BEFORE THE WHANGAREI DISTRICT COUNCIL AND NORTHLAND REGIONAL COUNCIL

IN THE MATTER	of the Resource Management Act 1991
AND	
IN THE MATTER	of a resource consent application by Northport Limited under section 88 of the Resource Management 1991 for a port expansion project at Marsden Point
APPLICATION NO.	APP.005055.38.01 LU 2200107

STATEMENT OF EVIDENCE OF DAVID ROBERT FOX

(ESTABLISHMENT OF TURBIDITY TRIGGERS)

24 August 2023

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INTRODUCTION

Qualifications and experience

1. My name is David Robert Fox.

2. I hold the following qualifications:
   (a) B.App.Sci (Monash University)
   (b) M.App. Sci (Monash University)
   (c) PhD (University of Wyoming)

3. I am Company Director of Environmetrics Australia Pty Ltd and Honorary Professorial Fellow at the University of Melbourne.

4. I have substantial experience teaching and researching in theoretical and applied statistics in Universities in Australia (University of Melbourne; Monash University; Curtin University), the United Kingdom (Exeter University), and the United States (University of Colorado; University of Wyoming). I have developed and delivered courses in mathematics, statistics, operations research, computer programming, research methods, and experimental design at all levels ranging from undergraduate to postgraduate studies and PhD. supervision.

5. In my role as Director of Environmetrics Australia I provide high-level statistical services to government, industry, and academia. Clients include: SA EPA, DEH, WA DEC, NSW EPA, VIC EPA, DPI (VIC), Parks Victoria, DSE (VIC), ERISS (NT), Australian Institute of Marine Science (AIMS), CSIRO, Port of Melbourne, Gladstone Ports Corporation, Lyttelton Port Corporation, Vision Environment Queensland, Enviser New Zealand, British Gas, QCLNG, University of Melbourne, QLD EPA, NSW DECC, Southern Rural Water, Goulburn-Murray Water, Sydney Water, Melbourne Water, ALCOA, WA Police Department, University of Western Australia, Placer Pacific, Ok Tedi Mining, University of Melbourne, Apache Energy, and Woodside Offshore Petroleum.

6. I have approximately 15 years' experience with The Commonwealth Scientific and Industrial Research Organisation (CSIRO) in various senior research management roles, including:
   (a) Manager, CSIRO Biometrics Unit, Perth;
   (b) Research Group Leader (Environmetrics);
   (c) Program Leader CSIRO Land and Water Division (110 staff; 6 sites across Australia);
   (d) Director, Environmental Projects Office;

(e) Business Director (Strategic Planning) CSIRO Land and Water Division (approx. 600 staff).

7. I have approximately 20 years' experience with University of Melbourne as Professorial Fellow and Director of Australian Centre of Environmetrics; Deputy Director of Australian Centre of Excellence in Risk Analysis; and Honorary Professorial Fellow.

8. I am (or have been) a member of various boards and panels including:

(a) Member, Cockburn Sound Management Council (2000-01)

(b) Member, Great Barrier Reef Water Quality Protection Plan Expert Group (2005-06)

(c) Member, Adelaide Coastal Waters Study Steering Committee (2001-2008)

(d) Member, Port Phillip Bay Environmental Study Technical Group (1993-96)

(e) Member, Australian Centre of Excellence for Risk Analysis Scientific Advisory Committee (2006 - 2012)

(f) Chair Working Group 5 (Monitoring and Reporting), National Water Quality Management Strategy Revision (2010 - 2014)

(g) Chair Statistics Sub-Group, National Water Quality Management Strategy Revision (2010 - 2014)

(h) Member Working Group 2 (Biological assessment), National Water Quality Management Strategy Revision (2010 - 2014)

(i) Member Working Group 3 (Physical-Chemical assessment), National Water Quality Management Strategy Revision (2010 - 2014)

(j) Member Working Group 4 (Toxicology and sediments), National Water Quality Management Strategy Revision (2010 - 2014)

(k) Member, Port of Gladstone dredge technical reference panel for Western Basin Dredge and Disposal Project (2009 – 2014)

(l) Member Lyttelton Port Corporation dredge technical advisory group (2016 – 2018)

(m) Project Leader, joint initiative between Australia, New Zealand, and Canadian governments to develop and implement new methods for toxicant guideline value derivation (2019 – present)

9. Other experience includes:

(a) Co-author of Australia and New Zealand Water Quality Management Strategy (2000, and 2018).

(b) Director Effluent Management Study for Melbourne Water ($2.5M/ 2year multi-disciplinary, multi-agency project to investigate causes associated with impacts of large sewage ocean outfall).

(c) Consultant to Port of Melbourne Corporation (2006-2007) – responsible for the establishment of risk-based trigger values for managing turbidity levels during capital dredging of Port Phillip Bay (Channel Deepening Project) 2006-2007.

(d) Director of Adelaide Coastal Waters Study (1999 – 2006). An $8M/ 4year, study involving over 50 researchers from 9 organisations to investigate causes of loss of over 5,200ha of seagrass off the coast of Adelaide.

(e) Consultant to Gladstone Ports Corporation (2009 – 2014):

- Responsible for: (a) identification of trigger values to monitor and manage turbidity levels in Port Curtis (Qld.) during capital dredging program (Western Basin Dredging Project); (b) identification and implementation of data processing activities for turbidity data including development of ADDM (anomalous data detection macro) software; (c) development of predictive modelling tools to predict both water column turbidity and benthic light; (d) development of light-based triggers for managing and protecting seagrass meadows during capital dredging;

(f) Consultant to Lyttelton Port Company (2016 - 2018):

- Responsible for: (a) turbidity data processing and analysis; (b) development of new methods for smoothing turbidity data to attenuate the impact of outliers; and development of the modified, intensity-frequency-duration (m-IFD) approach to setting turbidity trigger values for compliance and management of dredging operations.

10. I authored the report titled “Turbidity Monitoring for the Northport Expansion Project” (Fox 2023) ("Statistical Report”), which is attached to this statement of evidence as **Annexure A** and which forms the basis of parts of this statement of evidence. This report proposes the framework for the statistical treatment of monitored turbidity data which was developed and successfully deployed for the Lyttelton Port Company’s Channel Deepening Project.

11. I have established systems and processes for the transfer and processing of turbidity and water quality monitoring data that will be collected from autonomous loggers during the baseline monitoring and dredging campaigns for Northport’s proposed expansion project.

12. I have read the relevant parts of: the application documents (focussing on those aspects most relevant to my area of expertise – namely data processing, analysis and risk-based management activities associated with dredging); submissions; the Section 42A Report; and Northport’s proposed conditions.

Code of Conduct

13. I confirm that I have read the Code of Conduct for Expert Witnesses contained in the Environment Court Practice Note (2023) and I agree to comply with it. In that regard, I confirm that this evidence is written within my expertise, except where I state that I am relying on the evidence of another person. I have not omitted to consider material facts known to me that might alter or detract from the opinions expressed.

EXECUTIVE SUMMARY

14. In my evidence, I provide details of a statistical framework for the processing of turbidity data and the establishment of so-called turbidity trigger-values using techniques that I originally developed for the Lyttelton Port Company's (LPC) Channel Deepening Project (CDP). This framework is proposed to be implemented for Northport's expansion project.

15. The procedures are consistent with the recommended approaches in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC and ARMCANZ 2000) and the more recent guidance provided in Warne et al. (2018) – documents I co-authored. Importantly, the revised methodology used for the LPC-CDP addressed several deficiencies associated with the nationally recommended approach for smoothing raw data and rectified a significant flaw in the widely used *intensity, frequency, duration* (IFD) methodology originally proposed by McArthur et al. (2002) for the determination of trigger values (Fox 2016).

16. These methods were thoroughly peer-reviewed as part of the LPC-CDP consenting process and subsequently endorsed for use in that project to manage water quality during the dredging activities. That project has been implemented and **Jared Pettersson** confirms in his evidence that the methodology performed as intended. Importantly, **Jared Pettersson** advises that no material issues of concern with respect to elevated turbidity levels were reported during the LPC-CDP.

17. The key features of the methodology are:
   (a) Replacement of the default data smoothing technique known as the *exponentially weighted moving average* (EWMA) with the Kolmogorov-Zurbenko (KZ) filter. The KZ filter addressed two important concerns with the EWMA: (i) the data processing 'lag' was cut by 50% (from 6 hours to 3 hours) thus providing a more responsive tool for managing turbidity; and (ii) unlike the EWMA, the KZ filter is relatively insensitive to missing values in the turbidity time-series.
   (b) The modified IFD method (m-IFD) I developed for the LPC-CDP addressed and resolved a significant mathematical error in the way the original IFD method of

McArthur et al. (2002) calculated trigger-values. The resulting approach is both intuitive and simple to implement.

18. A brief description of the KZ filter and the m-IFD method are provided below.

(a) The Kolmogorov-Zurbenko (KZ) filter belongs to the class of low-pass filters. In essence the KZ filter is computed by taking *k* time iterations of a moving average (MA) filter of *m* points. It therefore has only 2 parameters – *k* and *m* both of which have clear physical interpretations. For the LPC-CDP, a KZ filter with *m=4* and *k=8* was used. In addition to its ease of computation and unlike the EWMA, the KZ filter easily deals with missing data situations and is near optimal (Yang and Zurbenko 2010). Computational details of the KZ filter are described in Fox (2016).

(b) The m-IFD method is the basis of the establishment of a tiered turbidity trigger system having three levels: A Tier 1 trigger provides an early-warning capability to alert project managers of an increasing turbidity environment and requires mitigation measures to reduce turbidity; the Tier 2 trigger alerts to an impending non-compliance situation which initiates heightened surveillance and mitigation measures; exceedance of a Tier 3 trigger signifies that turbidity levels are 'out-of-compliance'. Dredging operations would cease in the vicinity of the exceedance.

19. My Statistical Report (Fox 2023), attached to this evidence at **Annexure A**, sets out the proposed framework for the collection and processing of turbidity data during an approximate 12-month monitoring period prior to any works being undertaken. This background data will be used to: (a) characterise the *spatio-temporal* aspects of naturally occurring turbidity in the vicinity of Northport; and (b) develop a tiered 'early warning' mechanism to be used to monitor and manage turbidity levels in the harbour during the dredging program. The proposed approach draws upon the knowledge, expertise, and experience Environmetrics Australia has acquired over the past 17 years on major capital dredging projects in Australia and New Zealand. These methods have been subjected to exhaustive peer-review by scientific experts in both countries and their efficacy demonstrated by the successful management of turbidity during several large-scale dredging projects.

SCOPE OF EVIDENCE

20. This evidence is divided into four parts. Part 1 outlines the requirement for trigger levels, how these are computed and details on the statistical methodology for trigger level computation in my Statistical Report. Part 2 provides a response to issues raised by

submitters on the applications; Part 3 contains responses to issues raised in the section 42A report; and Part 4 addresses Northport's proposed conditions of consent.

21. My Statistical Report is **attached** to this evidence and covers:

(a) Data collection and processing for the purposes of quality assurance and establishing trigger levels. This section includes details on smoothing, signal extraction and pattern recognition, signal reconstruction and data imputation (inferring likely values for missing data on the basis of complex spatio-temporal statistical modelling);

(b) Characterising background turbidity and its relationship to total suspended sediment (TSS) concentration for the purposes of computing trigger values. This section includes discussion on tidal effects and the relationship between total suspended solids and turbidity; and

(c) The purposes, limitations and methodology for establishing trigger values based on background turbidity using a modified intensity-duration-frequency (IFD) approach.

PART 1: EXPLANATION OF TRIGGER VALUE APPROACH

Rationale

22. Trigger-values are used as an omnibus warning device. The terminology is deliberate since exceedance triggers a management response – typically an investigation into the cause(s) of a worsening condition and/or an associated management action. The Australian and New Zealand Marine and Freshwater Guidelines (2000) explicitly state they are not intended to be used in a punitive manner.

23. The use of 'trigger-values' for water quality monitoring during largescale dredging projects is justified by virtue of:

(a) It being a recommended strategy that has been extensively peer-reviewed and approved by the Australian and New Zealand regulators; and

(b) Well-established precedents in Australia, New Zealand and elsewhere in the world for their use in projects of similar size, scope, and complexity (for example, the Port of Melbourne's channel deepening project, Gladstone Port's Western Basin dredging project, Inpex's Ichthys dredging project in Darwin, Rio Tinto's Cape Lambert capital dredging works in Western Australia and LPC's recent CDP).

24. The monitoring strategy proposed for the present Northport project relies on the availability of comprehensive baseline data collected from suitably chosen sites for a period of at least 12 months. This approach underpins international best practice and has been successfully implemented in several Australian dredging projects, and more locally for the LPC CDP.

25. A sampling paradigm long-favoured by biologists and ecologists utilised the principles and procedures of before-after-control-impact or BACI designs. Statistical power is high when the attendant assumptions underlying the BACI approach are satisfied. However, contemporary water quality monitoring programs have moved away from these types of assessment. This is mainly due to:

(a) Environmental data invariably (and usually seriously) violates many of the underlying assumptions required for the legitimate use of these methods;

(b) Even when the assumptions are substantially met, the outcome is often a prosaic statement that the ‘control’ and ‘test’ sites are different;

(c) These designs do not provide quantification of trends in space and time; and

(d) They are inefficient in terms of resource allocation.

Approach

26. It is axiomatic that *change* is a relative concept. In order to responsively manage the dredging activities proposed in the application, we seek to understand how ‘natural’ or ‘background’ turbidity levels vary over the course of a year. Thus, the availability of at least one year of background data is required to establish ‘benchmarks’ against which future change can be assessed. There is a view that this is insufficient since longer-period phenomena such as inter-annual and decadal variation cannot be investigated. This is true. However, in the absence of a long-term monitoring data set, a viable compromise must be identified. Based on my involvement in other significant dredging projects in Australia, I believe the use of 1 year of background monitoring data provides sufficient information to reliably establish trigger values and other associated metrics as well as providing an adequate basis for the investigation of other important spatial-temporal dependencies and relationships. The only caveat I would add is that the frequency and intensity of ‘abnormal’ weather, oceanographic, or any other meteorological phenomenon during the background data collection period is not statistically different from long-term conditions.

27. Data acquisition for the Northport project commenced in September 2022 and will continue for 12 months. During this time, turbidity data at three locations in Whangārei Harbour are being obtained every 15 minutes to develop a comprehensive understanding of existing (or baseline) conditions. The location of the instruments and their rationale are set out in the evidence of **Jared Pettersson**.

28. This 'baseline data' will undergo processing and analysis (as discussed later in my evidence) to statistically profile the turbidity distributions at each location (which may also vary over time). As with any environmental monitoring program, the information collected is only a small sample from an infinite number of space-time combinations and as such, any inference about existing or future conditions is subject to uncertainty. This uncertainty should not be equated with poor decision-making; it is a facet of every statistical analysis based on a sample and is simply an expression of incomplete knowledge. What is important is how we treat this uncertainty. A statistical approach is the only scientifically credible and defensible way of decision-making under such uncertainty. This is the basis of the proposed strategy.

29. The modified intensity-frequency-duration (m-IFD) approach described in my Statistical Report (Fox 2023) identifies a probabilistic framework to balance the competing risks of lack of environmental protection on the one hand and unnecessary cessation of dredging operations on the other. Being a three-dimensional metric, the m-IFD approach is more sophisticated than more simplistic one-dimensional trigger-values. Furthermore, an added level of environmental surety is provided using a three-tiered m-IFD approach at each of the monitoring sites (the three-tiered system is described in the evidence of **Jared Pettersson**).

Processing background turbidity data

30. The organisation, preparation, and quality-assurance of monitored data is a critical activity that precedes the computation of management and compliance metrics. Errors, omissions, or the use of inappropriate statistical tools at this stage can profoundly affect derived values, rules, and alerts. The data processing and analysis steps expected to be implemented are discussed in the following sections.

(a) Data acquisition – background water quality data is collected from a network of telemetered buoys.

(b) Field quality-assured data undergoes further statistical quality assurance to: (a) identify (and where appropriate remove) aberrant readings; (b) reduce the influence of high-frequency oscillations in the turbidity data through a process of statistical filtering; and (c) where feasible, reconstruct the turbidity signal for those times when actual readings were unavailable.

(c) Turbidity measurements and contemporaneous TSS measurements manually collected are analysed to quantify the nature of the relationship between these two quantities. These relationships may vary over different sites and at different times. Knowledge of these 'TSS-NTU' relationships is critical for the incorporation of modelled dredge turbidity with measurements of natural background turbidity.

Establishing trigger values

31. The process of establishing trigger levels is an exercise in balancing two competing risks: the 'proponent risk' and the 'environmental risk'. These can be loosely thought of as the risks of false positive and false negative triggering respectively. A trigger value that is set too high will minimize the proponent's risk but at the expense of reduced environmental protection, while a trigger that is set too low will afford a high level of environmental protection but incur unnecessary expense and dredge downtime for the proponent.

32. Since its incorporation into the Australian and New Zealand Water Quality Guidelines (ANZECC/ARMCANZ 2000) the concept of a 'trigger value' (TV) has gained widespread acceptance among natural resource managers.

33. The thinking behind the TV development was that water quality assessments needed to move away from prosaic comparisons of a measured parameter against a reference as this fostered an unrealistic binary "pass/fail" notion of water quality.

34. Although TVs still rely on a numerical comparison, the subtle differences are:

(a) generally a tiered system of TVs is used; and

(b) exceedance of a TV initiates some sort of management response rather than punitive action.

35. On this latter point, the Guidelines are quite clear: *"exceedances of the trigger values are an 'early warning' mechanism to alert managers of a potential problem. They are not intended to be an instrument to assess 'compliance' and should not be used in this capacity".*[1]

[1] ANZECC/ARMCANZ 200, page 7.4-4

36. Furthermore, the ANZECC/ARMCANZ (2000) document advocated the use of locally-derived trigger values to replace de facto standards.

37. Several recently completed projects in Australia (e.g. those identified in paragraph 23) have extended the trigger-value methodology by incorporating the extra dimensions of duration and frequency of exceedances. Together with the trigger-value level (otherwise known as the *intensity*) this extended methodology is referred to as the IFD approach. It was originally proposed by U.S. EPA workers in 2002 although never implemented by them (pers. comm. between myself and lead author, Christopher McArthur, 2011).

38. A critical short-coming of the IFD approach as proposed by McArthur and his co-workers is that it allows for the simultaneous, and independent manipulation of all three parameters: intensity, frequency, and duration (of exceedances). As I argue in my Statistical Report and elsewhere, this serves to distort the true exceedance rate and this in turn has (in my opinion) led to the (unintended) use of overly liberal compliance programs – that is, a compliance program which affords a lower level of environmental protection than what was assumed. This is a consequence of the intimate coupling between all three parameters: changing either the permissible number (i.e. frequency) and/or the duration of exceedances above a stated threshold (i.e. intensity) will generate exceedance data whose high-order percentiles do not match the assumed intensity thresholds used to set the triggers.

39. Furthermore, the recent trend to incorporate the additional dimensions of frequency and duration (of exceedances) has been guided by U.S. research which lacked 'road-testing' and statistical assurance. My Statistical Report addresses these issues and provides a comprehensive review of the strengths and weaknesses of various approaches. This review underpins the recommended approaches to data processing and analysis of turbidity data including the computation of turbidity trigger values which are robust, statistically credible, and scientifically defensible.

40. As part of my preliminary background investigations commissioned by LPC I identified and corrected the flaw in the IFD approach originally proposed by McArthur et al. (2002). Unlike other projects (e.g. those mentioned in paragraph 23b, except for LPC's CDP) that used the flawed IFD approach, LPC's CDP implemented a modified IFD approach that corrected the error.

The modified IFD approach: m-IFD

41. The m-IFD approach is technical in its development and the detail is covered in my Statistical Report (Fox 2023) and hence will not be repeated here. A key feature of the

methodology is that is allows elevated (beyond ‘background’) levels of turbidity before ‘tripping’ the trigger. This trigger is a combination of a numerical threshold (informed by background and modelled dredge-related turbidity) and cumulative duration over a rolling 30-day period.

42. This is appropriate since we know dredging causes a temporary increase in turbidity. The critical understanding is that dredging alters the pattern of exceedances and not just the intensity.

43. Intensity, duration and frequency will be used to responsively manage the Northport expansion project dredge(s) as described in the evidence of **Jared Pettersson**. The final values for this will be inputted prior to the commencement of the dredging as part of the final EMMP once the full year of baseline data has been gathered.

44. For completeness, in my Statistical Report I flagged a number of issues that need to be addressed prior to the parameterisation of the *m*-IFD tiered trigger system. These relate to:

(a) The identification of ‘extreme’ weather and oceanographic events;

(b) The treatment of data collected during such events;

(c) Protocols for the treatment of ‘unusual’ or ‘aberrant’ turbidity readings;

(d) Procedures to deal with blocks of missing data due to instrument failure, communication issues, or other unforeseen events;

(e) Refinement of the data smoothing/filtering algorithm to balance responsiveness of the monitoring system with effective turbidity signal extraction;

(f) Experimental design and analysis to estimate the site-specific relationships between total suspended solids (TSS in mg/L) and turbidity measured in Nephelometric Turbidity Units (NTU);

(g) Harmonisation and integration of modelled TSS with background measurements.

45. Finally, I note that modelling of the sediment-related impacts on subtidal habitat and benthic communities for Northport’s proposed expansion project suggests that areas to the west of the port will be periodically subjected to elevated sediment concentrations which could adversely affect macrofaunal species. The scale, magnitude, and duration of effect will depend on a range of operational conditions and natural forcings. It should be noted that, although related, considerations of scale, magnitude and duration of

ecological impact do not directly translate to the *intensity*, *frequency,* and *duration* components of turbidity exceedances as defined in the *m*-IFD system.

TSS-NTU relationship

46. Water column turbidity can be measured in a variety of ways – either directly as a concentration of the total suspended sediment (TSS) or indirectly using light-based methods.

47. Two common light-based methods are the secchi disk and nephelometer. The secchi disk is either a plain white circular disk or a disk with alternating black and white quadrants. The depth at which the secchi disk is no longer visible provides a measure of water column turbidity. A more reliable method to measure turbidity is using a nepholometer - an instrument that has a light source and a detector. The amount of reflected light measured by the detector is a function of the density, size and shape of particles in suspension. Measurements obtained from a calibrated nephelometer are referred to as Nephelometric Turbidity Units (NTU).

48. For a well-mixed body of water, NTU readings will be highly correlated with actual TSS measurements, although this relationship requires explicit identification through a process of statistical calibration. This is because the predicted turbidity levels from the hydrodynamic modelling of the turbidity plumes generated by the dredging activities are expressed in TSS and the empirical data gathered are expressed as NTU.

49. My experience in similar dredging projects elsewhere has shown this TSS-NTU relationship varies over both time and space and thus the use of a single omnibus equation can potentially lead to large errors. Therefore, as identified above, for Northport's expansion project a process is proposed to estimate the site-specific and seasonal relationships between total suspended solids (TSS in mg/L) and turbidity measured in Nephelometric Turbidity Units (NTU)**PART 2: ISSUES RAISED BY SUBMITTERS**

50. As far as I can determine, issues relating to the statistical aspects of turbidity monitoring have not been raised in any of the submissions.

PART 3: RELEVANT MATTERS IN THE S42A REPORT

51. The s42A report contains several references to turbidity monitoring during dredging (mostly in the context of the development of ecological management plans). For example, under 'Mitigation' (paragraph 304): *"using best practice methods such as real*

time turbidity monitoring and triggers to maintain the effects of dredging plumes within acceptable limits". For reasons already given, the proposed turbidity monitoring program satisfies this requirement in my opinion. Later in the s42A report it is suggested that Channel Infrastructure's Crude Shipping Project dredging turbidity management conditions *"are suitable to apply to this application, with amendments for context"* (paragraph 659).

52. I have reviewed the Crude Shipping Project water quality monitoring program in Appendix 23 of Northport's application documents (Refining NZ Crude Shipping Project (AUT.037197) resource consent). While the monitoring program broadly fulfils the objectives of turbidity management during capital dredging, it suffers from a lack of specificity in places and imposes limits that do not appear to have been derived within a risk-based framework. To this extent, I believe the approach outlined in Fox (2023) provides a more robust and scientifically defensible methodology than that adopted for the Crude Shipping Project. My specific concerns with the Crude Shipping Project turbidity monitoring program are detailed below.

(a) **Baseline Water Quality Data Collection**

A minimum 12-month baseline monitoring period is required, and this is appropriate. For three of the 6 monitoring sites a key requirement is that *"Turbidity measurements shall be recorded … using fixed turbidity meters of the same type, specifications and manufacture".* This is inadequate in my view. At a minimum, the consented monitoring program should make clear matters relating to:

- Sampling frequency (for example 'continuous' monitoring using autonomous loggers has typically meant one NTU reading every 15 minutes).
- The *statistic* to be used as the recorded NTU measurement. NTU data loggers typically sample the water column at a frequency of 1Hz (i.e. one reading every second) for 30 seconds and then record the *arithmetic mean* of the resulting 30 values. However, this is a programmable option and other, equally valid statistics could be used – for example the *median* of the 30 values. In a highly energetic and turbid environment, the difference between a mean and median turbidity value could easily be an order of magnitude or more.
- Statistical QA/QC (Quality Assurance/Quality Control) methods – for example, articulation of how to deal with blocks of missing data; how to identify and what to do with aberrant data and outliers; how to interpret data collected during extreme weather events.

(b) **Receiving Water Quality Limits**

The receiving water quality limits (RWQLs) are specified as single, numerical 'lines in the sand' not to be crossed as a result of the dredging and disposal activities. This is a very dated and rigid approach to environmental management that ignores the reality that, even in the absence of any anthropogenic influences, natural conditions will periodically be abnormally high – for example during or just following a storm event. Without recourse to more advanced statistical modelling and analysis, it is impossible to determine the relative contributions of natural and dredge-related turbidity to the total measured turbidity. Further, there is lack of clarity about what constitutes an 'exceedance' of the RWQL. At face value, this would be whenever a single turbidity reading exceeds the RWQL. Generally, there is latitude in this interpretation so that, for example, an exceedance is not declared unless and until the cumulative number of hours for which the 6-hourly EWMA (say) was greater than the relevant trigger value in any rolling 30-day period is exceeded. This is the basis of the *m*-IFD method.

53. Related to the above, Northport currently holds capital and maintenance dredging consents associated with Berths 3-4. The water quality standards articulated in those consents aim to limit the impacts of dredge-related turbidity by ensuring *"the visual clarity (as using a black disk or Secchi disk) of harbour water shall not be reduced by more than 20% of the median background visual clarity at the time of measurement".* As noted in this evidence, it is proposed that turbidity-related impacts during Northport's proposed expansion project's dredging activities will be monitored and controlled via the implementation of the *m*-IDF method. This is a fundamentally different approach to the consented methods for Berths 1-4 and as such, no inference, or comparisons between the two approaches in terms of environmental protection are possible. The only comment I will make on this point is that whereas the *m*-IFD method is grounded in a probabilistic risk assessment that aims to keep turbidity levels to within those predicted by hydrodynamic modelling, no such basis is evident from limiting visual clarity to within 20% of median background levels.

PART 4: COMMENT ON DRAFT PROPOSED CONDITIONS ADVANCED BY NORTHPORT

54. I have reviewed and had input into Northport's proposed turbidity monitoring and management resource consent conditions, which are based on the conditions applying to LPC's CDP. The framework proposed by Northport through conditions adopts the statistical framework described in my evidence. I support Northport's proposed conditions to the extent they adopt the *m*_IFD method for turbidity

monitoring/management. In my opinion this approach represents current international best practice.

David Robert Fox
Environmetrics Australia

24 August 2023

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ANNEXURE A: TURBIDITY MONITORING FOR THE NORTHPORT EXPANSION PROJECT (FOX 2023)

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An Environmetrics Australia Technical Report

Turbidity Monitoring for the Northport Expansion Project

By
Prof. David R. Fox,

1 June 2023

Limitations Statement

This report documents statistical issues associated with the establishment of turbidity trigger values for a large-scale capital dredging project. Its findings, recommendations, and conclusions are based on desk-top investigations using *indicative* data sets. As such, no claim is made as to the applicability of the approaches to any specific project. The passage of time, manifestation of latent conditions or impact of future events may require further exploration, subsequent data analysis, and re-evaluation of the findings, observations, conclusions, and recommendations expressed in this document. Accordingly, Environmetrics Australia Pty. Ltd. accepts no liability or responsibility whatsoever for or in respect of any use of or reliance upon this document, its recommendations or any other information contained herein by any party.

Executive Summary

Northport Ltd has submitted applications to the Northland Regional Council (Ref. APP.040976.01.01) and the Whangarei District Council (Ref. LU2200107) for resource consents to enable the expansion of Northport's existing facilities to increase freight storage and handling capacity. Northport currently consists of three berths, with a fourth berth and associated reclamation consented but not yet constructed. The current application proposes to construct a fifth berth together with an associated 11.7ha reclamation. The expansion will necessitate the removal of approximately 1.7M m^3 of material during a capital dredge program, with the majority used to form the reclamation.

This report sets out a framework for the collection and processing of turbidity data during an approximate 12-month monitoring period *prior* to any works being undertaken. This *background data* will be used to: (a) characterise the *spatio-temporal* aspects of naturally occurring turbidity in the vicinity of the port; and (b) develop a tiered 'early warning' mechanism to be used to monitor and manage turbidity levels in the harbour during the dredging program.

The information, methods and protocols detailed in this report draw upon the knowledge, expertise and experience *Environmetrics Australia* has acquired over the past 16 years on major capital dredging projects in Australia and New Zealand. These methods have been subjected to exhaustive peer-review by scientific experts in both countries and their efficacy demonstrated by the successful management of turbidity during a number of large-scale dredging projects.

As detailed in this report, a number of matters need to be considered before the commencement of the baseline monitoring program. These relate to:

- The identification of 'extreme' weather and oceanographic events;
- The treatment of data collected during such events;
- Protocols for the treatment of 'unusual' or 'aberrant' turbidity readings;
- Procedures to deal with blocks of missing data due to instrument failure, communication issues, or other unforeseen events;
- Refinement of the data smoothing/filtering algorithm to balance responsiveness of the monitoring system with effective turbidity signal extraction;
- Experimental design and analysis to estimate the site-specific relationships between *total suspended solids* (TSS in mg/L) and turbidity measured in Nephelometric Turbidity Units (NTU);
- Harmonisation and integration of *modelled* TSS with background measurements;
- Development of turbidity 'trigger values' that underpin the early-warning and turbidity management system.

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1. INTRODUCTION

This report sets out a data processing and analysis framework to both monitor and manage turbidity levels during dredging operations associated with the Northport Expansion Project (NEP). The main components of this framework are: (i) pre-processing and statistical QA/QC of ‘raw’ turbidity data (measured in Nephelometric Turbidity Units or NTUs); (ii) establishment of turbidity ‘trigger values’ or TVs for use during the capital dredging program; and (iii) guidance for the implementation of a real-time turbidity monitoring and alerting system. The aims of (i) are to identify ‘aberrant’ readings and/or ‘outliers’ to ensure the integrity and reliability of subsequent statistical calculations. The objective of (ii) is to provide ecologically relevant metrics that provide natural resource managers and port authorities with a tiered, early-warning capability of turbidity levels of concern while (iii) provides computational details required to implement this early-warning mechanism.

1.1 Extreme Events

In the context of autonomously acquired turbidity data, the distinction between an *aberrant* reading and *outlier* has important ramifications. We define an *outlier* to be a truly erroneous observation whose occurrence is explainable through documented observation and/or other lines of evidence. *Importantly, the outlier status is <u>not</u> a declaration based on a subjective assessment of ‘extremeness’*. Situations that can give rise to outliers include, for example, instrument malfunction, data recording and/or transcription errors and (possibly) the influence of other extreme events such as long return period floods and storm events. Removal of data whose outlier status is either wholly or in part due to extreme weather events is a contentious issue with some arguing that the resulting high values are not true outliers but instead, are legitimate observations that are to be expected when monitoring the natural environment. The counter argument is that retention of such data will distort comparisons with background conditions that were quantified in the absence of such extreme natural events.

At some stage the Project Proponents and the Regulator will need to agree on: (i) what constitutes an ‘extreme’ natural event and (ii) the treatment of data collected during such an event and whether that treatment is the same for both baseline monitoring dredge monitoring. To facilitate that discussion, we next discuss some of the issues that need to be addressed in developing data inclusion/exclusion criteria.

Inclusion – Exclusion criteria

The NEP will monitor background turbidity at defined locations for not less than 12 months. This minimum sampling horizon is desirable since it allows seasonal effects in the turbidity signal to be captured. However, the representativeness of the baseline data can be significantly compromised if the 12-month period is characterised by an over- (or under-) representation of extreme oceanographic and/or meteorological events during the monitoring period. Definitive advice on how to best deal with this type of situation does not exist.

Our view is that if the statistical distribution of baseline turbidity data is significantly (in the statistical sense) altered by a pattern of extreme oceanographic and/or meteorological events whose probability of occurrence is deemed to be very low, then there is a *prima facie* case to undertake a statistical adjustment of the data to better reflect long-term, natural background conditions.

It is difficult to be prescriptive about exactly *how* this would be achieved in any given instance, but in general terms the approach would seek to adjust the data through a weighting scheme that attenuates the impact of the 'excess' storm events or adjusts to compensate for the under-representation of storm events. We do not believe data collected during a 'significant' storm event in the dredging phase of the project should undergo any such adjustment. Our reasons are twofold: (i) the baseline data will have already been adjusted to compensate for any over-representation of significant events; and (ii) decision-making about turbidity exceedances during dredging need to be taken in real-time. However, an overall assessment of whether there has been an excess number of extreme events during the dredging campaign cannot be made until dredging campaign is complete.

As an alternative to a statistical adjustment of the baseline data, separate sets of trigger values could be developed for several extreme-event scenarios using modelled turbidity impacts due to storms of different intensities and durations.

1.2 Unusual Events / aberrant data

Perhaps more common than turbidity outliers are the occurrences of *aberrant* turbidity readings. For example, instruments moored in the receiving water body will often 'see' (and hence record) both spatial and temporal 'patchiness' in water clarity. So, while the turbidity readings taken when a 'slug' of highly turbid water passes the instrument sensor are entirely legitimate, they are anomalous and not representative of the water quality more generally. One way of reducing sampling bias is to increase both the spatial and temporal resolution however this becomes prohibitively expensive.

The data smoothing technique proposed in section 2.3 of this report (known as the KZA filter) was successfully used to manage dredging operations during the Port of Lyttleton's Channel Deepening Project (LPC 2018). A key feature of the KZA filter is its robustness to these 'spiky', transient turbidity readings. Accordingly, (and on the assumption the NEP adopts the KZA methodology), we do not believe there is any need to make any additional adjustment or remove these transient turbidity readings.

In the following sections of this report, we provide details of turbidity data processing and the development and use of early-warning sentinel based on turbidity 'triggers'. It is important to appreciate from the outset that this is an imprecise science. Implicit in the use of turbidity to monitor a marine environment for adverse impacts is the strong, but largely untested assumption that the aquatic ecosystem and all that it comprises will be 'protected' provided turbidity is kept below a threshold level. While this assertion has intuitive appeal (for example, we know seagrass need light and turbidity attenuates the photosynthetically active component of light), the *level* or threshold value that achieves the overarching objective of ecosystem protection more generally is unknown and perhaps unknowable – even if one exists.

Current best practice as articulated in the ANZECC/ARMCANZ (2000 a,b) Australian and New Zealand Water Quality Guidelines (and the update by Warne et al. 2014) provides an initial starting point but is not prescriptive. While the Guidelines outline a framework for water quality assessments, they acknowledge the need and indeed advocate the use of locally derived procedures and metrics that are best suited to the specific environment and circumstances under consideration. With this in mind, we believe the Guidelines provide a substantive 'fall-back' position when the science and data are insufficient to refine and enhance the recommended monitoring and reporting procedures.

2. DATA PROCESSING

<u>NB</u>: The recommendations and guidance provided in this section relate to the processing of baseline turbidity data and trigger-value derivation.

We recommend two stages of data integrity checks be undertaken. The first stage checks are to be performed by the contractor responsible for data collection. This preliminary screening of the raw data should be limited to annotating entries in the data file to flag instances of individual readings that the contractor knows to be: (i) an *outlier* due to documented and verifiable faulty, unreliable, or unserviceable equipment or telemetry issues; or (ii) an *aberrant* observation obtained during adverse weather or oceanographic conditions.

Stage 2 checks draw upon statistical QA/QC procedures and should be performed by a professional statistician. The focus of stage 2 checks is to:

- Identify extreme and unusual data in terms of their *statistical* properties.
- Use statistical data imputation techniques in accordance with agreed protocols to overcome problems created by blocks of missing data.
- Use statistical smoothing techniques in accordance with agreed protocols to attenuate the influence of aberrant observations.

2.1 Missing values

This section is included for completeness and acknowledges the challenges presented by large blocks of missing data in both the pre-dredging and during-dredging data collection phases of the project. While statistically sound, the remedial actions suggested here have not been comprehensively assessed as part of any Australian or New Zealand dredging project. Accordingly, this section should be regarded as an articulation of further R&D requirements.

Missing values are problematic for statistical analyses generally but pose challenges in environmental settings since different methods of treating the 'missingness' will produce different outcomes thus potentially leading to different environmental assessments. Fortunately, this problem is largely avoided when dual turbidity loggers are used. However Environmental Management Plans need to anticipate periods of missing data and articulate data management procedures during such times.

An example of a turbidity data having some relatively large gaps in the temporal sequence is shown in Figure 1. These large gaps cannot be overcome by smoothing techniques such as the KZ filter (section 2.3) and cause the complete breakdown of the EWMA smoothing technique.

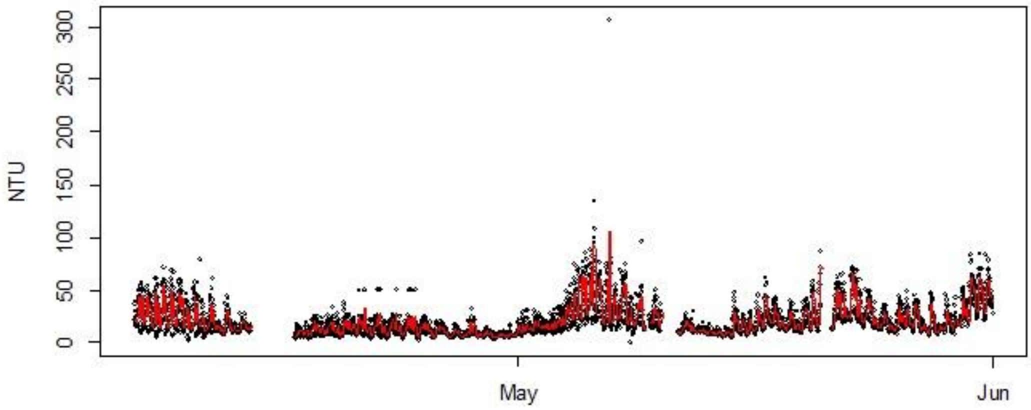
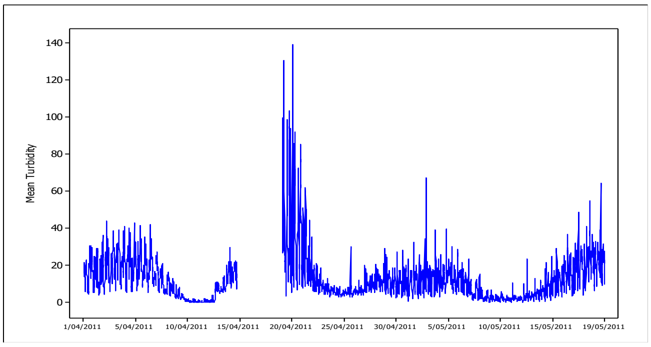


Figure 1. Example of raw turbidity data (open circles) with missing values. Smoothed signal shown in red.

To date, the only effective and credible means of dealing with the level of 'missingness' indicated in Figure 1 is to *impute* the values of the missing data using advanced statistical modelling techniques. Models developed by *Environmetrics Australia* utilise information on ancillary variables such as wind speed, wind direction, tide, currents, and rainfall together with the autoregressive properties of the sequence prior to and following the missing period to reconstruct the missing temporal sequence. An example of the results of this approach are shown in Figure 2 which shows the in-filling of a 3-day gap in turbidity readings.



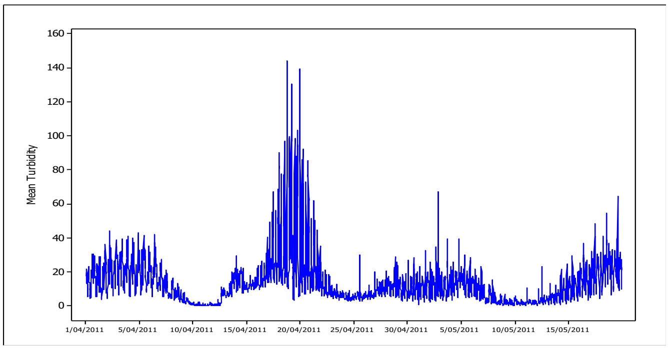


Figure 2. Illustration of temporal 'in-filling' of raw turbidity data. Original series with 3-day gap (left) and after data imputation (right).

Whether or not project proponents commission R&D work to develop local adaptations of predictive background turbidity models and project-specific methods of data imputation is largely a cost-benefit decision for them. Without these tools there is little that can be done to overcome blocks of missing data other than to simply record "NA" in the data record and revert to a management response driven more by heuristics than science. Whatever these actions and management decisions are, they need to be documented in the EMP. Further considerations associated with missing data in the context of turbidity monitoring are discussed in Fox (2018).

2.2 Smoothing

Statistical smoothing may be viewed as a companion activity to the aberrant data detection issue discussed in the previous section although the emphasis is somewhat different.

There are numerous statistical smoothing techniques available to smooth turbidity data and estimate the underlying signal. For many years, the preferred smoothing technique for autonomous turbidity data was the *exponentially weighted moving average* or EWMA as described in the Australian and New Zealand Water Quality Guidelines (ANZECC/ARMCANZ 2000a,b).

The EWMA was successfully used as both a *management* and *compliance* tool during the Port of Melbourne's Channel Deepening Project (https://en.wikipedia.org/wiki/Port_Phillip_Channel_Deepening_Project) and Gladstone Port Corporation's Western Basin Dredging and Disposal Project (https://www.gpcl.com.au/ports-and-trade/major-projects/western-basin-dredging-and-disposal-project/).

A *moving average* (MA) is a locally-weighted average that attenuates high frequency oscillations in a time-varying signal and hence is referred to as a *low-pass* filter. The simplest MA is based on the concept of stepping a 'window' across the time series and plotting the (arithmetic) mean of the points falling in the window. The *degree of smoothing* is controlled by the width of the window. *Weighted* moving averages operate in the same way except data falling within the windows are not equally weighted as they are in the simple MA. While various weighting schemes are available, most assign the greatest weight to observations near the centre of the window and diminishing with increasing distance from the centre.

While the overall performance of the EWMA as a dredge monitoring and management tool has been judged to be highly successful and appropriate, operationally, the 6-hour time delay introduced by the EWMA computation can be problematic in that it unnecessarily delays response times when worsening water quality is self-evident. Another, potentially more serious drawback of the EWMA is its inability to be calculated once missing data in the turbidity time-series are encountered. This is due to the *recursive* nature of the EWMA's computation meaning the current value of the EWMA is dependent on the previous value, and so if the previous value is "missing" the current value cannot be calculated and it too is flagged as “missing”. A robust smoothing technique that does not suffer from this drawback is the Kolmogorov-Zurbenko (KZ) filter.

THE KOLMOGOROV-ZURBENKO (KZ) FILTER

The Kolmogorov-Zurbenko (KZ) filter belongs to the class of low-pass filters and as such is potentially useful for smoothing turbidity time-series data. In essence the KZ filter is computed by taking *k* time iterations of a moving average (MA) filter of *m* points. It therefore has only 2 parameters – *k* and *m* both of which have clear physical interpretations. In addition to its ease of computation and unlike the EWMA, the KZ filter easily deals with missing data situations and is near optimal (Yang and Zurbenko 2010).

2.3 Use of the KZ filter for dredging projects

The use of the KZ filter to monitor and managing turbidity was first used during Lyttleton Port Corporation’s Channel Deepening Project (Fox 2016). The proposed methodology was approved following a rigorous scientific peer-review as part of Environment Canterbury’s Consent process and was a key component of the raw turbidity data processing system adopted by LPC. For the LPC CDP, a K-Z filter with $m = 4$ and $k = 8$ was used. Anecdotal evidence following the LPC CDP suggests the K-Z filter performed very well although there was possibly scope to re-examine the choice of *m* and *k* with a view to reducing the time-delay (3 hours) that this {*m,k*} combination induced in the turbidity calculations (J. Pettersson, *pers. com.*).

3. HARMONISING MODELLED AND MEASURED TURBIDITY

A basic tenet of the environmental consent process for the proposed dredging activity is that, overall, there is no measurable increase in background turbidity levels beyond what has been predicted by hydrodynamic modelling. Output from hydrodynamic models represents the *additional* total suspended sediment (TSS) arising from the dredging operations and is expressed as a concentration (typically in mg/L). In-situ turbidity loggers use a light-based proxy for TSS known as nephelometric turbidity units or NTU. Although not perfect, NTU measurements are generally strongly correlated with TSS and this relationship can be exploited to harmonise modelled output with monitored data.

3.1 Characterising the TSS-NTU relationship

The precise functional form of the TSS-NTU relationship can not be determined in advance of any data collection. Experience has shown that individual site and possibly seasonal models need to be developed to account for spatial and temporal influences on the TSS-NTU relationship. In any event, the model given by Equation 1 which converts TSS at site *i* during season *j* into NTU has been found to provide a good compromise between complexity and usefulness.

$$NTU = \alpha_{ij} \cdot TSS^{\beta_{ij}} \tag{1}$$

The parameters α_{ij} and β_{ij} require estimation and this is typically done during the baseline data collection period using contemporaneous measurements of both NTU and TSS at about 0.5m depth. The details of this aspect of the baseline monitoring program will require careful planning and elicitation *prior* to the commencement of baseline monitoring and should be undertaken by a multidisciplinary team with expertise in field sampling, hydrodynamics, statistics, and local knowledge of the environment to be monitored.

4. DEVELOPING A TIERED TURBIDITY TRIGGER SYSTEM

For the NEP, we propose to adopt the same turbidity alerting system that was successfully used by LPC for its channel deepening project. The approach utilised the related concepts of *intensity*, *frequency*, and *duration* (IFD) of turbidity 'exceedances' proposed by McArthur at al. (2002).

A thorough appraisal of the statistical and mathematical underpinnings of the IFD method undertaken by *Environmetrics Australia* for the LPC revealed serious shortcomings that had hitherto gone undetected despite the methodology having been adopted for major projects in Australia (Rio Tinto's Cape Lambert project, Woodside's Northwest Shelf project, Chevron's Wheatstone and Gorgon projects, and Inpex's Ichthys project).

Since the IFD method forms the kernel of the proposed turbidity monitoring and 'compliance' program, we believe it important that all stakeholders have a common understanding of both the concepts and mechanics of the approach. These are explained in the next section.

4.1 The Intensity-Frequency-Duration (IFD) method

The three components of the IFD approach are identified in Figure 3. The IFD method originally contemplated by McArthur at al. (2002) treated the three components as if they were *independent* and set trigger values on the intensity and duration. As was shown by Fox (2018) this is incorrect.

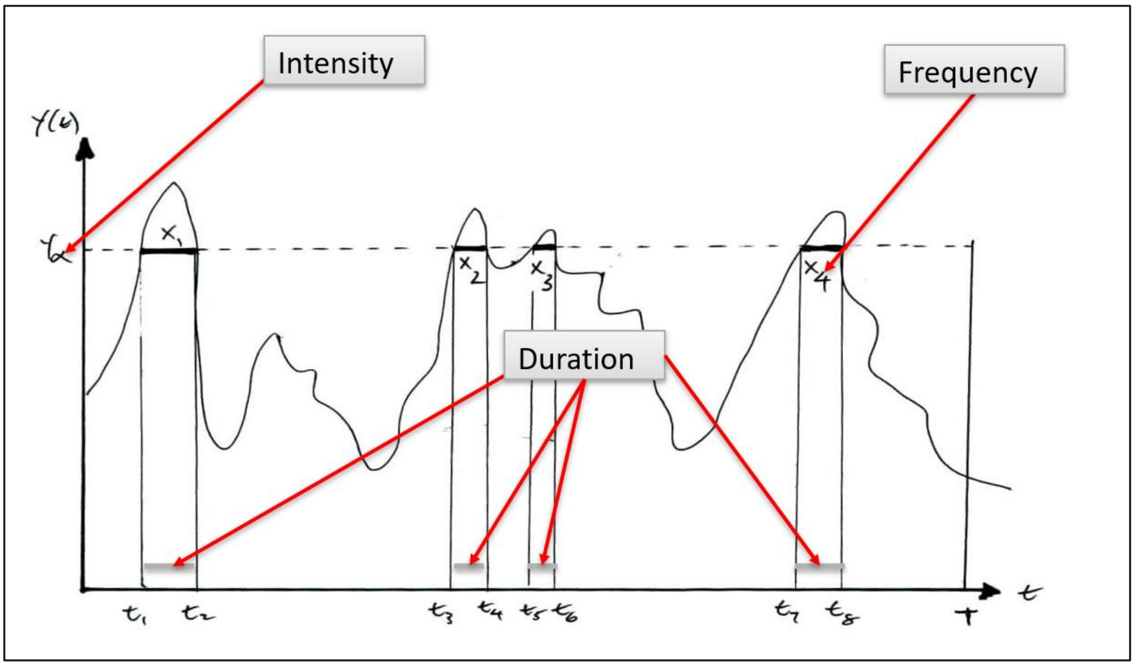


Figure 3. Depiction of IFD components for a turbidity time-series (see text for explanation).

4.2 Which data to use?

The use of turbidity 'trigger values' as an early-warning mechanism for dredging projects was an adaption of water quality monitoring procedures espoused in the Australian and New Zealand Water Quality Guidelines (ANZECC and ARMCANZ 2000). That advice was predicated on the notion of a trigger-value being set as some high-order percentile of *background* conditions.

The incorporation of *frequency* and *duration* (of exceedance) considerations into the trigger-value derivation process was the result of individual jurisdictions and projects taking on board ANZECC and ARMCANZ (2000) advice (for toxicants), that wherever possible, water-quality assessments should be based on locally derived criteria.

The approval of large-scale dredging projects and their embedded monitoring programs served to provide regulatory endorsement of the incremental modifications to the trigger-value methodology. The difficulty was that no one had stopped to undertake an holistic assessment of the *statistical* implications of what had been approved.

The reliance on the analysis of only background conditions for establishing trigger values was challenged during the review of the McArthur et al. (2002) IFD method Fox (2018). Their procedure was predicated on the key requirement that the trigger-value methodology "*requires that natural SSCs [suspended sediment concentrations] plus that due to disposal cannot exceed the natural bounds"* MacArthur et al. (2002).

Fox (2018) demonstrated that the MacArthur et al. (2002) IFD method which allowed for *simultaneous* increases in both frequency and duration of exceedances resulted in outcomes in the 3D background I-F-D space that were infeasible. The procedure was thus incapable of honouring the proponent's own requirement that natural turbidity plus that due to dredging cannot exceed natural bounds.

Furthermore, Fox successfully argued during the LPC Consent hearing (Christchurch, May 1-9, 2017) that basing turbidity triggers on background data alone was logically inconsistent with the objectives of the consenting process. The argument advocating the use of background turbidity *plus* modelled turbidity in developing a modified IFD trigger system went as follows:

(i) Dredging (temporarily) increases turbidity and that increase has been quantified by hydrodynamic modelling;

(ii) Approval of the project gives license to (i);

(iii) The monitored turbidity signal during dredging cannot honour a relationship between the I, F and D components that were derived from background turbidity alone;

(iv) The I, F, and D components of turbidity exceedances need to be adjusted to capture the characteristics of the modified turbidity signal. Limits can then be placed on these components which:

(v) acknowledge the link between I – F – D components; and

(vi) ensure that more extreme turbidity events during dredging are within the limits of what has been predicted.

In view of the foregoing, we do not believe it necessary to re-visit the arguments in support of the use of background *and* modelled turbidity for the development of the

IFD trigger-value methodology for the NEP. The results of detailed mathematical and statistical investigations into the modified IFD (m-IFD) were provided as part of the LPC CDP consenting process and are available at ECAN's website (https://bit.ly/3wjK4hN).

We next outline the computations involved in the m-IFD method.

4.3 Assimilation of modelled TSS data and baseline monitoring data

The output from hydrodynamic modelling is predicted hourly *additional* suspended sediment (TSS) concentrations arising from dredging activities at Tier 3 monitoring locations The steps involved in combining this data with the background data are outlined in the box below.

1. Express modelled TSS concentrations (mg/L) as a turbidity in NTU;
2. Apply K-Z filter to empirical turbidity data;
3. Average smoothed turbidity data over 1-hour periods;
4. For each site:
    a. Merge data from steps 1 and 2 by month, day, and hour (year is disregarded);
    b. Add modelled NTU and background NTU to obtain total NTU.

4.4 The modified IFD method (m-IFD)

> *"Overall, we are satisfied that the m-IFD approach provides adequate assurance in this case".*
> *From Commissioners' consent decision on LPC's CDP project, Environment Canterbury*

The essence of the m-IFD procedure is the recognition that the fraction of time in an exceedance state must be no greater than α - the level used to determine the intensity trigger for discrete event sampling. Since it is the product of both frequency and (average) duration which determines the total exceedance time, these two components do not need to be separately managed – only the total time.

For example, suppose the reporting period is 30 days or 720 hours. Using an intensity trigger based on the 95th. percentile of the turbidity data implies that only 5% of turbidity readings will exceed this level (assuming an 'in-control' process). Equivalently, the total time that turbidity exceeds this trigger can be no more than 36 hours. The composition of exceedance events contributing to this 36-hour duration limit is somewhat immaterial – it could be due to many short-duration exceedances, a small number of long exceedances or, as is more likely, a range of durations.

Implementation and management of this system is very simple having only two steps:

1. For a chosen intensity level α determine the intensity trigger, Y_α ;
2. For a fixed monitoring interval $[0,T]$ set a limit on the cumulative exceedance time equal to $\alpha \cdot T$.

Thus, for a 30-day moving window, the *Allowable Cumulative Exceedance Times* (ACET) for $\alpha = \{0.8, 0.95, 0.99\}$ are 144 hours, 36 hours, and 7.2 hours respectively.

A management response is required when the limit in 2 above has been (or is about to be) exceeded.

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APPENDIX 1: Implementing the KZ Filter

The Kolmogorov-Zurbenko (KZ) filter belongs to the class of low-pass filters and as such is potentially useful for smoothing turbidity time-series data. In essence the KZ filter is computed by taking *k* time iterations of a moving average (MA) filter of *m* points. It therefore has only 2 parameters – *k* and *m* both of which have clear physical interpretations. In addition to its ease of computation and unlike the EWMA, the KZ filter easily deals with missing data situations and is near optimal (Yang and Zurbenko 2010).

The KZ filter applied to a time series $X(t), t = 0, \pm1, \pm2, \ldots,$ is given as:

$$KZ_{m,k}\left[X(t)\right] = \sum_{s=-k(m-1)/2}^{k(m-1)/2} \frac{a_s^{m,k}}{m^k} X(t+s) \tag{6}$$

where $a_s^{m,k}$ are given by the polynomial coefficients of $\left(1+z+\cdots+z^{m-1}\right)^k$

$$\sum_{s=-k(m-1)/2}^{k(m-1)/2} z^{s+k(m-1)/2} a_s^{m,k} = \left(1+z+\cdots+z^{m-1}\right)^k \tag{7}$$

Computations

As mentioned above, the KZ filter computed by taking *k* time iterations of a moving average (MA) filter of *m* points as follows as described in Yang and Zurbenko (2010):

1. First iteration is to apply a MA filter to *m* points:

$$KZ_{m,k=1}\left[X(t)\right] = \frac{1}{m} \sum_{s=-(m-1)/2}^{(m-1)/2} X(t+s) \tag{8}$$

2. Second iteration is to apply a MA operation to the result of the first iteration:

$$KZ_{m,k=2}\left[X(t)\right] = \sum_{s=-(m-1)/2}^{(m-1)/2} \frac{1}{m} KZ_{m,k=1}\left[X(t+s)\right]$$

$$= \sum_{s=-2(m-1)/2}^{2(m-1)/2} \frac{a_s^{m,k=2}}{m^2} X(t+s) \tag{9}$$

3. k^{th} iteration:

$$KZ_{m,k}\left[X(t)\right] = \sum_{s=-k(m-1)/2}^{k(m-1)/2} \frac{a_s^{m,k}}{m^k} X(t+s) \tag{10}$$

Implementation in EXCEL

For the LPC CDP, Fox (2016) recommended using the K-Z filter with $m = 4$ and $k = 8$. An alternative to the iterated application of a 4-point moving average to the raw turbidity data is the use of equation 1 directly. A formula for computing the coefficients $a_s^{m,k}$ was not provided by Yang and Zurbenko (2010) and so these have been obtained by direct computation elsewhere. Denoting the scaled coefficients $\frac{a_s^{m,k}}{m^k}$ in equation 1 by $w(s,m,k)$ we see that $KZ_{m,k}\left[X(t)\right]$ is a *weighted average* of the current turbidity reading and the immediately adjacent (in time) $\frac{k(m-1)}{2}$ values either side of it. This is because $\sum_s w(s,m,k) = 1$.

For $w(s,4,8)$, a weight of 0.123474 is applied to the current raw data value. Diminishing weights are applied to the neighbouring 12 data points either side of the current raw data value. These are {0.11792, 0.102661, 0.081299, 0.058334, 0.03772, 0.02179, 0.011108, 0.004913, 0.001831, 0.000549, 0.000122, 0.000015}. As can be seen from Figure 1, the pattern of weighting is very similar to a gaussian weighting scheme.

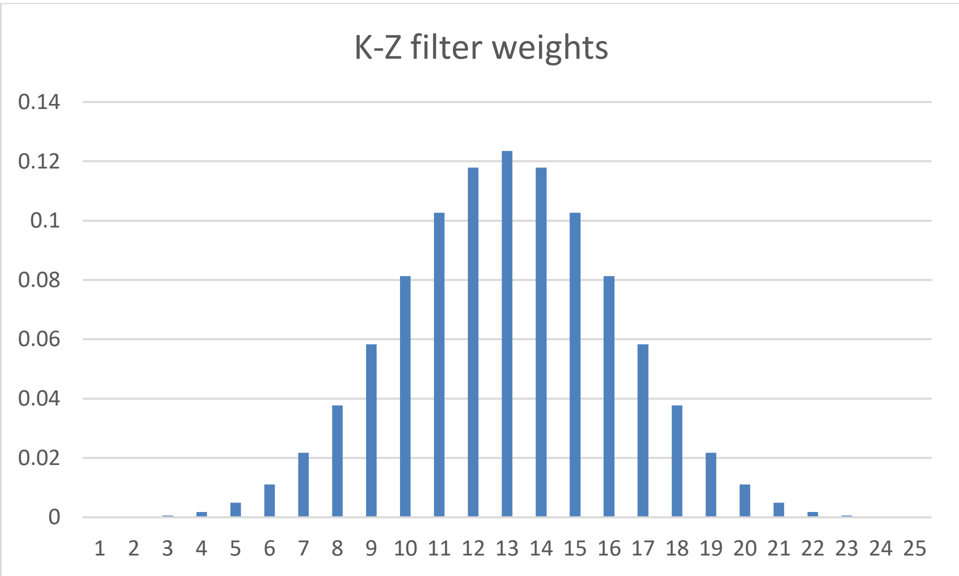

Figure 4. Distribution of weights *w(s,4,8)*.

Implementation in Excel is straightforward as is illustrated in Figure 2 which shows the underlying calculation for the raw turbidity reading at CH1 on 1/11/2016 at 14:31. The recorded turbidity was 4 NTU. This is given the highest weight of 0.123474. The next highest weight of 0.11792 is applied to each of the 2 adjacent readings (3.85 and 4.1). A weight of 0.102661 is applied to the next pair (3.55, 3.65) and so on. Multiplying each of the 25 measured turbidity readings by its corresponding weight and summing gives the final result shown in the highlighted cell. As can be seen from the formula bar at the top of Figure 2, the whole calculation is achieved with one line of code which can be copied and pasted in all the remaining cells to be populated with smoothed data.

D112 | {=SUM(C100:C124*coeffs!$A$1:$A$25)}

	A	B	C	D	E	F	G
98	CH1	1/11/2016 11:01	4.65	4.488857			
99	CH1	1/11/2016 11:16	4.55	4.403583			
100	CH1	1/11/2016 11:31	4.45	4.327945			
101	CH1	1/11/2016 11:46	4.4	4.257495			
102	CH1	1/11/2016 12:01	3.95	4.192333			
103	CH1	1/11/2016 12:16	3.9	4.134992			
104	CH1	1/11/2016 12:31	3.9	4.088			
105	CH1	1/11/2016 12:46	4.4	4.052113			
106	CH1	1/11/2016 13:01	3.5	4.025907			
107	CH1	1/11/2016 13:16	4.05	4.006563			
108	CH1	1/11/2016 13:31	4.4	3.991221			
109	CH1	1/11/2016 13:46	4.15	3.978144			
110	CH1	1/11/2016 14:01	3.55	3.96701			
111	CH1	1/11/2016 14:16	3.85	3.958221			
112	CH1	1/11/2016 14:31	4	3.95172			
113	CH1	1/11/2016 14:46	4.1	3.94591			
114	CH1	1/11/2016 15:01	3.65	3.937377			
115	CH1	1/11/2016 15:16	4.2	3.921663			
116	CH1	1/11/2016 15:31	3.85	3.894909			
117	CH1	1/11/2016 15:46	4.35	3.8559			
118	CH1	1/11/2016 16:01	3.8	3.808003			
119	CH1	1/11/2016 16:16	3.7	3.76055			
120	CH1	1/11/2016 16:31	3.5	3.729277			
121	CH1	1/11/2016 16:46	3.55	3.735545			
122	CH1	1/11/2016 17:01	3.65	3.803899			
123	CH1	1/11/2016 17:16	3.15	3.957862			
124	CH1	1/11/2016 17:31	3.45	4.214423			
125	CH1	1/11/2016 17:46	3.45	4.578029			
126	CH1	1/11/2016 18:01	3.9	5.035984			
127	CH1	1/11/2016 18:16	5.7	5.556922			
128	CH1	1/11/2016 18:31	6.6	6.093458			
129	CH1	1/11/2016 18:46	6.95	6.589646			
130	CH1	1/11/2016 19:01	7.85	6.991738			
131	CH1	1/11/2016 19:16	8.55	7.259772			
132	CH1	1/11/2016 19:31	9	7.377002			
133	CH1	1/11/2016 19:46	9.25	7.353405			
134	CH1	1/11/2016 20:01	7.05	7.221899			

filtered_all | coeffs

APPENDIX 2: Turbidity data processing and analysis

I: Data Processing: Quality Assurance

1. Turbidity data will be collected at times, places and sampling frequencies set out in the EMMP;
2. Data integrity and quality will be assured via a two-stage process: (i) an initial QA/QC of the raw turbidity data; and (ii) a comprehensive *statistical QA/QC* of the supplied turbidity data.
3. The first-stage QA/QC activities will be undertaken at the time of data acquisition using procedures and processes specified by the responsible Contractor;
4. The *statistical QA/QC* component will be undertaken by an accredited statistician and utilise statistical methods consistent with the activities described in this report.

II: Data Processing: Smoothing

1. The impact of transient, high-frequency oscillations in the time-series of quality-assured turbidity data will be reduced through a process of statistical smoothing;
2. The smoothing technique will be an implementation of the Kolmogorov-Zurbenko (KZ) Filter with parameters $m=4$ and $k=3$ as described in **Appendix** 1 of this report.

III: Data Processing: Treatment of Missing values

1. Treatment of missing individual turbidity readings shall be in accordance with procedures and processes specified by the Contractor responsible for the implementation of the turbidity monitoring program;
2. Treatment of contiguous blocks of missing data for periods in excess of 24 hours shall utilise methods identified in Appendix 3 of this report.

IV: Statistical Analysis of Background Turbidity

1. Data used to develop a statistical profile of background turbidity shall have undergone steps I-III above;

2. Statistical procedures used to develop the background turbidity profile shall be consistent with those outlined in this report, including (but not limited to):

   - Graphical, tabular and numerical summaries organised by site and time;

   - Quantification of spatial and temporal patterns, dependencies and anomalies in the measured turbidity signals;

   - Investigation into the influences of natural forcings such as wind speed, wind direction, rainfall, currents, and tide.

   - Estimation of the parameters in the NTU-TSS relationship and assessment of spatial-temporal dependencies of same;

- Identification of appropriate theoretical distributions to describe overall turbidity properties;

- Assessment of the representativeness of climatic and oceanographic conditions during the background data collection period.

V: Trigger Values

1. Trigger values will utilise monitored data that has undergone steps I-III and augmented with the incremental turbidity due to dredging as predicted by hydrodynamic modelling. The conversion between modelled TSS and NTU will be achieved using the models identified in IV above;
2. The modified IFD approach as detailed in Appendix 2 of this report shall be used to establish numerical trigger values;
3. The *intensity* levels associated with the 'Tier 1, 'Tier 2, and 'Tier 3 classifications shall correspond to high order., percentiles of the data in V.1 above (80^{th}., 95^{th}., and 99^{th} are suggested);
4. The permissible number (*frequency*) of 'Tier1, 'Tier2, and 'Tier3 exceedances in a reporting period will be determined in accordance with the method outlined in section 4.6 of The Report and attached as **Appendix D**;
5. The maximum average *duration* of 'Tier 1, 'Tier 2, and 'Tier 3 exceedances in a reporting period will be determined in accordance with the method outlined in section 4.6 of The Report and attached as **Appendix D**;
6. The management response associated each of the 'Tier 1, 'Tier 2, and 'Tier 3 triggers is <u>not</u> required provided both the number and average duration of turbidity exceedances in the reporting period are within the limits identified in V.4 and V.5 above;
7. Contemporaneous control charting of *median* turbidity at sentinel sites and the rolling 80^{th}. percentile of turbidity at a selected reference site(s) as described in section 4 of The Report may be used as an internal LPC back-up monitoring tool.

V1: Cause and Effect

1. In the event turbidity conditions resulting in a 'Tier 3' exceedence a detailed analysis of all turbidity data obtained from steps I-III up to and including the time of exceedance will be undertaken using methods described in sections 2.2 and 2.3 of The Report;
2. The findings associated with the analyses undertaken in V1.1 will be used by LPC to assist in the assessment of the relative contributions of 'natural' and dredge-related turbidity to the measured turbidity signal.

APPENDIX 3: Treatment of missing blocks of data

An advantage of the KZ Filter (*see Appendix 1*) is that it is robust to the presence of small amounts of missing data. With a 15-minute time-increment and *m=3* and *k=3*, the KZ-filter will be a weighted average of the current turbidity reading and the three adjacent readings. Although a smoothed turbidity reading will be produced at the same frequency as the sampling (ie. one every 15 minutes) it will lag the raw data by 45 minutes. As discussed in The Report, missing data pose various challenges for the subsequent statistical analysis and treatment of the turbidity series. Under the scheme outlined in this document, the KZ filtering of data can continue provided there is no more than six (6) contiguous missing values of the recorded turbidity. Where more than 6 contiguous readings are reported as 'missing', advanced statistical modelling techniques as discussed in section 2.1 shall be used to statistically 'impute' the likely values of the missing data. This data imputation will be done in such a way that the resulting sequence:

(i) is consistent with the autocorrelation of the actual data recorded prior to the period of 'missingness';
(ii) utilises actual data recorded at nearby locations using spatial covariance modelling techniques;
(iii) has statistical properties that are consistent with actual data recorded immediately prior and following the period of 'missingness'.