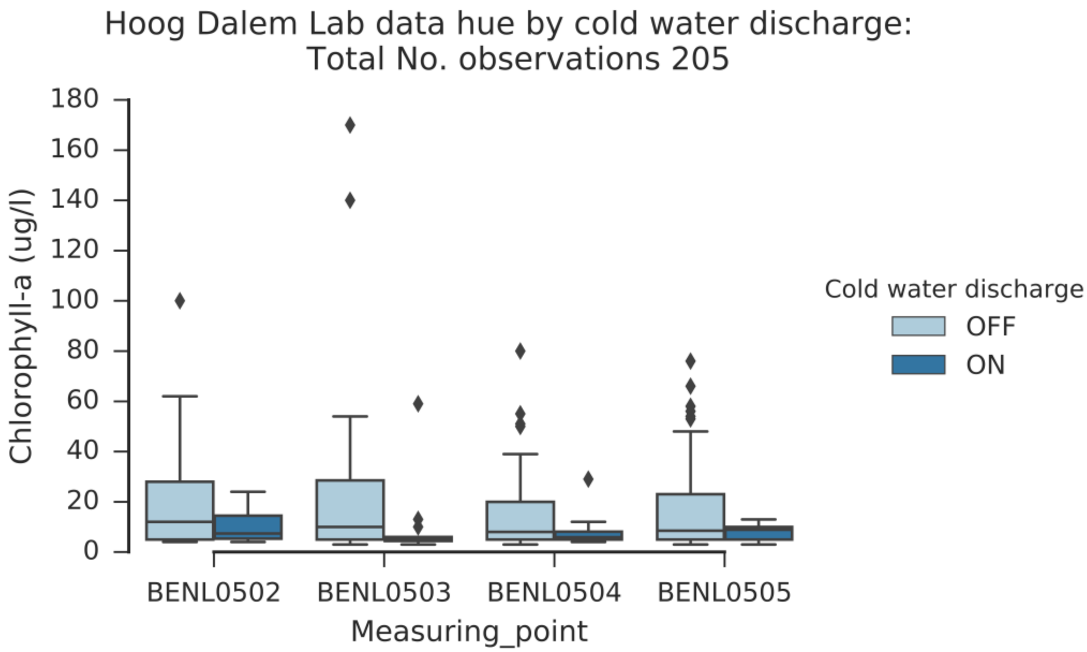


Figure 7.84 Box plot – laboratory data – Chl-a

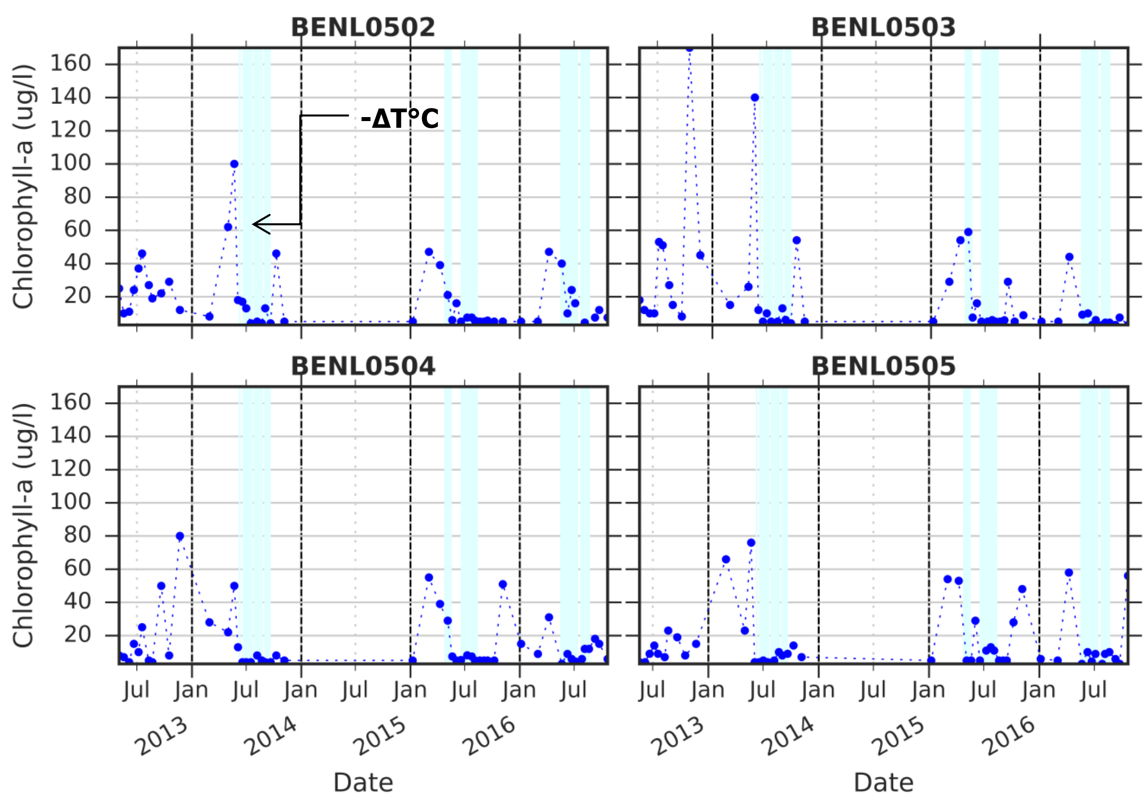


Figure 7.85 Time series plot – laboratory data – Chl-a

B) PHEOPHYTIN-A

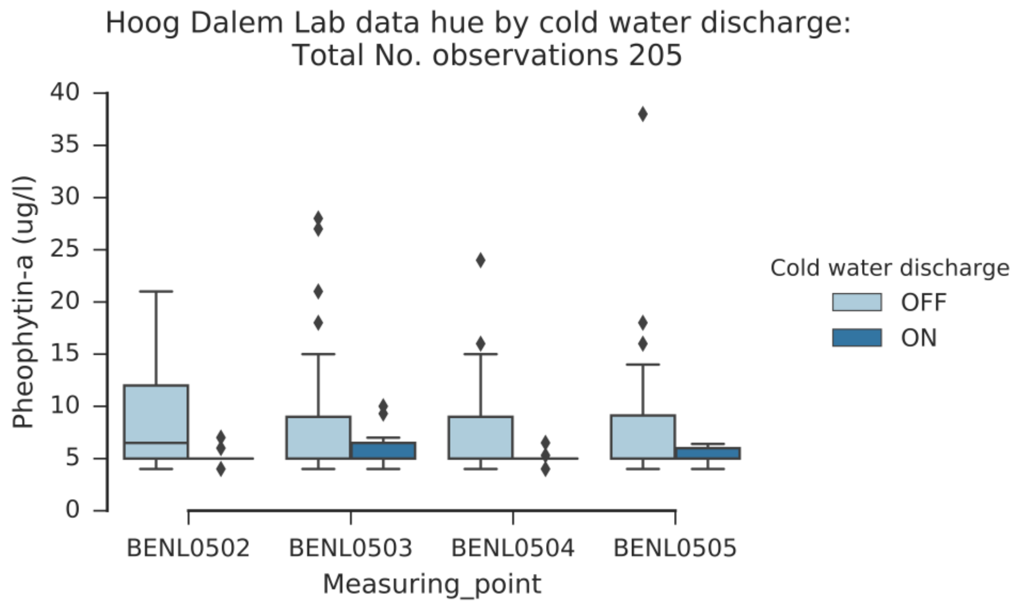


Figure 7.86 Box plot – laboratory data – Pheo-a

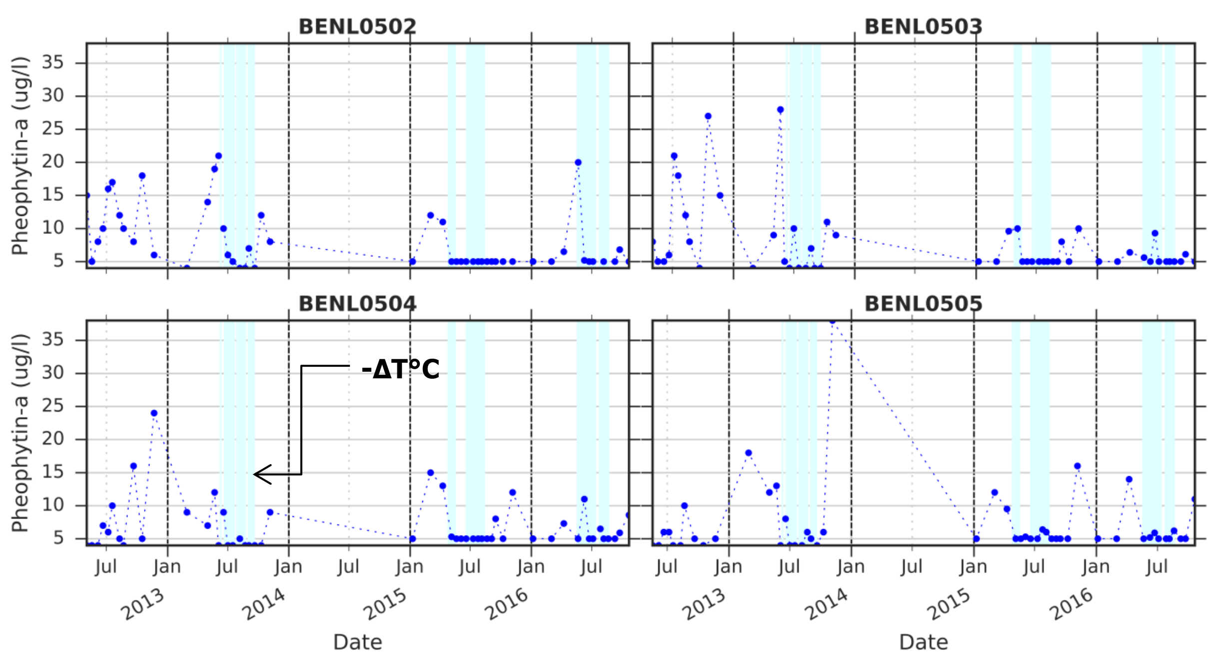


Figure 7.87 Time series plot – laboratory data – Pheo-a

H. SALINITY

A) ELECTRICAL CONDUCTIVITY

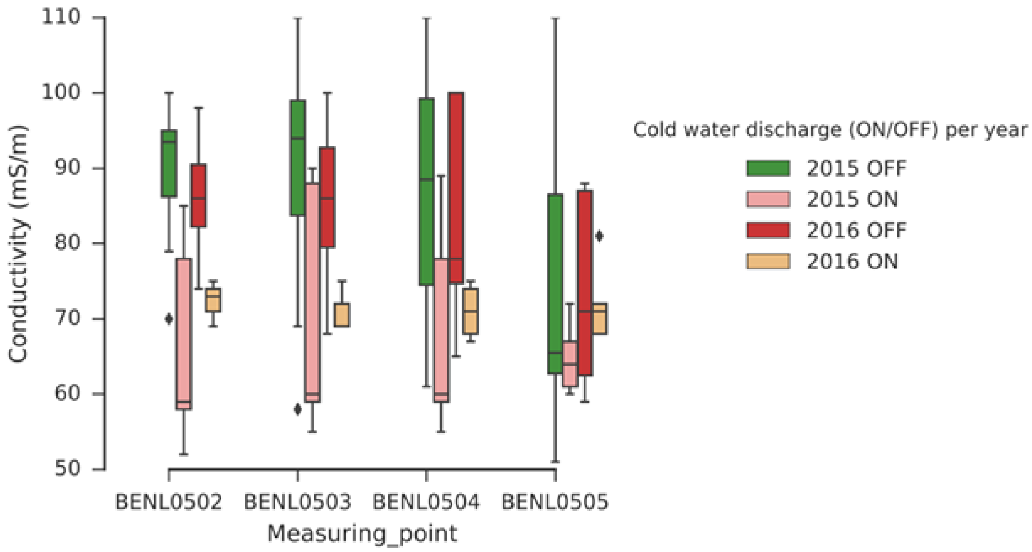


Figure 7.88 Box plot – laboratory data – EC

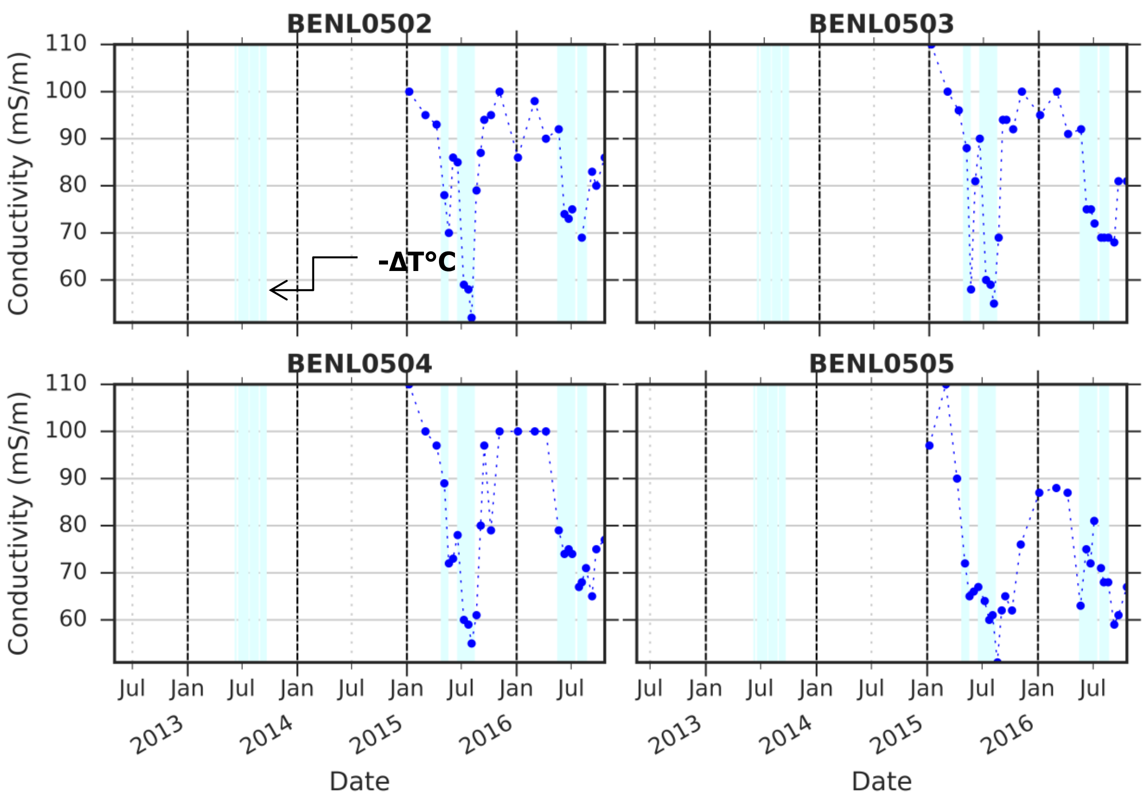


Figure 7.89 Time series plot – laboratory data – EC

B) CHLORIDE

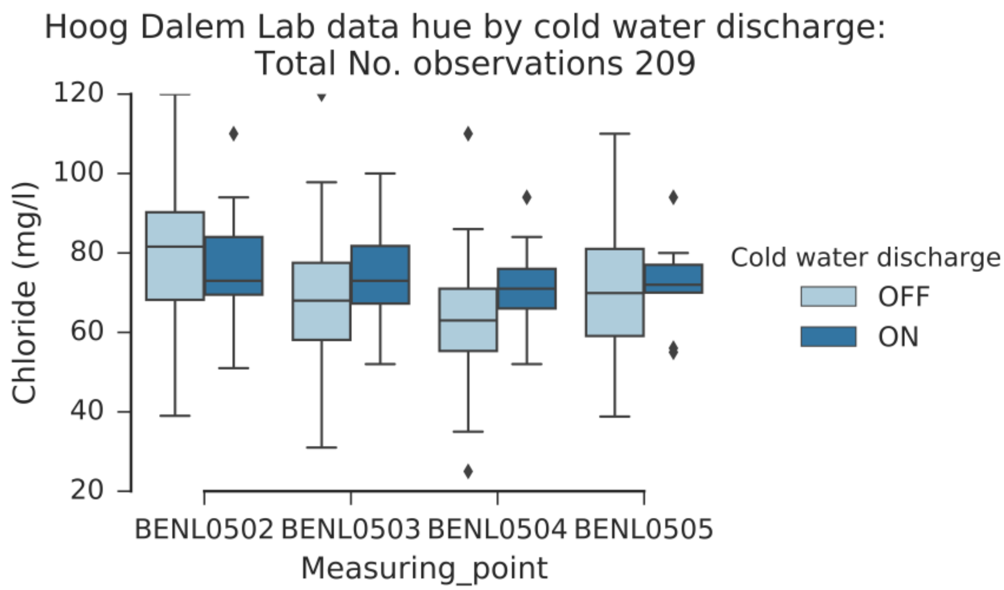


Figure 7.90 Box plot – laboratory data – chloride

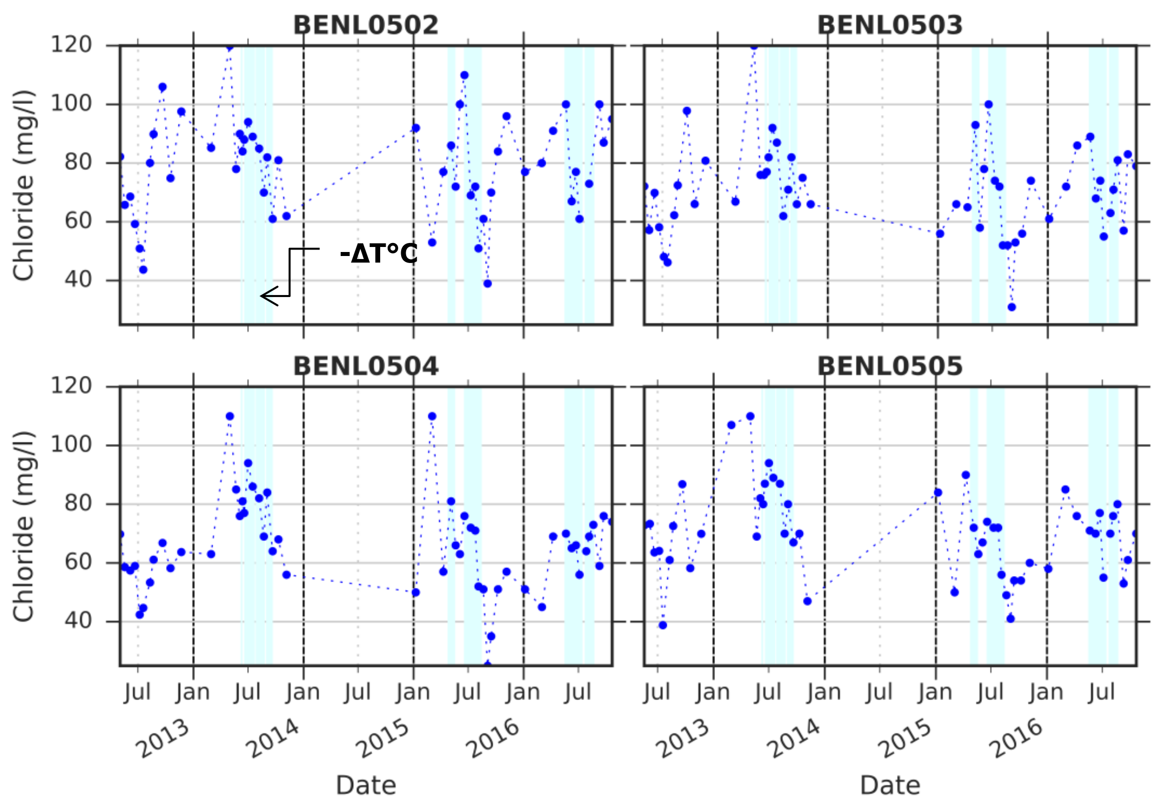


Figure 7.91 Time series plot – laboratory data – chloride

I. ACIDITY

A) PH

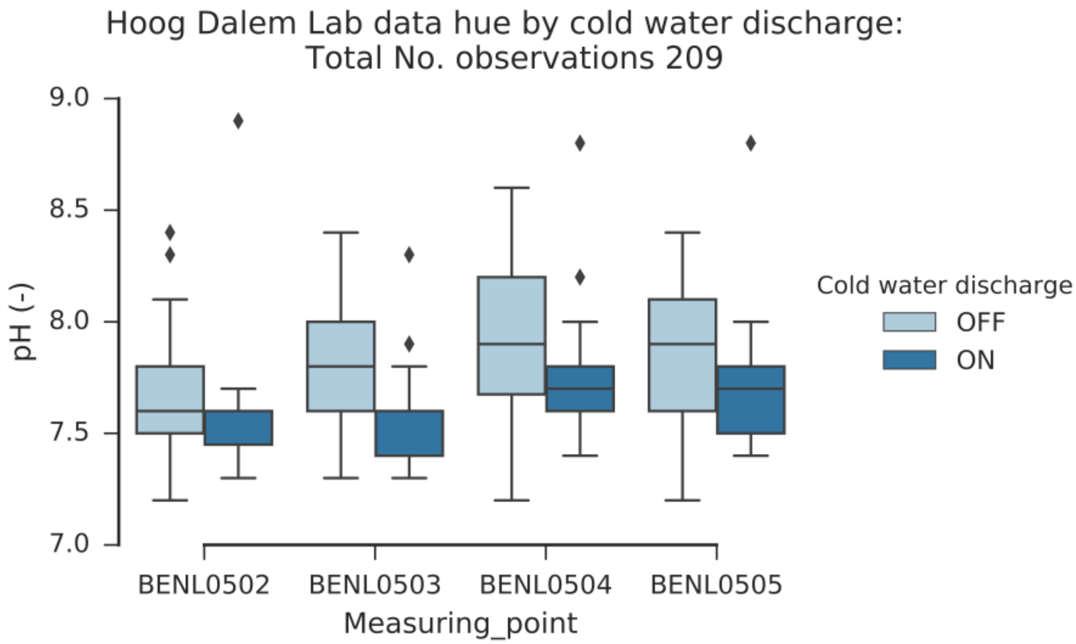


Figure 7.92 Box plot – laboratory data – pH

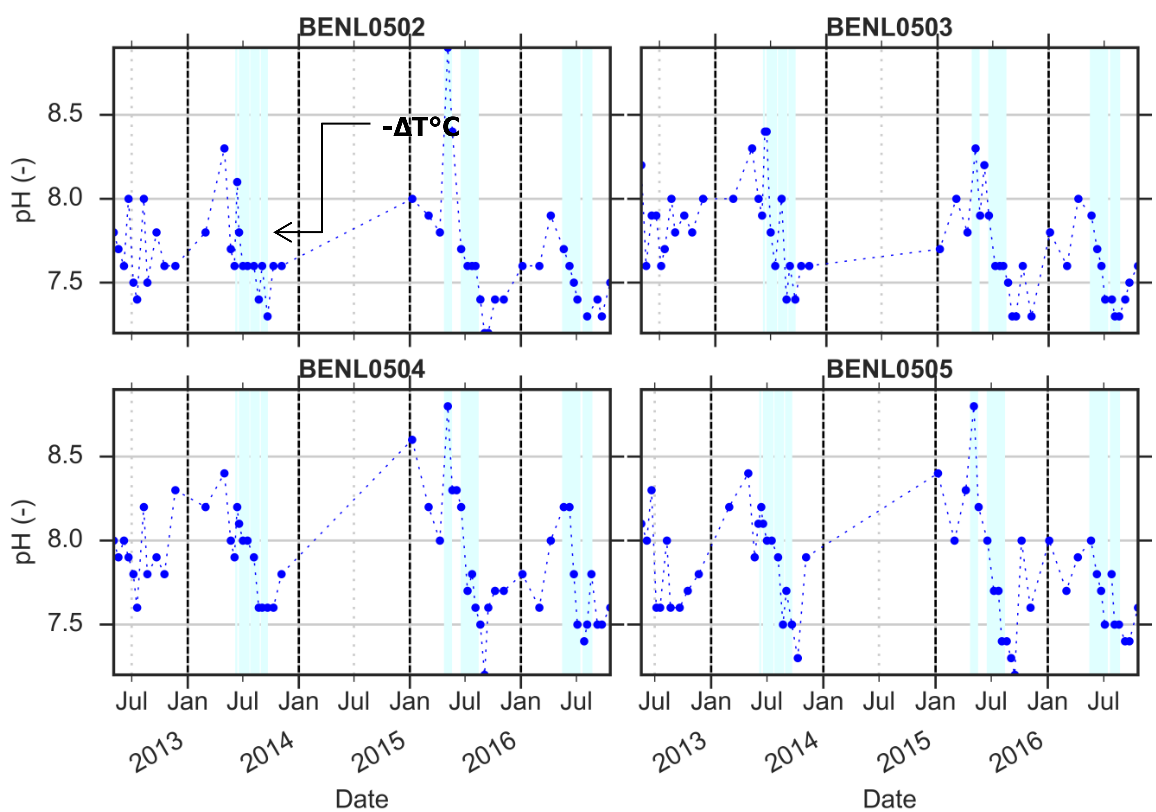


Figure 7.93 Time series plot – laboratory data – pH

B) BICARBONATE

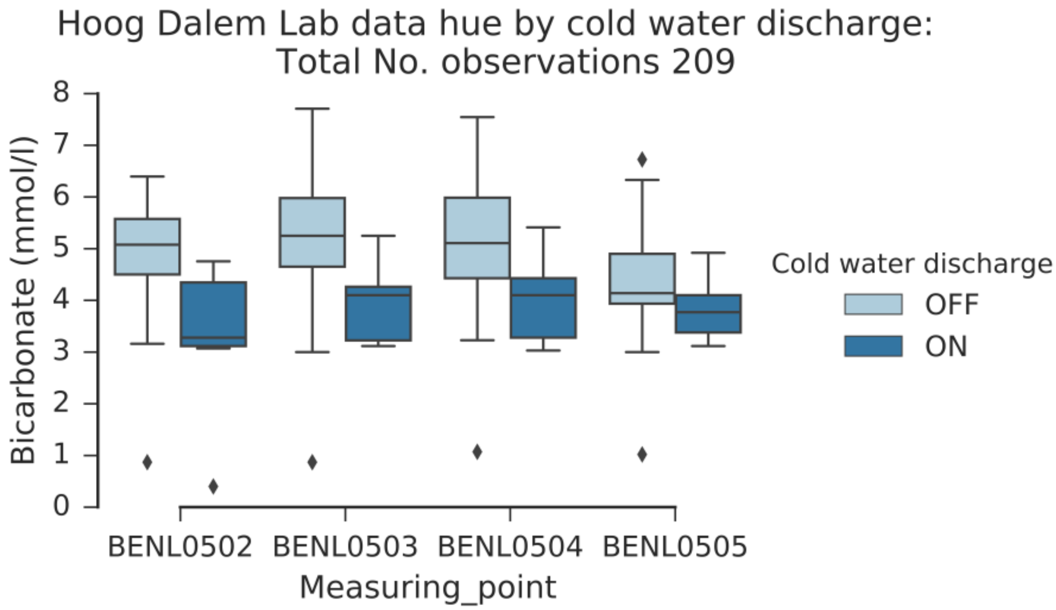


Figure 7.94 Box plot – laboratory data – bicarbonate

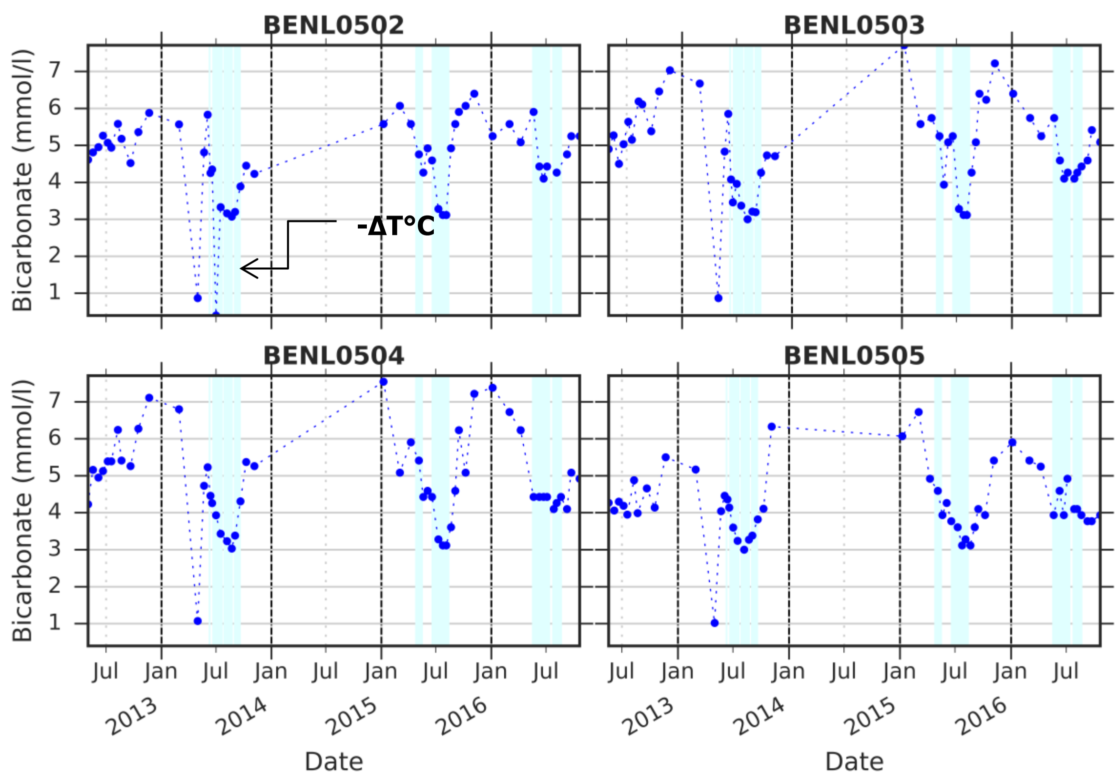


Figure 7.95 Time series plot – laboratory data – bicarbonate

J. IRON

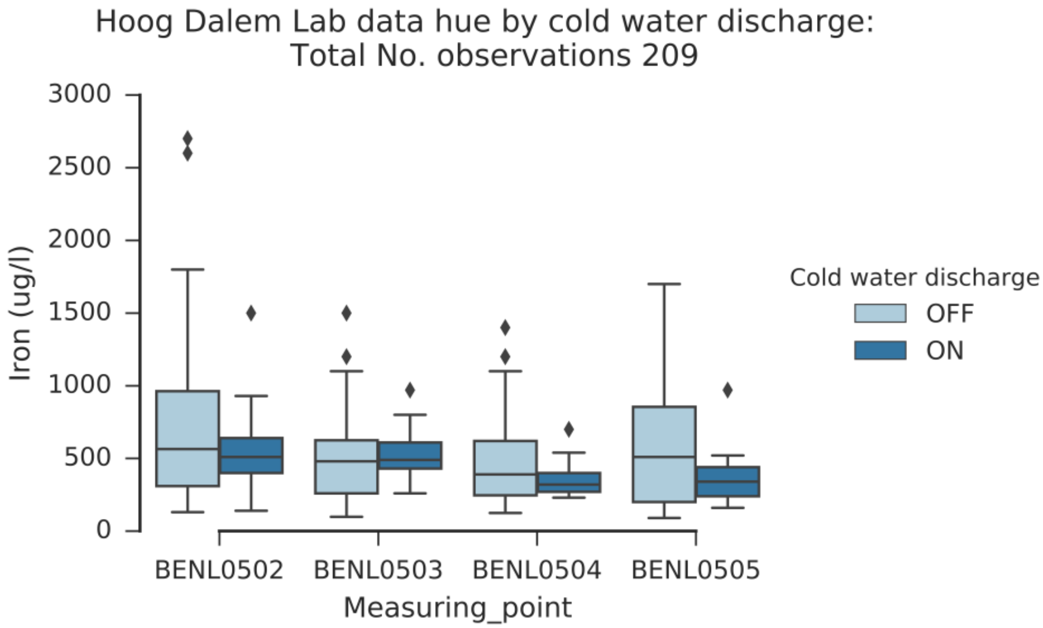


Figure 7.96 Box plot – laboratory data – iron

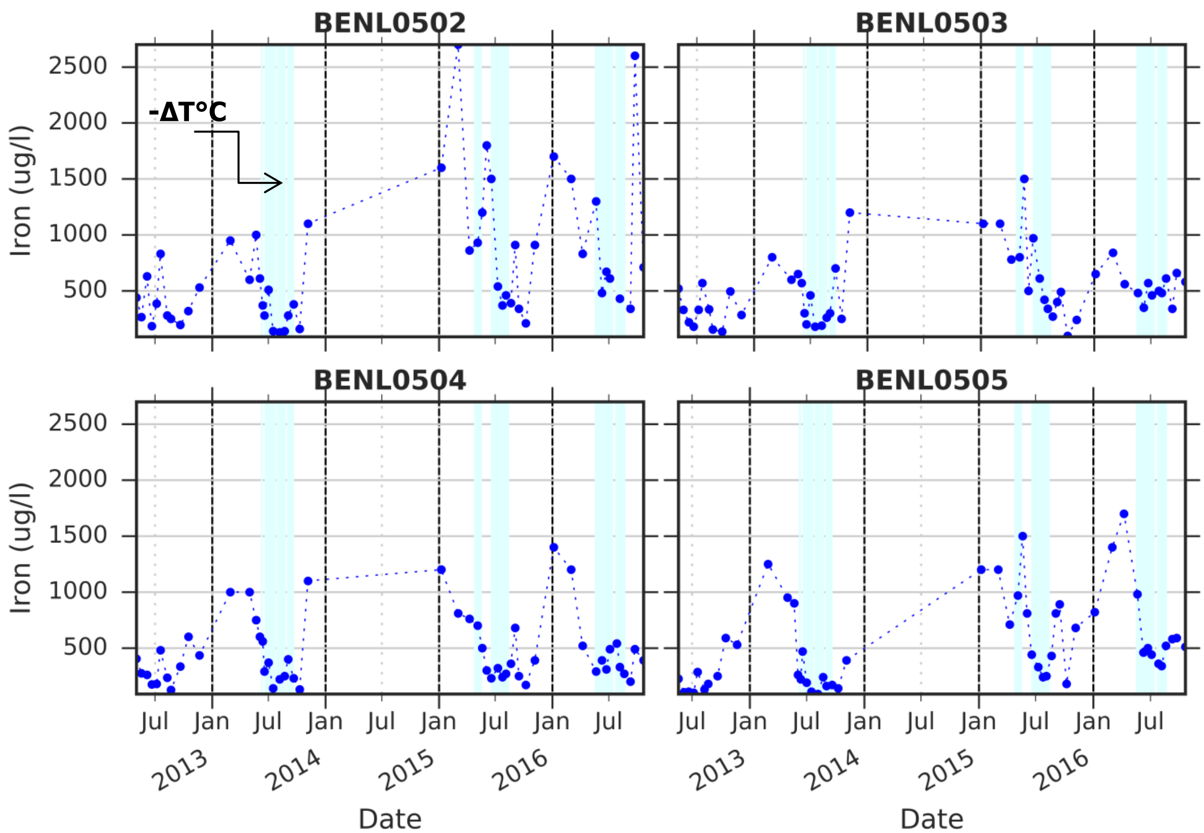


Figure 7.97 Time series plot – laboratory data – iron

APPENDIX VI - TROPHIC STATE INDEX

To gain further insight into the nutrient and chl-concentrations measured, the trophic state was further explored to better understand what the observations represent. To find the trophic state of the channel at Hoog Dalem, the trophic state index (TSI) by Carlson (1977) has been estimated. The TSI is used to indicate the trophic level of a water body, originally developed for lakes and can be applied as an indicator for more stagnant waterways. Three different types of TSI were be calculated based on the SD, Chl-a and TP. There are three main TSI categories; oligotrophic, mesotrophic (combination of oligotrophic and eutrophic) and eutrophic. Each trophic state is defined by the criteria that the algal biomass doubles from a base value for each trophic state. The trophic state is based on a reciprocal relationship between algal biomass concentration and SD/transparency, for each doubling of algal biomass, the SD halves, see the below equation. (Carlson, 1977)

$$TSI(SD) = 10\left(6 - \frac{\ln SD}{\ln 2}\right)$$

A further two parameters were used to estimate the TSI, Chl-a and TP.

$$TSI(Chl) = 10\left(6 - \frac{2.04 - 0.68 \ln Chl}{\ln 2}\right)$$

$$TSI(TP) = 10\left(6 - \frac{\ln \frac{48}{TP}}{\ln 2}\right)$$

Table 7.5 Trophic status

Lake trophic condition	TSI value	SDT (m)	Chl-a (µg/l)	TP (mg/L)	Description
Oligotrophic	<30	>8	< 0.95	<0.006	Clear water, oxygen throughout the year in the hypolimnion.
	30-40	8-4	0.95-2.6	0.006-0.012	Hypolimnia of shallower lakes may become anoxic.
Mesotrophic	40-50	4-2	2.6-7.3	0.012-0.024	Water moderately clear; increasing probability of hypolimnetic anoxia during summer.
Eutrophic	50-60	2-1	7.3-20	0.024-0.048	Anoxic hypolimnia, macrophyte problems possible.
	60-70	0.5-1	20-56	0.048-0.096	Blue-green algae dominate, algal scums and macrophyte problems.
Hypereutrophic	70-80	0.25-0.5	56-155	0.096-0.192	Light limited productivity). Dense algae and macrophytes.
	>80	<0.25	>155	0.192-0.384	Algal scums, few macrophytes.

References: http://www.secchidipin.org/index.php/monitoring-methods/trophic-state-equations/ and Michigan lakes

The TSI at Hoog Dalem for all measuring points is provided in the below graph, the typical TSI ranges from 40-80, Mesotrophic to Hypereutrophic. Theoretically, the TSI derived from SD, Chl-a and TP should be similar and this similarity is exhibited in the plotted results. Based on two papers, the TSI based on Chl-a is the most accurate representation of TSI (Carlson, 1977) and (Schneider & Melzer, 2003). From the results, TSI based on Chl-a was generally lower than TSI estimated based on SD (transparency) and TP.

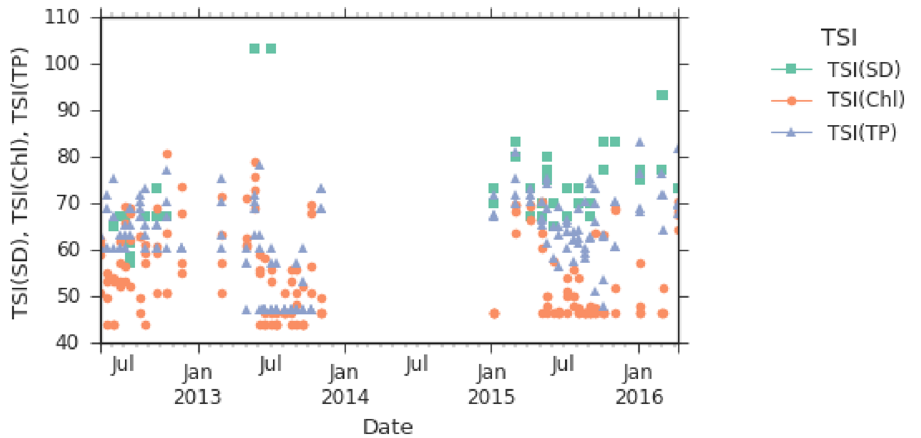


Figure 7.98 Time series plot – laboratory data – trophic state index

During summer months, June, July and August, the TSI based on chl-a appeared to be generally lower during 2015 than in 2012. The median TSI was higher at BENL0502 and BENL0503 during 2012 and 2013. In 2015 the TSI(Chl) along BENL0502 to BENL0504 did not vary considerably, generally in the range 45-50, mesotrophic and at BENL0505 the median TSI(Chl) was eutrophic, 50-60. Measuring points BENL0502 and BENL0503 had a higher TSI than BENL0504 and BENL0505, except in 2015. The TSI(Chl) at measuring point BENL0502 and BENL0503 reduced from eutrophic (range 50-70) in 2012 to mesotrophic (range 40-50) in 2015. During 2012 there was no cold water discharge and in 2015 the cold water discharge was more frequent than in 2013.

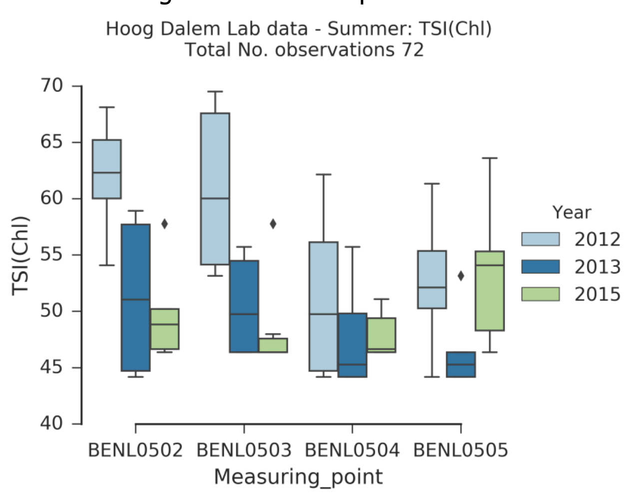


Figure 7.99 Box plot for each measuring point per year – laboratory data – trophic state index – Summer – Chl-a

TSI based on TP and SD/transparency is presented in the next box-plot, based on this graph the TSI appeared to be generally lower during 2013 than in 2012 and 2015. Note that the lowest detectable TP reading was 0.02mg/l, this explains the uniform lower value during 2013. Hence, it is possible that during 2013, the water in the channel could have been oligotrophic (<40). The median TSI during 2012 and 2015 was similar along the channel, except at BENL0504. During 2012 and 2015, the TSI(TP) along the reach was eutrophic (range 50-70), typically around 65, and on occasion was in excess of 70, hypereutrophic.

During 2013 there was only one reading taken once at each measuring point and the SD during these readings was below the minimum detectable of 0.05m. Hence, the 2013 reading is not reliable. In 2012, only one reading was taken each at BENL0504 and BENL0505. Hence, not many conclusions can be made for the STI based on SD. In general, the TSI(SD) follows a similar trend as TSI(TP).

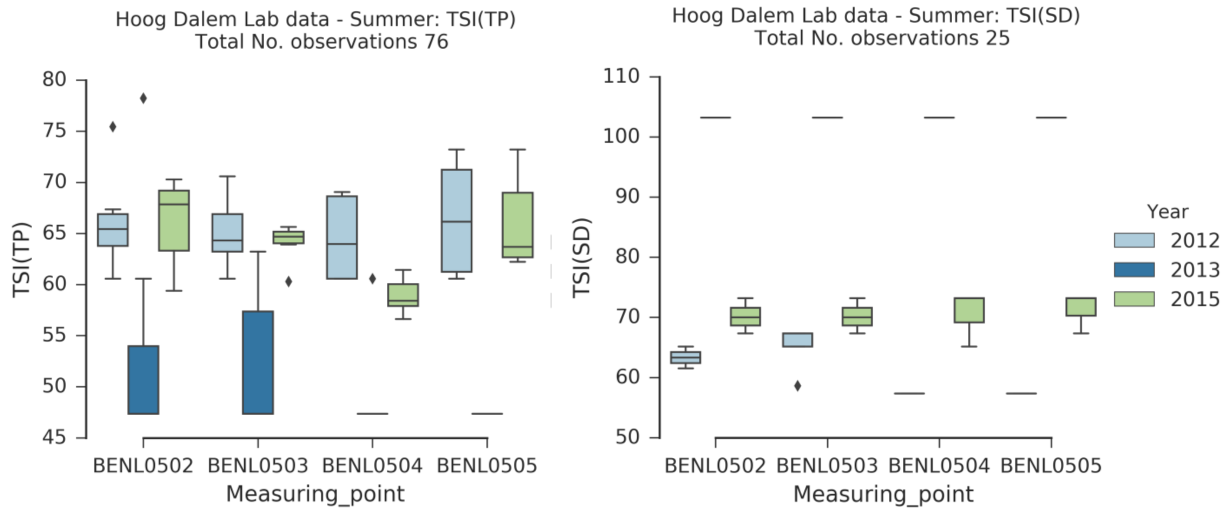


Figure 7.100 Box plot for each measuring point per year – laboratory data – trophic state index – Summer – TP and SD

Based results presented in the previously discussed box-plots, a more detailed presentation of the TSI during 2015 for each measuring point is provided within the next four graphs. The following graphs illustrate the fluctuation in TSI during 12 months. Outside of summer months, the algal production is generally limited by light availability and temperature, TSI based on TP and Chl-a is most representative during summer, based on the relationship between TP and SD, which is the basis for the TSI(TP) equation.

At BENL0502, from January until April, the three TSI generally follow a similar trend, with TSI(SD) and STI(TP) values are similar, while the TSI(Chl) is lower. During May to June, a sharp decline in TSI(Chl) can be observed, while the TSI(TP) and TSI(SD) slightly increase. For measuring point BENL0502 and BENL0504, from May to June until September to October, the TSI(Chl) has an inverse relationship to the other two TSI values, at BENL0503 and BENL0505 all three TSI values generally follow a similar trend. The TSI(Chl) is the parameter that best represents the algal biomass.

The TSI(TP) variance differs from the TSI(Chl) and TSI(SD), the exact reasoning for this would require further investigation. There are some general interpretations where the three TSI differ, from the paper "Using Differences Among Carlson's Trophic State Index Values in Regional Water Quality Assessment," by Richard A. Osgood. The interpretation that is likely applicable for Hoog Dalem is:

- TSI (TP) = TSI (SD) >TSI (CHL) Non-algal particulates or colour dominate light attenuation

Conversely, during 2012 and 2013, TSI(Chl) and TSI(TP) demonstrate a similar trend and plot closer together.

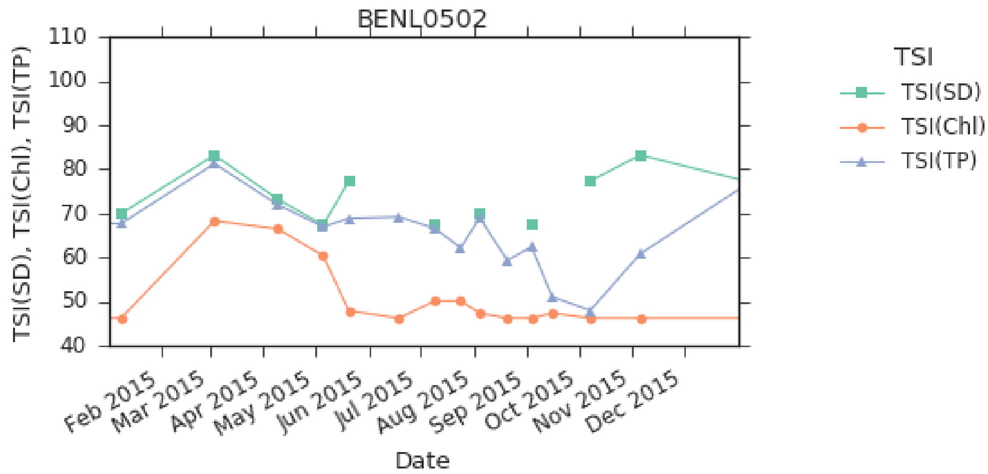


Figure 7.101 Time series plot - 2015 – laboratory data – trophic state index – BENL0502

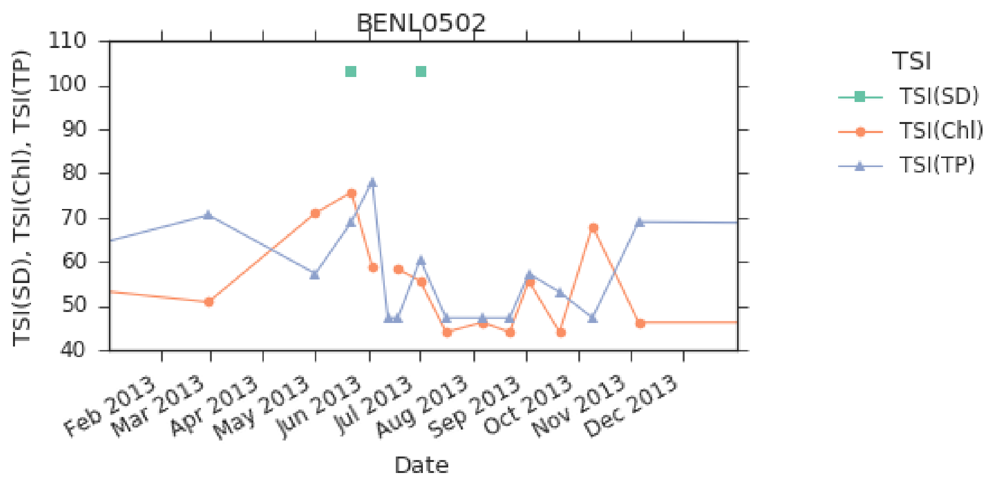


Figure 7.102 Time series plot - 2013 – laboratory data – trophic state index – BENL0502

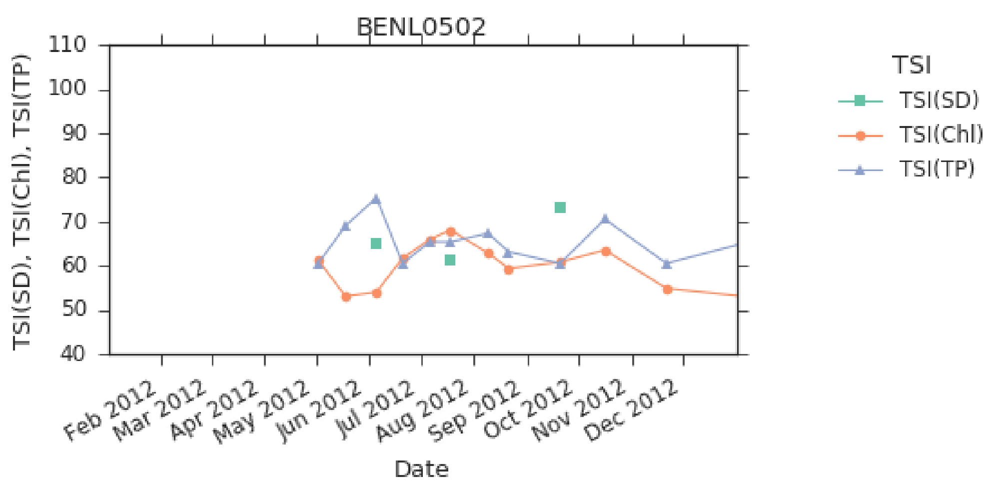


Figure 7.103 Time series plot - 2012 – laboratory data – trophic state index – BENL0502

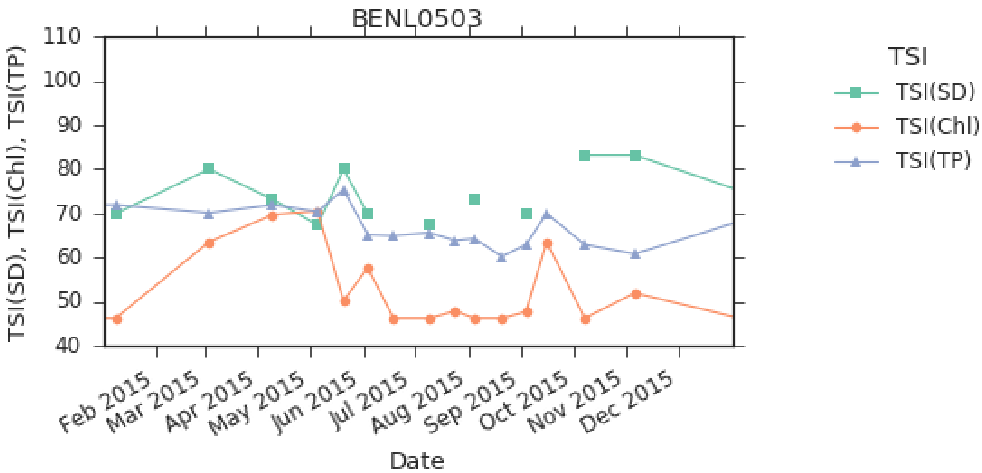


Figure 7.104 Time series plot - 2015 – laboratory data – trophic state index – BENL0503

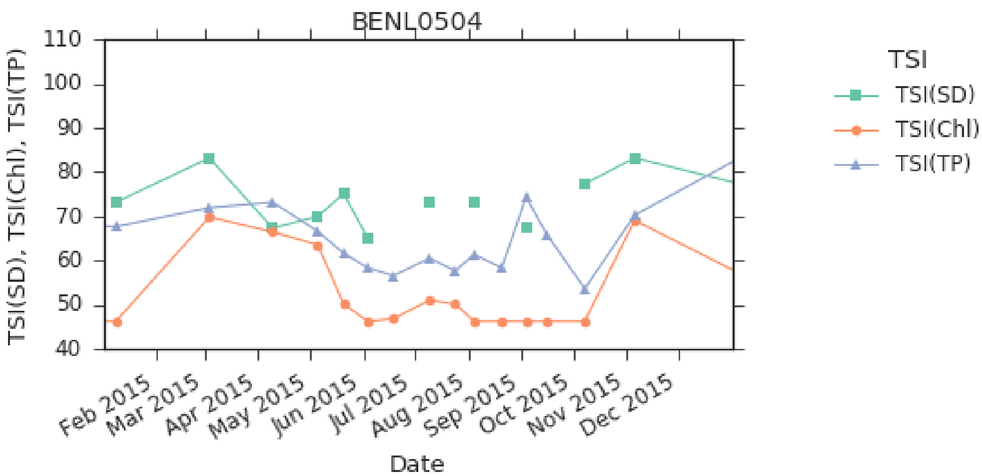


Figure 7.105 Time series plot - 2015 – laboratory data – trophic state index – BENL0504

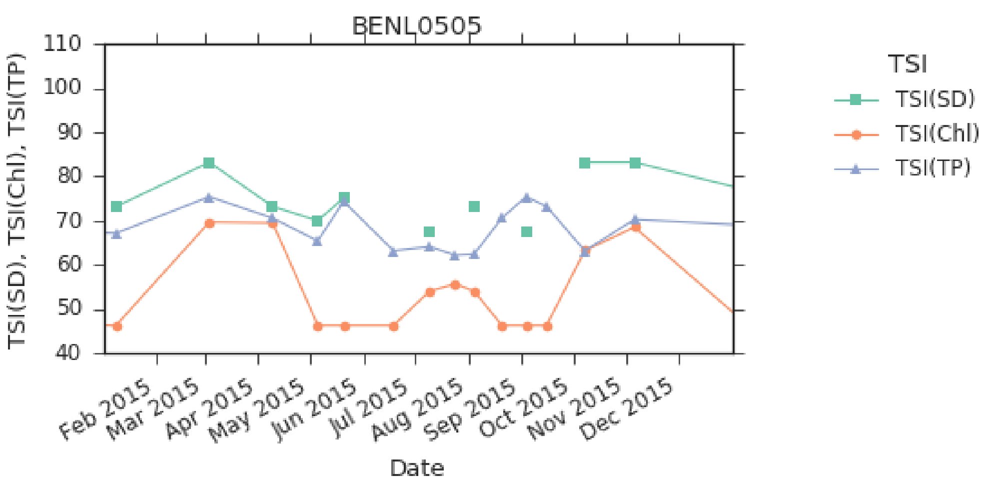


Figure 7.106 Time series plot - 2015 – laboratory data – trophic state index – BENL0505

ELODEA NUTTALLII ECOLOGY OBSERVATIONS

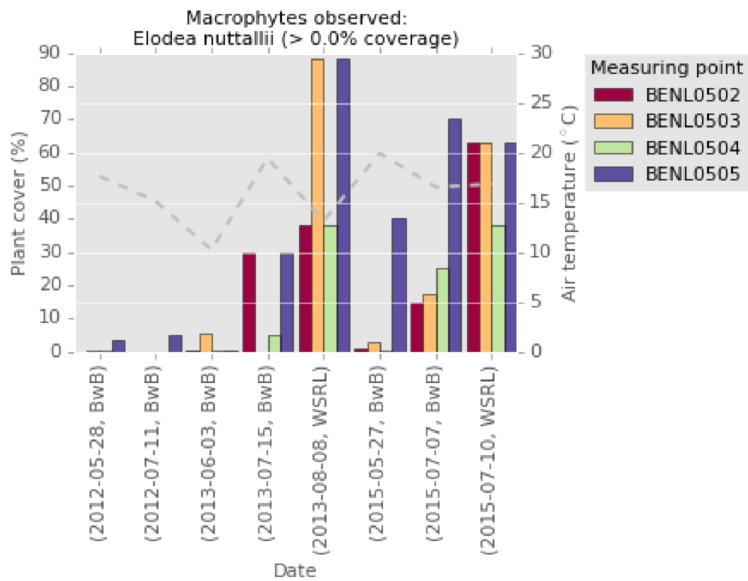


Figure 7.107 *Elodea nuttallii* abundance at Hoog Dalem (note the method of ecological survey is different for BwB and WSRL)

DUCKWEED ECOLOGY OBSERVATIONS

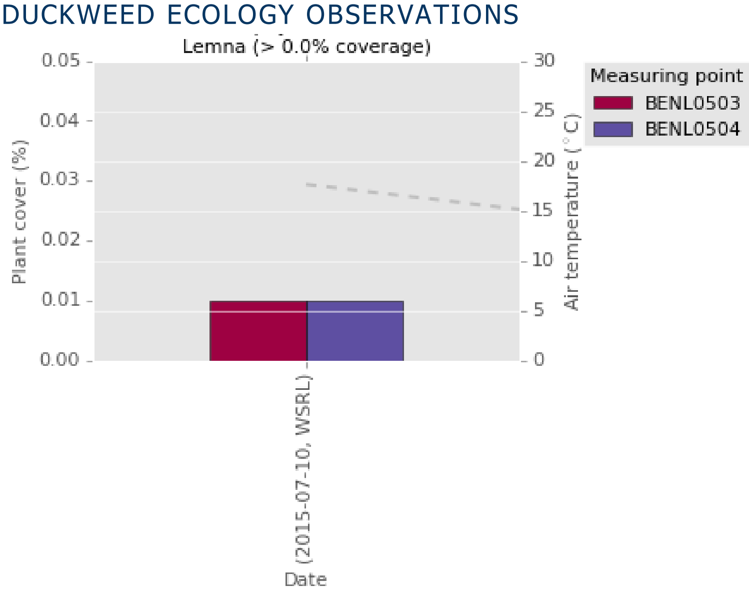


Figure 7.108 *Lemna* abundance at Hoog Dalem

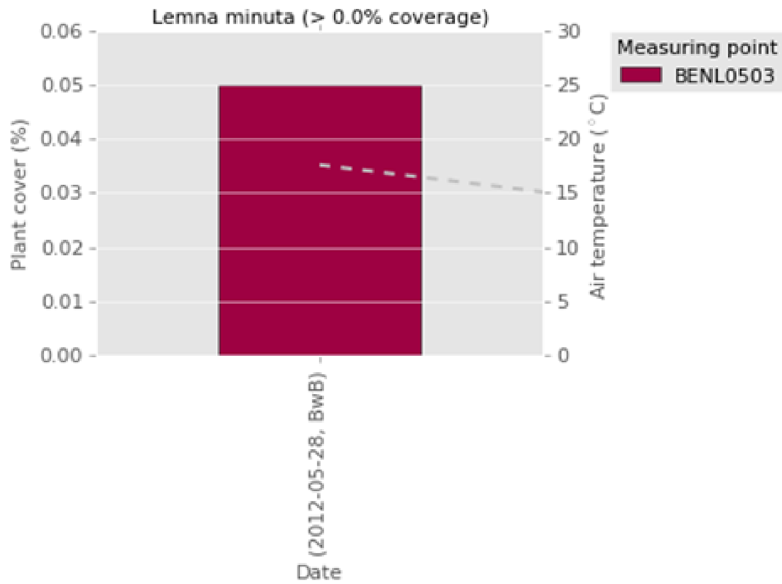


Figure 7.109 *Lemna minuta* abundance at Hoog Dalem

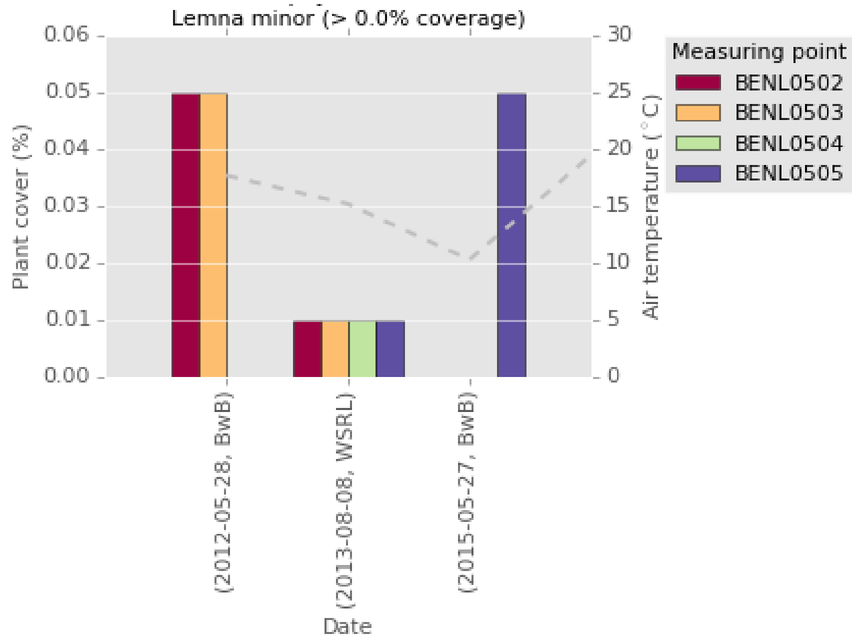


Figure 7.110 *Lemna minor* abundance at Hoog Dalem

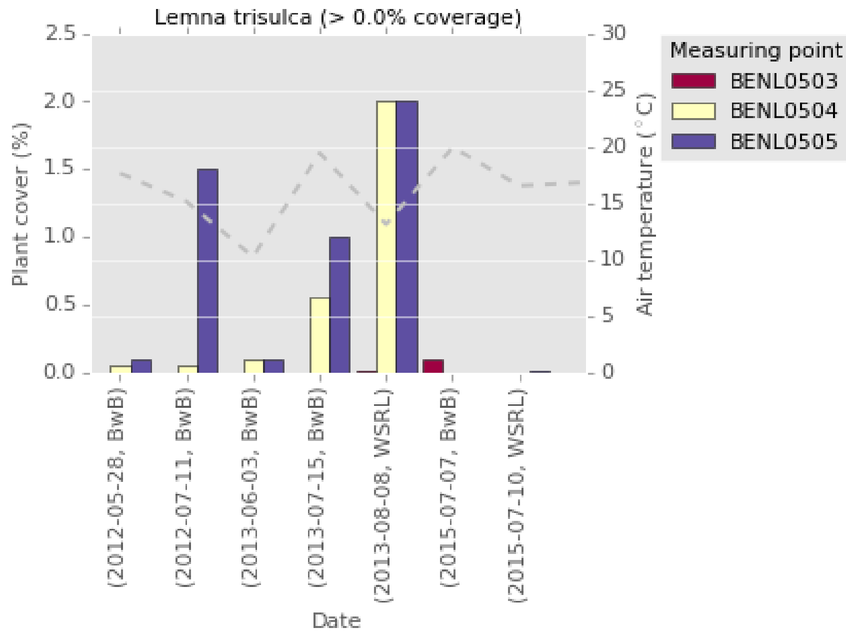


Figure 7.111 *Lemna trisulca* abundance at Hoog Dalem

MACROPHYTE MODEL EQUATIONS

Delwaq macrophyte modelling takes into consideration the maximum growth rate of the plant and the sum of the biomass in the water column and biomass stored in the root zone at the beginning of the growing season. The modelling of submerged macrophytes includes dominant external factors that affect growth, water temperature, light availability and maximum age. The growth is also strongly dependent on the nutrients available. The equations shown are for submerged macrophytes, in the macrophyte model floating macrophytes (such as Duckweed) are classified as 'emerged'. Growth of emerged macrophytes has been excluded in the following summary since the equations are very similar, for later report editions this may be elaborated on.

$If\ SM_i < MaxSM_i$, then:

$Growth\ SM_i = (SM_i + RM_i) \times MaxGrowthSM_i \times LimLightSM_i \times LimTSM_i \times LimAgeSM_i$

Otherwise: $GrowthSM_i = 0$

Definition of terms:

a.	SM_i	Biomass of submerged (SM) species *i*	$(gC \cdot m^{-2})$
b.	$Growth\ SM_i$	Growth of SM species I	$(gC \cdot m^{-2} \cdot d^{-1})$
c.	$MaxGrowthSM_i$	Potential growth rate of SM species *i*	(d^{-1})
d.	$LimLightSM_i$	Light limitation factor of SM species *i*	$(-)$
e.	$LimTSM_i$	Temperature limitation factor of SM species *i*	$(-)$
f.	$LimAgeSM_i$	Age limit of submerged (SM) species *i*	$(-)$

Nutrient limitation is calculated in Delft 3D based on a half saturation concentration, the equation is shown below. For rooted macrophytes, nutrients can be sourced from the soil and this means that rooted vegetation growth is not limited to the nutrients available in the water. Macrophytes that are not rooted are dependent on the nutrients in the water column, this includes species that are floating and microalgae that absorb most of their nutrients form the water, such as Chari.

$LimNut\ SM_i = min(LimPO_4SM_i, \max(LimNH_4SM_i, LimNO_3SM_i))$

Where:

- $LimNH_4SM_i = \frac{NH_4}{NH_4+NH_4hsSM_i}$
- $LimNO_3SM_i = \frac{NO_3}{NO_3+NO_3hsSM_i}$
- $LimPO_4SM_i = \frac{PO_4}{PO_4+PO_4hsSM_i}$

Definition of terms:

a.	$LimNutSM_i$	Nutrient limitation factor for SM species *i*	$(-)$
b.	NH_4	Ammonia concentration	$(gN \cdot m^{-3})$
c.	NH_4hsSM_i	Half saturation concentration NH_4 for growth 1. of SM species *i*	$(gN \cdot m^{-3})$
d.	$LimNH_4SM_i$	NH_4limitation factor for SM species *i*	$(-)$
e.	NO_3	Nitrate concentration	$(gN \cdot m^{-3})$
f.	NO_3hsSM_i	Half saturation concentration NO_3 for growth 1. of SM species *i*	$(gN \cdot m^{-3})$
g.	$LimNO_3SM_i$	NO_3limitation factor for SM species *i*	$(-)$
h.	PO_4	Ortho-phosphorus concentration	$(gP \cdot m^{-3})$
i.	PO_4hsSM_i	Half saturation concentration PO_4 for growth 1. of SM species *i*	$(gP \cdot m^{-3})$
j.	$LimPO_3SM_i$	PO_4limitation factor for SM species *i*	$(-)$

Early in the growing season, rooted macrophytes uptake nutrients via the rhizome/root zone as the foremost nutrient source to initiate growth. The nutrient sourced from the rhizome/root system is carbohydrate, glucose sugars, once this source is completely consumed by the growing macrophyte uptake of nutrients is sourced via the roots.

$If\ (GrowthEM_i + GrowthSM_i) \times dt < (RH_i - RHmin_i)$

Where:

- $CtranslocRHtoEM_i = GrowthEM_i$
- $CtranslocRHtoSM_i = GrowthSM_i$

Otherwise:

- $CtranslocRHtoEM_i = 0$
- $CtranslocRHtoSM_i = 0$

$If (GrowthEM_i \times NCratEM_i + GrowthSM_i \times NCratSM_i) \times dt < (NRH_i - NRHmin_i)$

Where:

- $NtranslocRHtoEM_i = GrowthEM_i \times NCratEM_i$
- $NtranslocRHtoSM_i = GrowthSM_i \times NCratSM_i$

Otherwise:

- $NtranslocRHtoEM_i = 0$
- $NtranslocRHtoSM_i = 0$

$If (GrowthEM_i \times PCratEM_i + GrowthSM_i \times PCratSM_i) \times dt < (PRH_i - PRHmin_i)$

Where:

- $PtranslocRHtoEM_i = GrowthEM_i \times PCratEM_i$
- $PtranslocRHtoSM_i = GrowthSM_i \times PCratSM_i$

Otherwise:

- $PtranslocRHtoEM_i = 0$
- $PtranslocRHtoSM_i = 0$

In the model settings for Delft3D delwaq, the growth rates of macrophytes increase when the temperature exceeds 20°C. The rate of growth decreases for temperature lower than 20°C until a critical temperature is reached, where macrophyte growth stops. The equations below outline the temperature limitation input.

- $If\ T > TcritEM_i$, then: $LimTEM_i = k_{T20}EM_i^{T-20}$
  - Otherwise: $LimTEM_i = 0$
- $If\ T > TcritSM_i$, then: $LimTSM_i = k_{T20}SM_i^{T-20}$
  - Otherwise: $LimTSM_i = 0$

Definition of terms:

a. T Temperature (℃)
b. $TcritEM_i$ Critical temperature for growth EM species I (℃)
c. $LimTEM_i$ Temperature limitation factor for EM species i $(-)$
d. $k_{T20}EM_i^{T-20}$ Temperature coefficient for EM species i $(-)$
e. $TcritSM_i$ Critical temperature for growth SM species I (℃)
f. $LimTSM_i$ Temperature limitation factor for SM species i $(-)$
g. $k_{T20}SM_i^{T-20}$ Temperature coefficient for SM species i $(-)$

MACROPHYTE MODEL INPUTS

Table 7.6 Summary of macrophyte inputs for model

Parameter	Unit	Description	Lemna	Reference	Elodea	Reference
Constants for MaxMacro - maximum biomass macrophytes						
HSIEMi / HSISMi	-	Habitat suitability [23]	1	See footnote	1	See footnote
PotEMi/ PotSMi	gC/m^2	Potential biomass	150	Based on mean from several papers (Lasfar, et al., 2007) (Pomogyi, 1989) (van der & Klink, 1991) (Driever, Nes, & Roijackers, 2005) (Lüönd, 1983)	85	(Nagasaka, 2004)
Constants for submerged macrophyte						
IbotSeg	-	Bottom segment number Manual 5.8.2/p160 - distribution of plant in water column	N/A		0.1	Least exponential distribution available
SwDisSMi	-	Shape type	N/A			
FfacSMi	-	Form factor lin: F = M(mean)/(M/Hmax) - 50 is maximum >96% in top 10% of water column	N/A		1	Homogenous distribution in the profile
HmaxSMi	-	Max Height SM	N/A		25 (ranges from 25-	(Nagasaka, 2004, p. 132)

[23] The habitat suitability is 0 for when it is not suitable for a macrophyte to grow given the conditions and 1 when conditions are suitable for the macrophyte to grow. Since the macrophytes modelled have been observed on the site before, the habitat suitability is assigned 1.

Parameter	Unit	Description	Lemna	Reference	Elodea	Reference
					50cm in 1m depth)	
RootDeSMi	-		N/A		0.03	Fine roots for anchoring only
RadSatSMi	W/m^2	total radiation growth saturation	N/A		30	Delwaq default
Constants						
ExtVlSMi	1/m	total extinction coefficient visible light	N/A		0.248	Assumed same as for algae
PPmaxEMi/ PPmaxSMi	1/d	potential growth rate macrophyte	0.28	(Lasfar, et al., 2007)	0.063	(Eugelink, 1998)
EM01thresh	gC/m^2	threshold biomass EM01 in growth	1	Site observation	1	Site observation
RH0imin	gC/m^2	minimal biomass RH01	0	Judgement / calibration	0	Judgement / calibration
NRH0imin	gC/m^2	minimal NRH01	0.5	Judgement / calibration	0.5	Judgement / calibration
PRH0imin	gC/m^2	minimal PRH01	0.03	Judgement / calibration	0.003	Judgement / calibration
NH4crEMi/ NH4crSMi	gN/m^3	critical NH4 conc. macrophyte emerged	0.1	Judgement / calibration	0.1	Judgement / calibration
NO3crEMi	gN/m^3	critical NO3 conc. macrophyte emerged	0.1	Judgement / calibration	N/A	
PO4crEMi	gN/m^3	critical PO4 conc. macrophyte emerged 01	0.002	Judgement / calibration	N/A	
CO2crSMi	gC/m^3	critical CO2 conc. macrophyte submerged	N/A		0	Delwaq default
MinDLEMi/ MinDLSMi	d	minimal day length for growth	0.3	(Lasfar, et al., 2007)	0.3	Assumed same as EM
OptDLEMi/ OptDLSMi	d	Day length for growth saturation	0.67	(Lasfar, et al., 2007)	0.67	Assumed same as EM
TcritEMi/ TcritSMi	°C	critical temperature for growth	5	(Lasfar, et al., 2007)	4	(Nagasaka, 2004)
TcPMxEMi / TcPMxSMi	-	temperature coefficient for growth EM01	1.15	Estimated based on (Lasfar, et al., 2007)	1.15	Assumed same as EM
K1DecaEMi/ K1DecaSMi	1/d	first order autumn decay rate EM01	0.0102	Judgement / calibration	1.02^{-4}	Judgement / calibration
TcDecaEMi/ TcDecaSMi	-	temperature coefficient for decay EM01	1.03	As for similar floating plants	1.003	Judgement / calibration
FrEMtoRHi/ FrSMtoRHi	-	fraction EM/SM that becomes RH01	0.5	Judgement / calibration	0.5	Judgement / calibration
NCRatEMi / NCRatSMi	gN/gC	N:C ratio	0.2	Delwaq default	0.2	Delwaq default
PCRatEMi / PCRatSMi	gP/gC	P:C ratio	0.02	Delwaq default	0.02	Delwaq default
NCRatRHi	gN/gC	N:C ratio RH01	0.2	Delwaq default	0.2	Delwaq default
PCRatRHi	gP/gC	P:C ratio RH01	0.02	Delwaq default	0.02	Delwaq default
FrPOC1EMi	-	fraction of decay EMi/SMi that becomes POC1	0.5	Delwaq default	0.5	Delwaq default

Parameter	Unit	Description	Lemna	Reference	Elodea	Reference
FrPOC2EMi	-	fraction of decay EMi/SMi that becomes POC2	0.3	Delwaq default	0.3	Delwaq default
FrPOC3EMi	-	fraction of decay EMi/SMi that becomes POC3	0.2	Delwaq default	0.2	Delwaq default