An Environmetrics Australia Technical Report

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Turbidity Triggers for Lyttleton Port Company's Channel Deepening Project

(Environment Canterbury Certified)

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26 April 2018

Limitations Statement

This report documents the process by which turbidity trigger values have been established for the Lyttleton Port Company's Channel Deepening Project. Its findings, recommendations, and conclusions are based on statistical analyses of LPC background turbidity data sets. As such, no claim is made as to the applicability of the approaches to other projects. 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

This report provides details and results associated with the establishment of turbidity trigger values to be used during the Lyttelton Port Company's (LPC) Channel Deepening Project (CDP).

The CDP involves a large-scale dredging program to remove a total of approximately 18 million cubic metres of sediment and place it in a 1,250 hectare off-shore disposal site. This activity has the potential to adversely impact the marine ecosystem and controls are therefore required to provide an early warning mechanism of potentially unacceptable water quality.

The use of 'turbidity trigger values' has become *de facto* industry best practice for large-scale dredging projects such as the CDP. Not only is this approach endorsed by the Australian and New Zealand governments (ANZECC/ARMCANZ 2000a, b), but recent experience (particularly in Australia) with projects of similar scope and objectives has demonstrated the dredging activity can be managed to successful completion without any long-term environmental harm and/or impacts that were not predicted by the environmental impact assessment.

While this experience provides a level of assurance that the use of turbidity trigger values and companion data processing activities will achieve the desired outcome, the science underpinning environmental trigger values has been hampered by several unresolved issues. These relate to: the treatment of aberrant observations; identification of appropriate smoothing techniques; a lack of a consistent methodology for handling missing data; and statistical flaws with the integration of exceedance frequency and duration.

Preparatory work undertaken by *Environmetrics Australia* leading up to Environment Canterbury's consent application hearing in May 2017 resolved these issues and articulated technically sound and practical approaches for turbidity monitoring and management before, during, and after dredging. These refinements and enhancements have undergone rigorous independent scientific review by Crown appointed experts and form part of the Consent Orders granted on 6 March 2018. The refined turbidity monitoring strategy known as the *m*-IFD approach represents a world-first for such projects and is expected to become *de facto* 'best practice'.

List of Figures

Table of Contents

1. INTRODUCTION

The purpose of this report is to provide a summary of data processing activities and results of the statistical analysis of background turbidity data collected to develop turbidity trigger values for the LPC CDP.

Condition 9 of the Consent Order issued 6 March 2018 requires a written report to be provided at least two months prior to the commencement of dredging which demonstrates that the turbidity triggers and Tier 3 Compliance Level have been established in accordance with the conditions of the Consent Order.

Specifically, this report addresses part 9 of those Orders which require requires LPC to (among other things):

- Establish turbidity triggers and a Tier 3 Compliance Level for 14 of the surface telemetered turbidity monitoring locations, each with an *intensity* and *allowable duration*. This is to be done using the baseline turbidity data plus the predicted Dredging Turbidity at each location using the methodology outlined in Fox (2016).

The Fox (2016) report provides detailed discussion on many aspects of the background data collection and processing activities and accordingly this material will not be repeated here.

2. WATER QUALITY MONITORING AND THE BACKGROUND DATA SET

The background turbidity monitoring project has been running continuously since September 2016. Physical and chemical parameters (including turbidity measured as NTU) are recorded once every fifteen minutes at the inshore and offshore sites shown in Figure 1. This program has been implemented and maintained by Vision Environment who are also responsible for the functional quality assurance – quality control (*f-QA/QC)* activities described in Fox (2016). Details of the monitoring activities and discussion of results are contained in the series of Water Quality Environmental Monitoring Services monthly reports issued by Vision Environment.

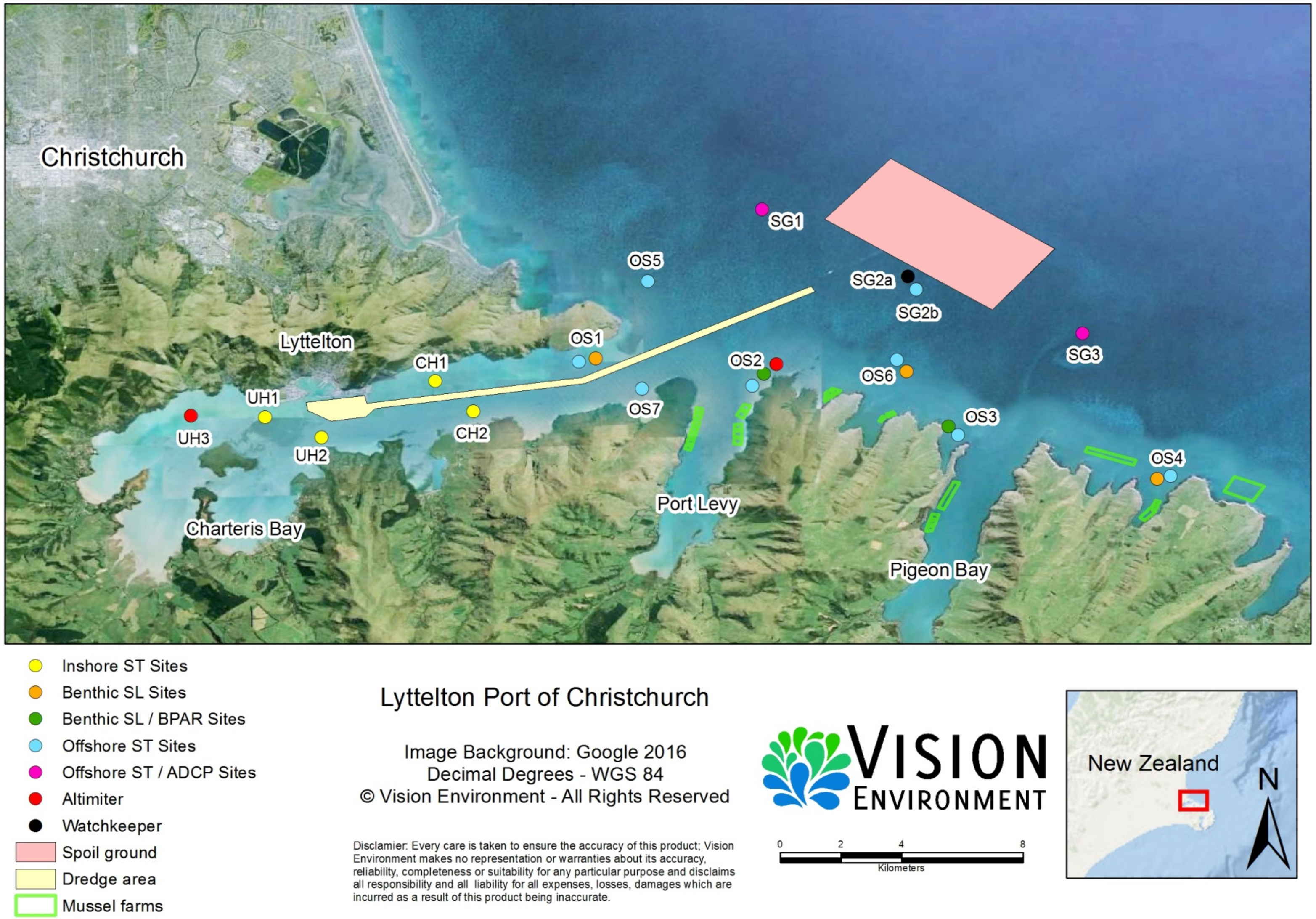


Figure 1. Water quality monitoring locations. (ST= subsurface telemetry, SL = self-logger, BPAR = benthic photosynthetically active radiation, ADCP = Acoustic Doppler Current Profiler). *Source: Vision Environment*.

2.1 Characterisation of the background data set

Condition 8.3 of the aforementioned Consent Order requires the Consent Holder to "carry out baseline monitoring over a period of at least one year prior to the first commencement of Dredging". The results presented in this report are based on the one-year period November 1, 2016 to October 31, 2017. The commencement of the one-year period is somewhat arbitrary but in this instance was chosen to be as soon as practicable after instrument deployment having due regard to data quality issues in the implementation stages of the monitoring program.

An overall synopsis of the data collection effort is shown in box 1.

Box 1. Characteristics of the background data collection effort.

Number of sites (surface and benthic):	*19*
Sampling frequency:	*15 minutes*
Number of possible samples per site in period:	*35,040*
Potential number of samples in period (all sites):	*655,760*
Actual number of samples collected (all sites):	*595,774*
Overall data recovery rate (all sites):	*89.5%*
Overall data recovery rate (excluding benthic sites):	*98.1%*

A detailed breakdown of the sample sizes and data recovery rates by site is given in Table 1.

Important note: *Results for benthic sites shown in this report are provided for completeness only. These sites do not form part of the turbidity monitoring network to be used to manage dredging.*

It is evident from Table 1 that data recovery for the 13 surface sites to be used for Tier 3 compliance monitoring has been very high – typically about 99%. This is an important observation which has ramifications for data imputation which is discussed in section 2.3.

Table 1. Actual sample sizes and data recovery rates by site for the period 1 November 2016 to 31 October 2017.

site	N	Recovery
CH1	34,839	99.4%
CH2	34,600	98.7%
OS1	33,495	95.6%
OS1 Benthic	21,738	62.0%
OS2	34,138	97.4%
OS2 Benthic	23,596	67.3%
OS3	34,530	98.5%
OS3 Benthic	23,107	65.9%
OS4	34,610	98.8%
OS4 Benthic	27,718	79.1%
OS5	33,642	96.0%
OS6	34,341	98.0%
OS6 Benthic	18,205	52.0%
OS7	33,453	95.5%
SG1	34,699	99.0%
SG2b	34,849	99.5%
SG3	34,896	99.6%
UH1	34,627	98.8%
UH2	34,691	99.0%

Graphical summaries of the data are shown in the form of time-series plots (Figures 2 to 5) and empirical probability density plots (Figures 6 to 9). The completeness of data capture for surface sites is clear from an inspection of the time-series plots – there being no obvious gaps or omissions. On the other hand, the time-series plots for the benthic sites are characterised by significant gaps in the data record. This is a direct consequence of the difficulty in maintaining proper instrument deployment and operation at depth in a highly energetic environment and not a flaw with the instrumentation as such.

Focusing on the time-series for surface sites several general observations can be made:

(i) the raw turbidity data is highly variable resulting in a very 'spiky' trace;

(ii) there are short-lived events that give rise to exceedingly large turbidity readings that are not representative of more general turbidity trends;

(iii) there are low-frequency periodic trends in the raw turbidity signal (depicted by the solid blue line in Figures 2 to 5) that are most likely the result of lunar cyclical patterns.

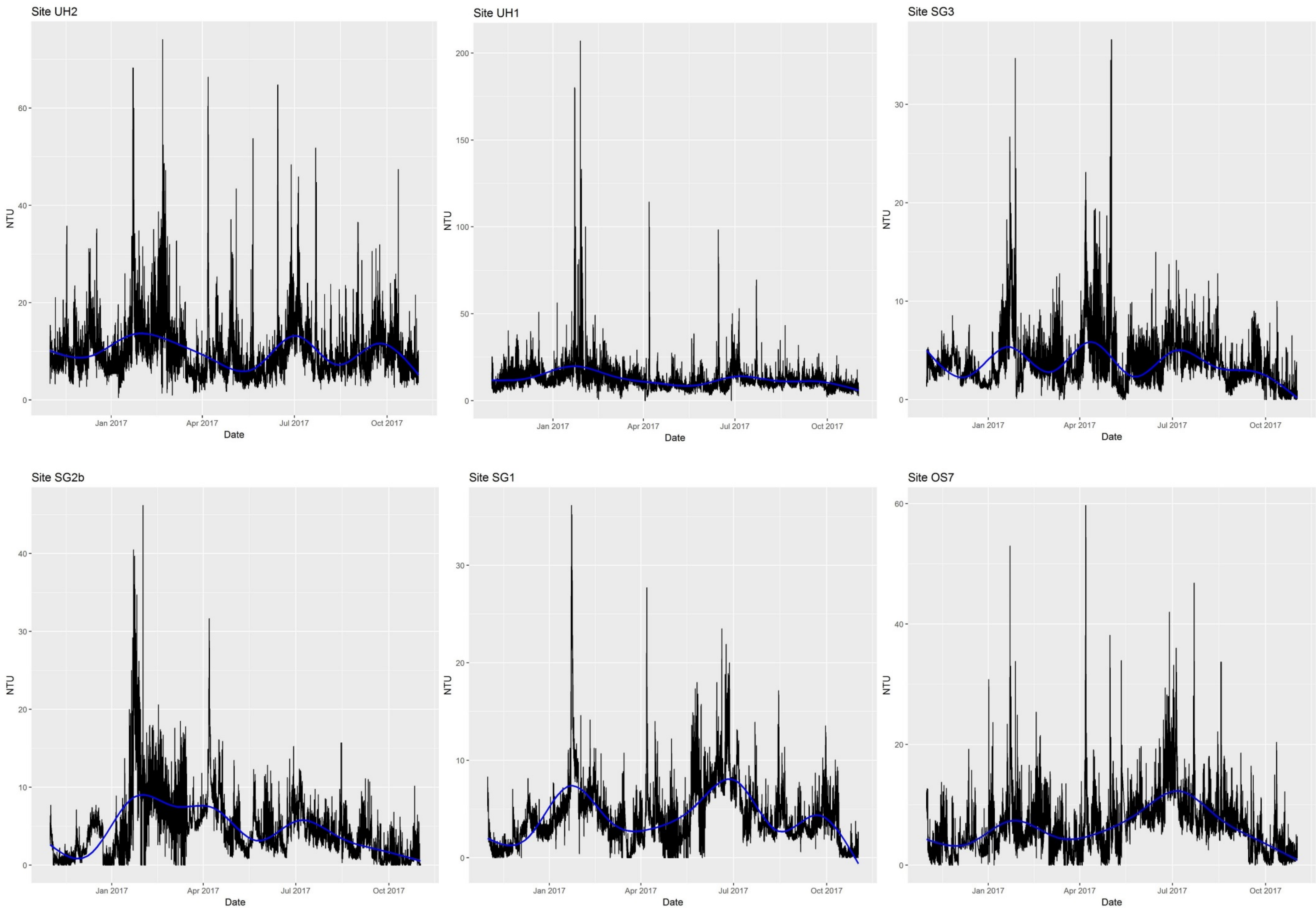


Figure 2. Time series plot of raw background turbidity data (black trace) together with trend (blue trace) during the baseline monitoring period for sites UH2, UH1, SG3, SG2b, and OS7.

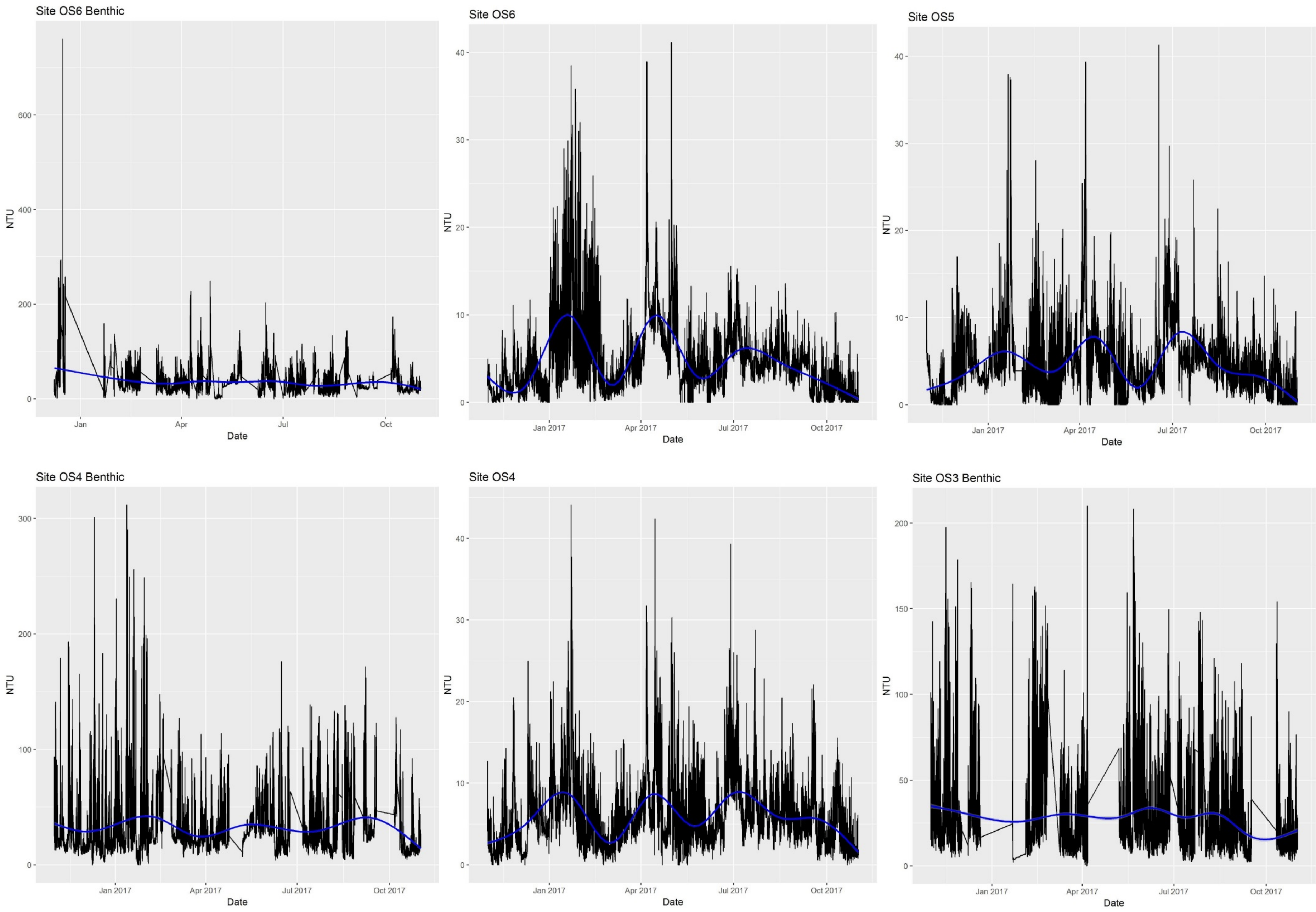


Figure 3. Time series plot of raw background turbidity data (black trace) together with trend (blue trace) during the baseline monitoring period for sites OS6, OS5, and OS4.

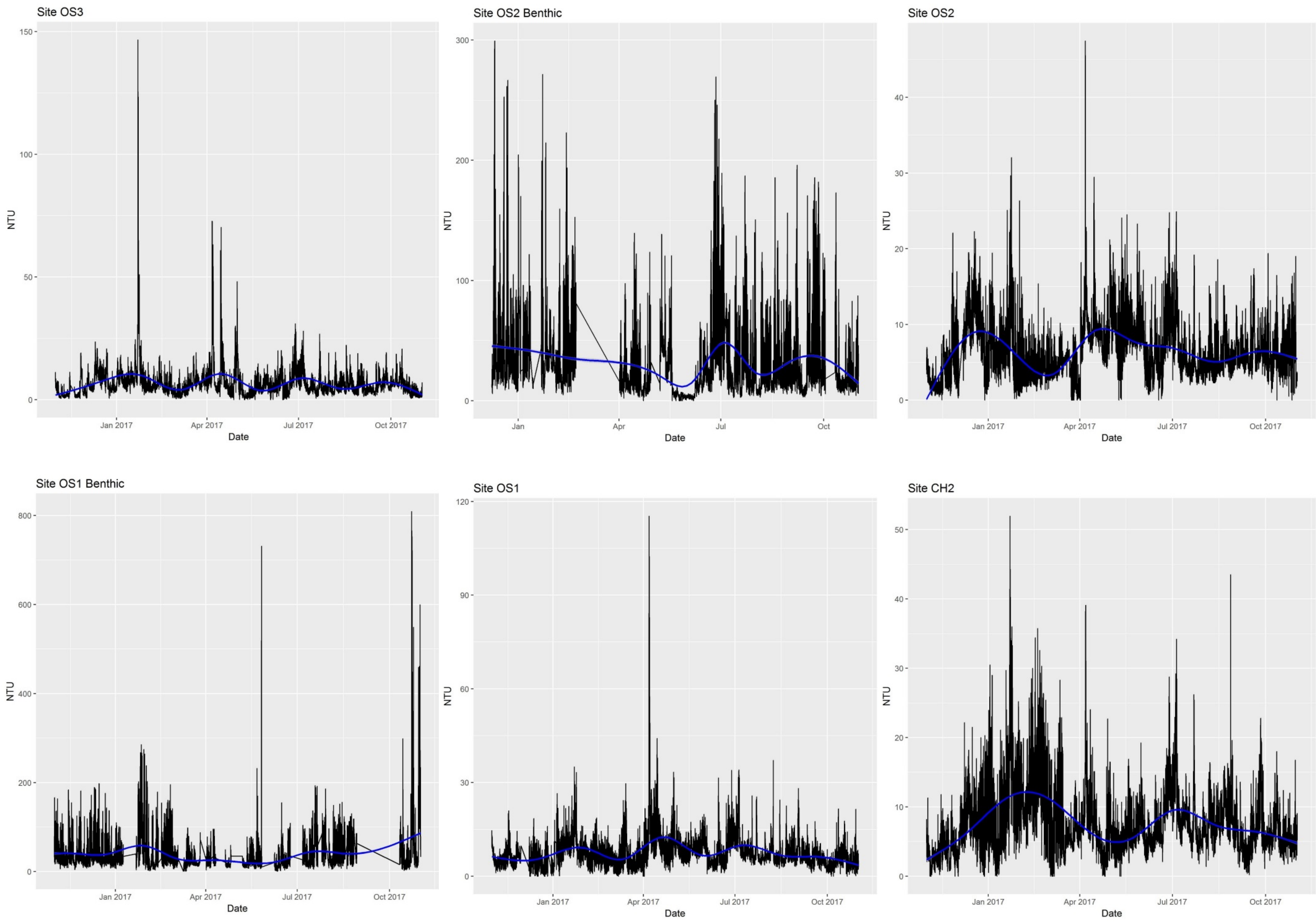


Figure 4. Time series plot of raw background turbidity data (black trace) together with trend (blue trace) during the baseline monitoring period for sites OS3, OS2,OS1 and CH2.

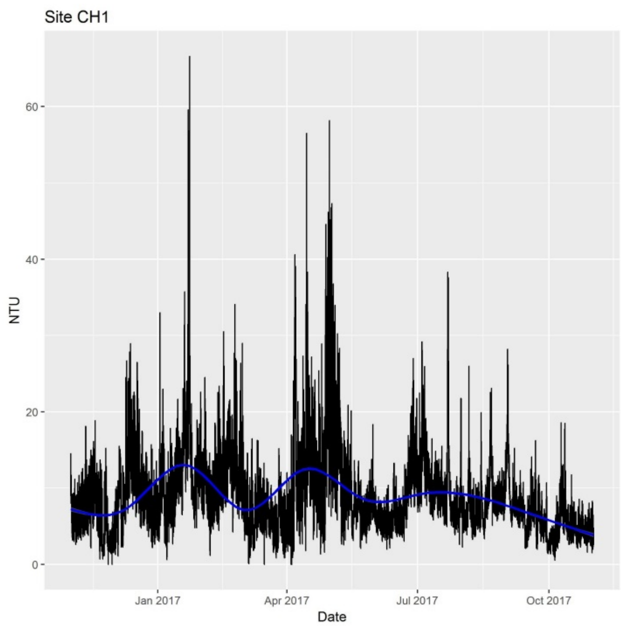


Figure 5. Time series plot of raw background turbidity data (black trace) together with trend (blue trace) during the baseline monitoring period for site CH1.

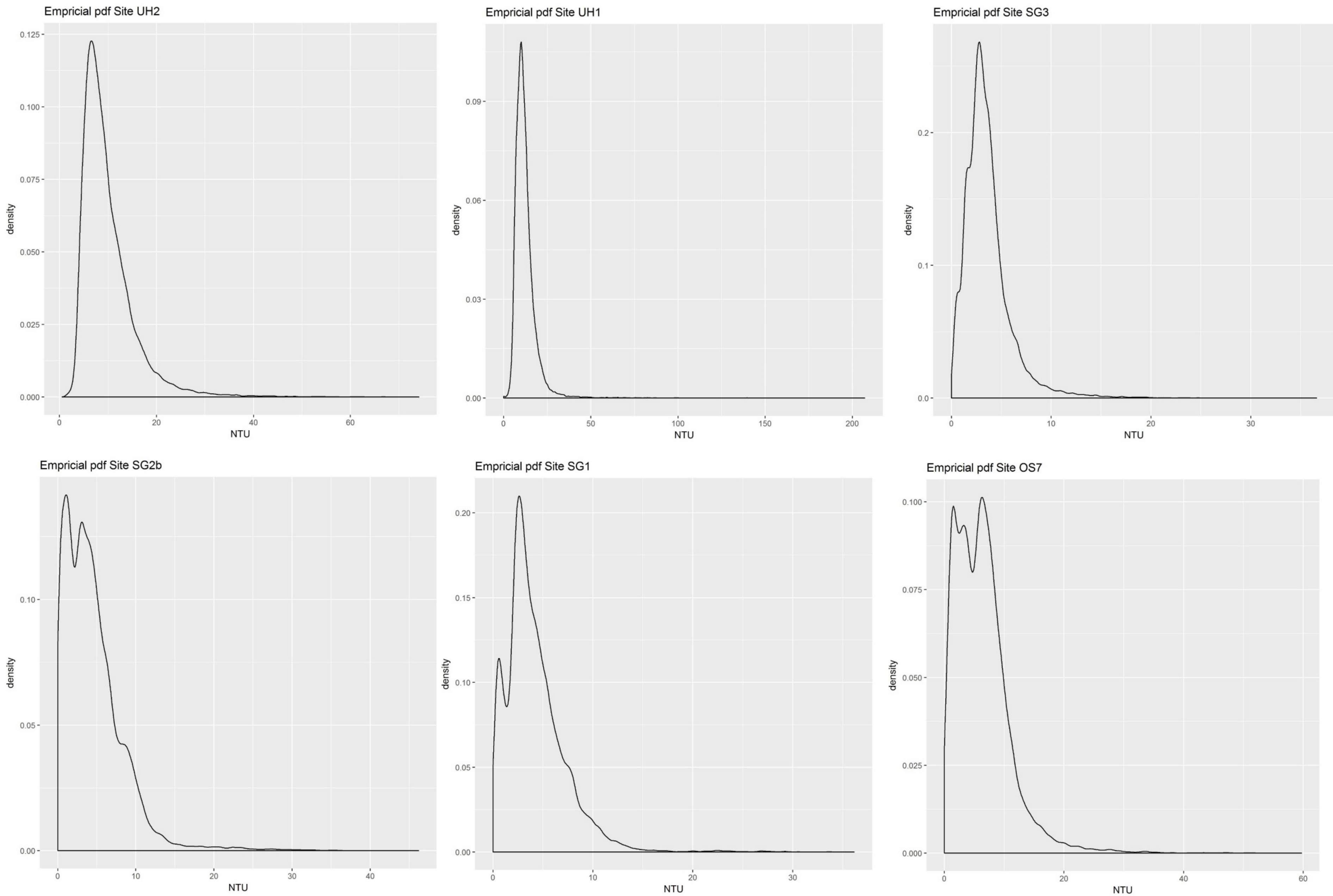


Figure 6. Empirical probability density plots of background turbidity data during the baseline monitoring period for sites UH2, UH1, SG3, SG2b, SG1, and OS7.

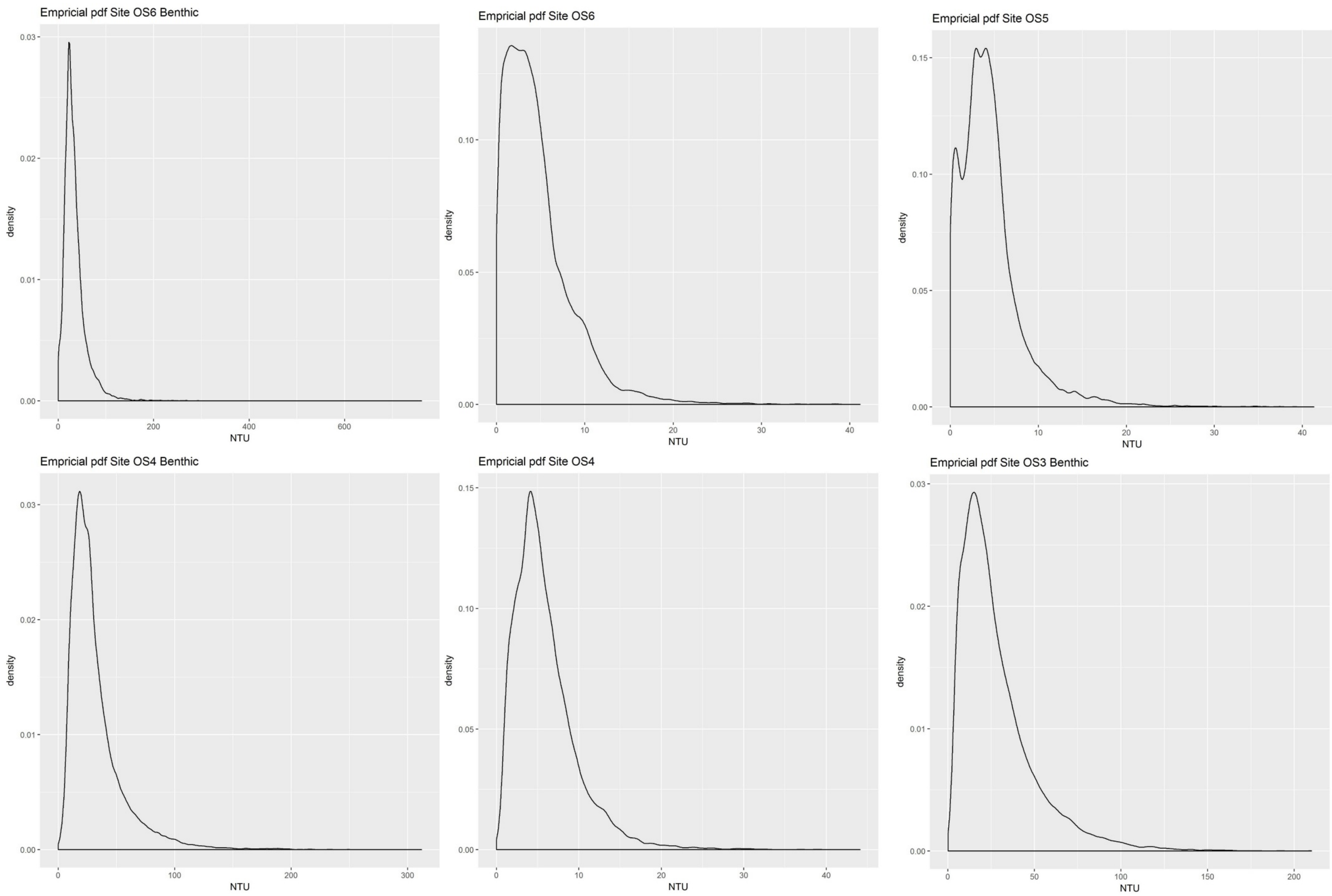


Figure 7. Empirical probability density plots of background turbidity data during the baseline monitoring period for sites OS6, OS5, OS4, and OS3.

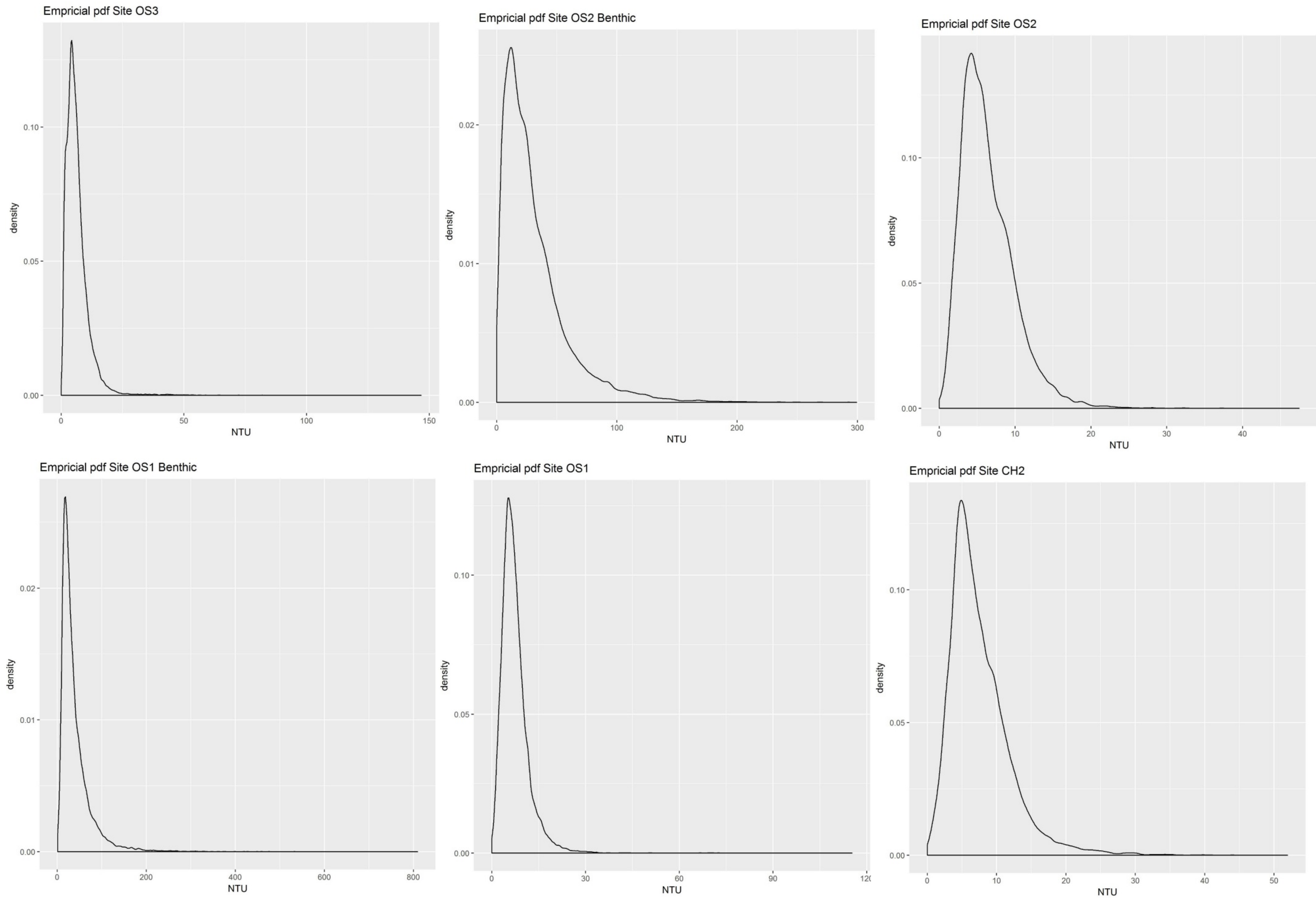


Figure 8. Empirical probability density plots of background turbidity data during the baseline monitoring period for sites OS3, OS2, OS1, and CH2.

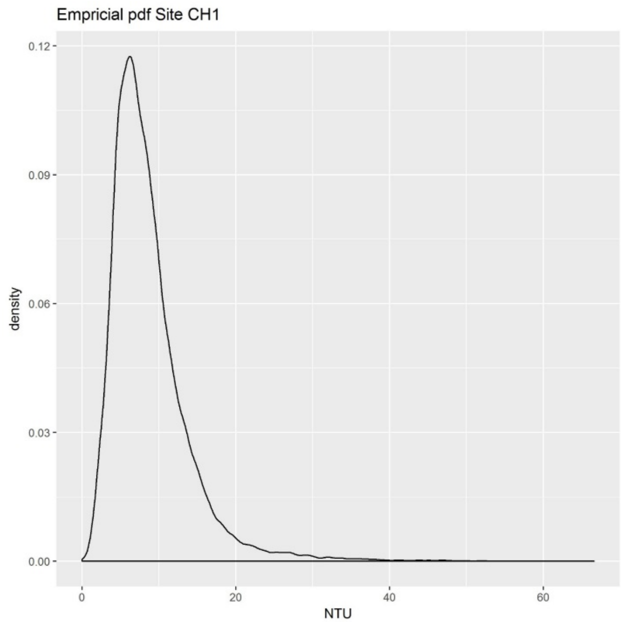


Figure 9. Empirical probability density plot of background turbidity data during the baseline monitoring period for site CH1.

Observations (i) – (iii) above are typical of background turbidity and have been observed in many other places around the world.

The empirical probability density plots of Figures 6 – 9 provide a good visual check of the assumption that turbidity data is well-described by a log-normal probability model. While not of widespread interest, this observation is important for the adjustment process described in section 5 of this report whereby initial turbidity triggers are modified to account for the extra variation/uncertainty introduced from finite sample sizes.

2.2 Turbidity data filtering

The framework and logic for the development and use of turbidity triggers was laid out in Fox (2016). A central tenet of the methodology is that trigger values, however determined, must balance the competing risks of environmental harm and project viability. Trigger values that are set unreasonably low afford very high levels of environmental protection but impose unrealistic (and unnecessary) constraints on dredge operations and management. Overly conservative trigger values would seriously compromise both the timeliness and economic viability of a dredging project. Conversely, trigger values that are set too high will not impede dredging operations even under the most adverse conditions thus increasing the likelihood of environmental harm.

Within this risk-based framework, is a recognition that the marine ecosystem is resilient and certainly unaffected by transient spikes of very high water column turbidity. Although for the LPC CDP there is no keystone species that serves as a 'canary in the cage', several large-scale dredging projects have established turbidity triggers to minimise the likelihood of impact on seagrasses which are thought to represent the ecosystem component most at risk from increased turbidity. It is generally understood by ecologists that, while vulnerable, most species of seagrass can withstand very low light regimes for periods of up to 2 weeks. With this in mind, it is inappropriate to have a management response to elevated turbidity triggered by transient events on a sub-hourly timescale. Accordingly, it has become standard practice for both trigger values and compliance comparisons to utilise smoothed or filtered turbidity data. The issue of data filtering has been discussed in Fox (2016) but in general terms, this process can be likened to more commonplace filtering mechanisms such as noise-cancelling headphones and polarising sunglasses which aim to improve the quality of the signal by filtering out distracting components.

For the LPC CDP the use of the Kolmogorov-Zurbenko (K-Z) filter with parameters $m=4$ and $k=8$ has been consented. Technical details of the K-Z filter are provided in Wang and Zurbenko (2010) and its implementation for the CDP discussed in Fox (2016). The general scheme is depicted in Figure 10 whereby a weighted average is applied to the raw data within a window of some pre-defined width. This window is incrementally 'stepped' across the data and the averaging process repeated.

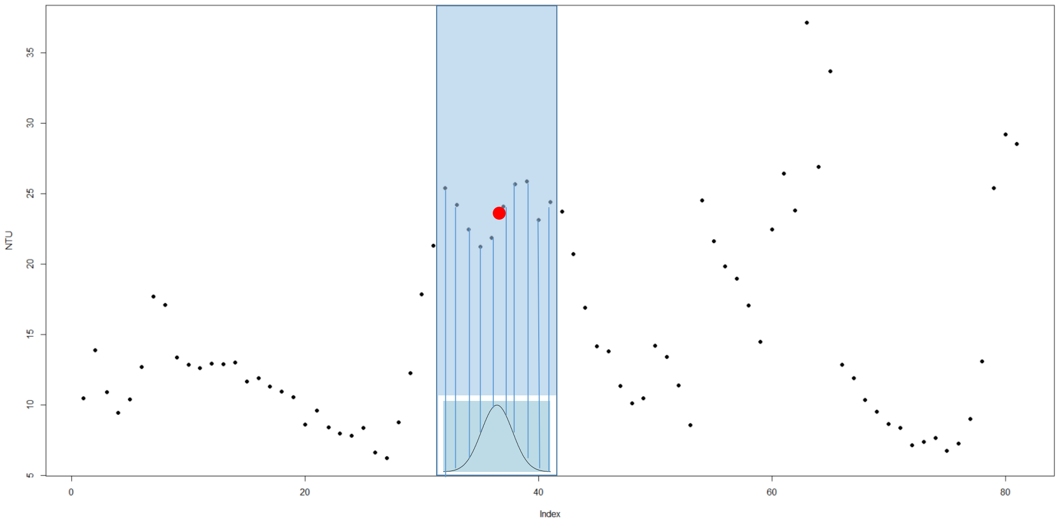


Figure 10. Turbidity time series data (solid black circles) with Gaussian-weighted moving average (solid red circle). Weights applied to the individual data values are derived from the Gaussian curve (solid black line).

2.3 Treatment of missing values

Several issues associated with water quality data collection and processing activities during large-scale dredging activities were discussed in Fox (2016). With respect to missing values it was noted that data imputation using sophisticated statistical models had been successfully demonstrated in other dredging projects. It was also noted that procedures for the robust imputation of missing turbidity data was a critical activity for monitoring programs that used the Exponentially Weighted Moving Average (EWMA) for data smoothing as the recursive nature of this algorithm meant that the process terminated as soon as missing data were encountered. Importantly, this issue does not arise for LPC's CDP since smoothing is achieved using the more robust K-Z filter which does not suffer this limitation in the presence of missing data. In any event, Fox (2016) recommended that with respect to the methods for dealing with missing data "they need to be documented in the EMMP".

After due consideration of the quality and quantity of background data collected for the CDP coupled with the robustness of the K-Z, it is our further recommendation that data imputation of missing turbidity data is unwarranted. The technical basis for this recommendation is detailed in Fox (2018).

3. STATISTICAL ANALYSIS OF BASELINELINE TURBIDITY DATA

An exhaustive analysis of the baseline turbidity data has been undertaken to inform the development of turbidity triggers for used during the CDP.

The time-series plots in Figures 11 to 15 illustrate the effectiveness of the K-Z smoothing of the raw data. This is further supported by the statistical summaries presented in Table 2. Taken together, the plots and the summaries indicate that the smoothing process has succeeded in meeting the dual objectives of attenuating transient peaks in turbidity with little loss of signal integrity. The numerical summaries confirm that the only significant difference between the raw and filtered signals is on the extreme values. Thus, we see from Table 2 for example, the turbidity means, medians and quartiles for the raw and filtered data are very similar while the maximums have on average been reduced by about 40% for the benthic sites and about 20% for the non-benthic sites. Also evident from the time-series plots is a concomitant attenuation of the rapidly fluctuating raw turbidity signal – for example the February - March period for site CH2 in Figure 11.

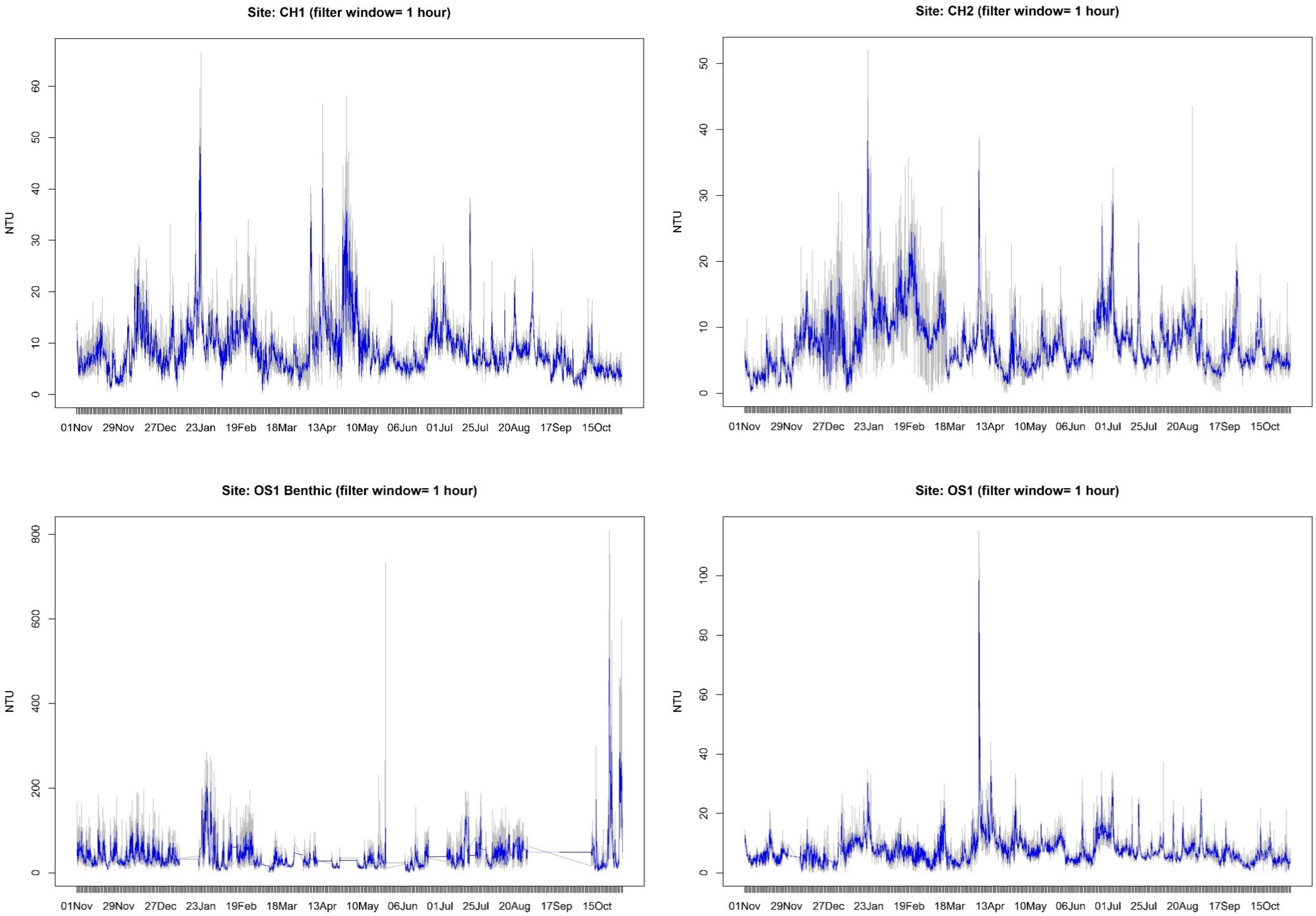


Figure 11. Time series plot showing raw turbidity (grey line) and filtered turbidity (blue line) during the baseline monitoring period for sites CH1, CH2, and OS1.

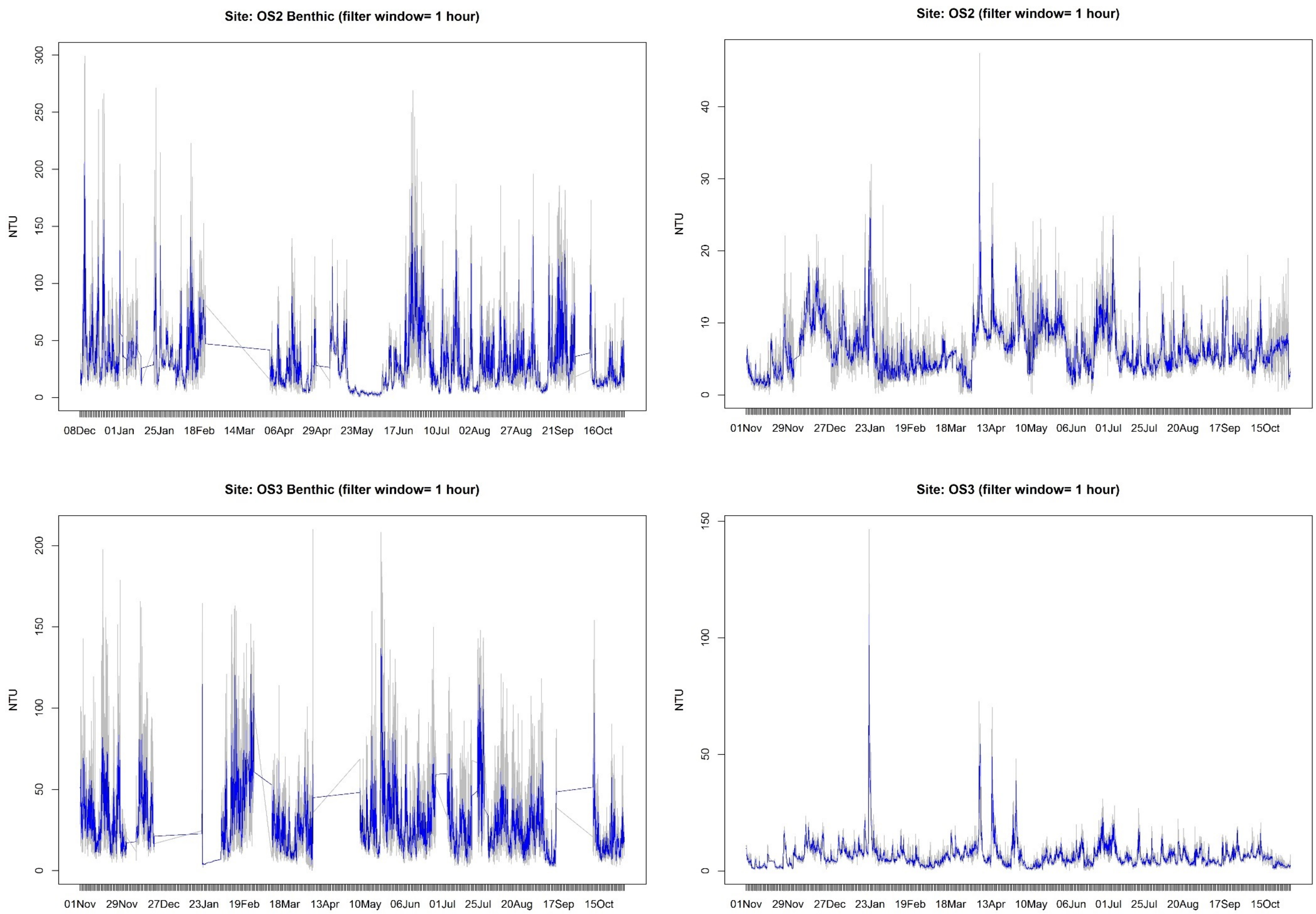


Figure 12. Time series plot showing raw turbidity (grey line) and filtered turbidity (blue line) during the baseline monitoring period for sites OS2 and OS3.

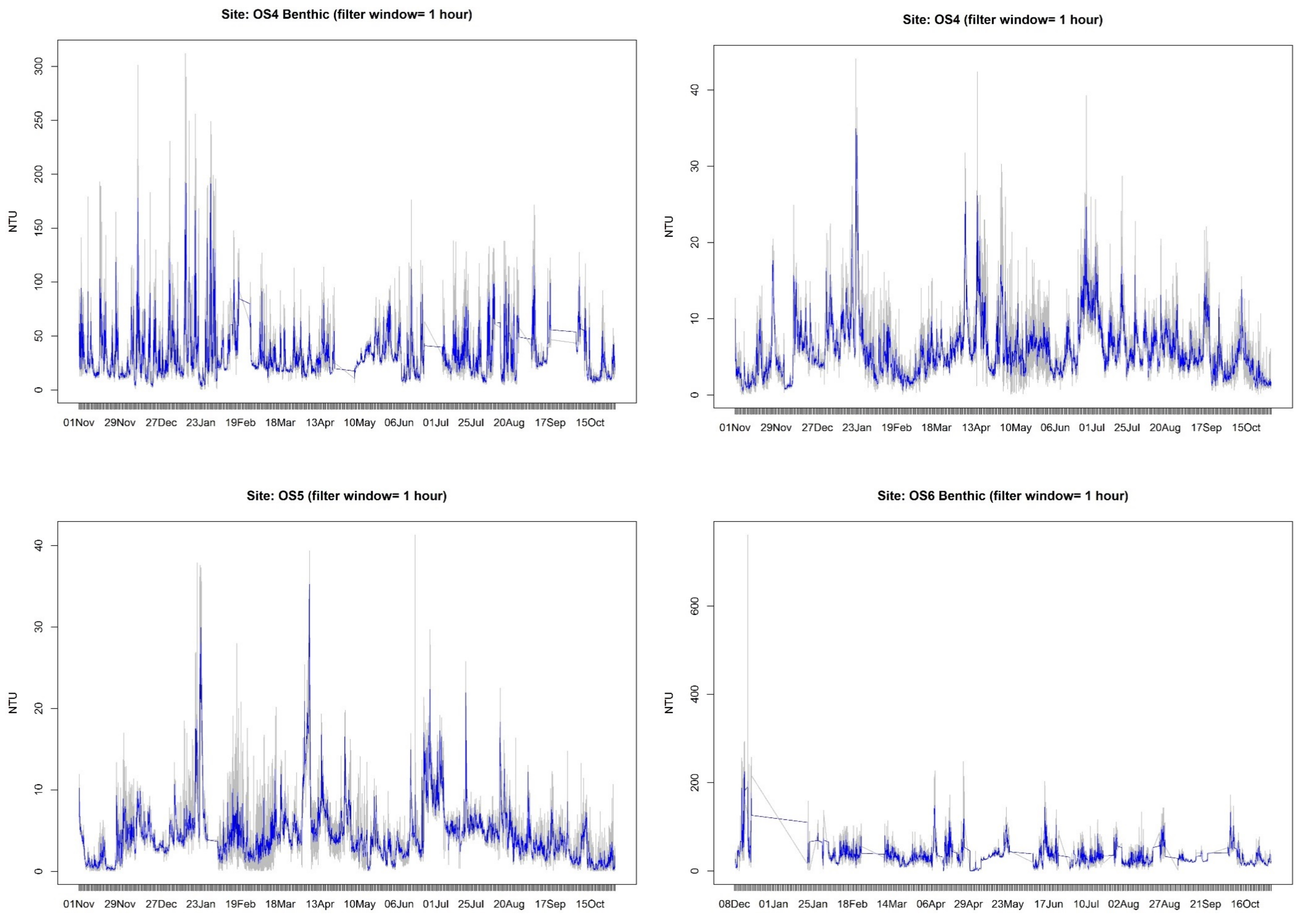


Figure 13. Time series plot showing raw turbidity (grey line) and filtered turbidity (blue line) during the baseline monitoring period for sites OS4, OS5, and OS6.

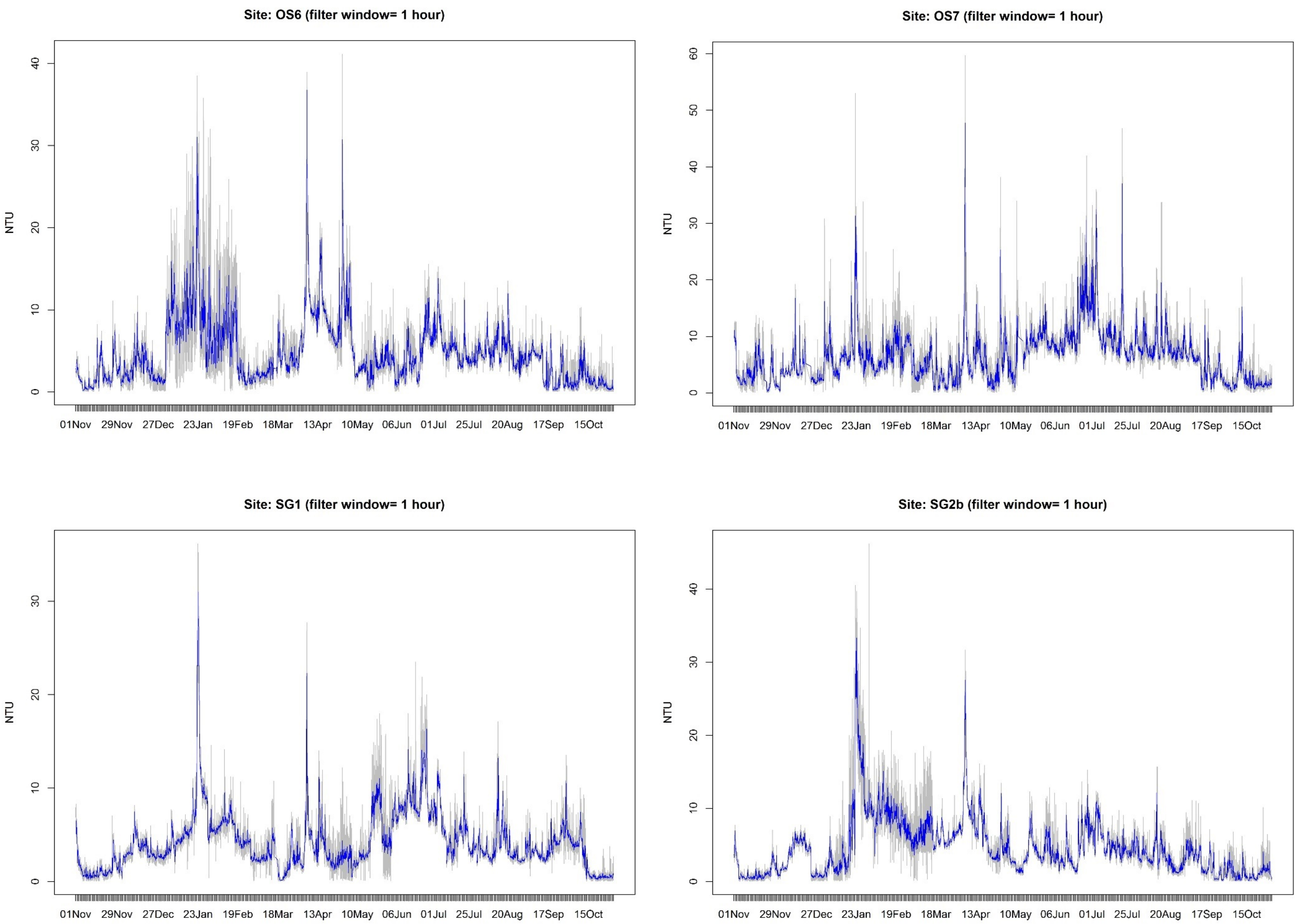


Figure 14. Time series plot showing raw turbidity (grey line) and filtered turbidity (blue line) during the baseline monitoring period for sites OS6, OS7, SG1, and SG2b.

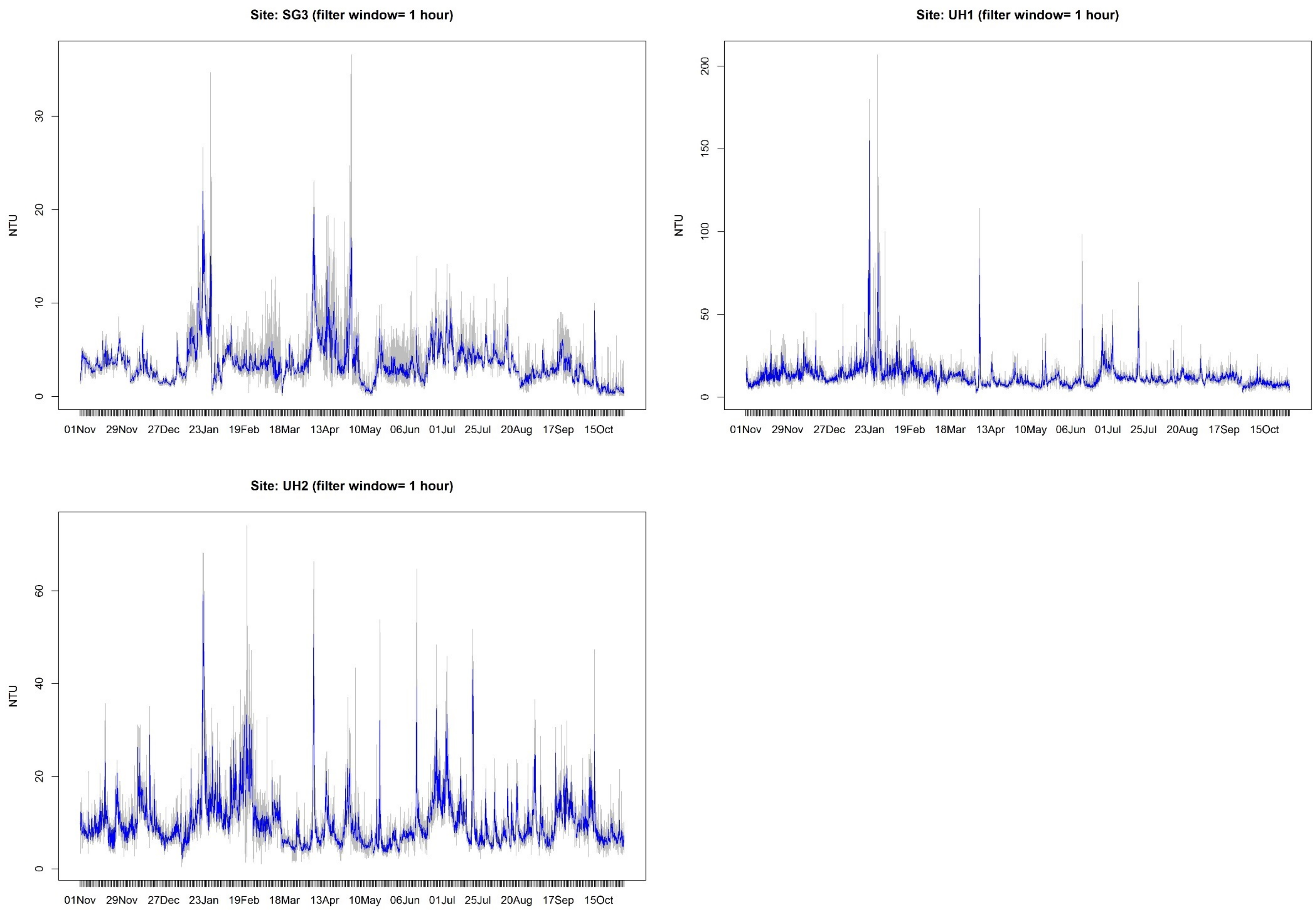


Figure 15. Time series plot showing raw turbidity (grey line) and filtered turbidity (blue line) during the baseline monitoring period for sites SG3, UH1, and UH2.

Table 2. Summary statistics for raw and filtered turbidity data for the baseline period.

Site	Type	min	Q1	Q2	mean	Q3	max	P80	P95	P99
CH1	measured	0.100	5.450	7.650	8.753	10.650	66.600	11.600	17.750	28.850
	filtered	0.776	5.591	7.705	8.753	10.592	49.685	11.514	17.320	27.333
CH2	measured	0.050	4.600	6.600	7.566	9.600	51.950	10.400	15.500	23.500
	filtered	0.300	4.724	6.718	7.566	9.590	38.334	10.324	15.041	22.067
OS1	measured	0.050	4.600	6.600	7.499	9.150	115.300	9.950	15.500	23.750
	filtered	0.628	4.748	6.597	7.499	8.996	98.653	9.765	14.903	22.812
OS1 BENTHIC	measured	0.700	17.800	28.200	40.470	48.350	809.000	55.200	105.800	207.428
	filtered	1.017	20.032	31.393	40.474	48.647	507.998	53.952	93.744	201.774
OS2	measured	0.050	3.850	5.700	6.406	8.300	47.450	9.000	12.950	17.800
	filtered	0.558	3.996	5.703	6.406	8.282	35.500	8.938	12.367	17.031
OS2 BENTHIC	measured	0.300	12.260	23.500	31.220	40.800	299.300	46.000	86.800	136.515
	filtered	1.052	13.447	25.849	31.218	41.711	206.628	46.527	79.089	114.951
OS3	measured	0.100	3.450	5.400	6.548	8.050	146.650	8.900	14.500	27.391
	filtered	0.535	3.587	5.382	6.548	8.078	110.143	8.908	14.138	27.290
OS3 BENTHIC	measured	0.050	13.300	22.200	28.380	36.600	210.000	41.200	72.300	108.988
	filtered	3.001	15.564	24.695	28.380	37.288	136.823	41.045	62.414	86.788
OS4	measured	0.050	3.300	5.100	5.908	7.550	44.100	8.300	13.200	19.700
	filtered	0.500	3.521	5.151	5.908	7.432	34.945	8.054	12.786	18.257
OS4 BENTHIC	measured	0.400	17.100	25.550	32.070	38.600	311.800	43.450	78.725	124.990
	filtered	3.213	18.006	26.806	32.066	39.741	191.508	43.995	71.896	104.510
OS5	measured	0.050	2.350	4.000	4.631	5.800	41.300	6.350	11.350	18.537
	filtered	0.151	2.555	4.037	4.631	5.668	35.248	6.164	11.014	17.824

Table 3 (cont.)

Site	Type	min	Q1	Q2	mean	Q3	max	P80	P95	P99
OS6	measured	0.050	1.950	3.800	4.712	6.200	41.150	7.150	11.800	19.071
	filtered	0.158	1.988	3.888	4.712	6.320	36.769	7.188	11.307	17.957
OS6 BENTHIC	measured	0.100	20.000	28.600	34.240	41.900	761.000	46.000	78.300	127.401
	filtered	0.263	21.120	29.978	34.243	41.184	225.228	45.179	72.854	117.045
OS7	measured	0.050	3.000	5.800	6.359	8.450	59.700	9.200	14.400	23.109
	filtered	0.228	3.059	5.954	6.359	8.425	47.802	9.085	14.019	22.185
SG1	measured	0.050	2.300	3.550	4.223	5.550	36.150	6.150	9.650	13.900
	filtered	0.128	2.408	3.584	4.223	5.468	30.992	6.109	9.485	13.523
SG2b	measured	0.050	1.800	3.850	4.612	6.250	46.200	6.950	10.950	20.250
	filtered	0.092	1.834	3.903	4.612	6.245	33.291	6.880	10.488	19.517
SG3	measured	0.050	2.188	3.150	3.587	4.400	36.600	4.750	7.700	12.800
	filtered	0.208	2.323	3.229	3.587	4.315	21.986	4.668	7.309	12.553
UH1	measured	0.700	8.650	11.000	12.420	14.100	207.000	15.100	21.850	38.902
	filtered	1.789	8.874	11.180	12.421	14.058	154.888	14.998	21.102	36.978
UH2	measured	0.500	6.350	8.500	9.936	11.900	74.100	12.900	19.850	31.555
	filtered	2.139	6.534	8.578	9.936	11.951	59.332	12.881	19.309	29.449

4. ASSIMILATION OF MODELLED TSS DATA AND BASELINE MONITORING DATA

The incorporation of the (predicted) contribution to total turbidity from dredging operations into the development of the *m*-IFD trigger values has been allowed under the Consent conditions. Trigger values have conventionally been established with reference to high order percentiles of background turbidity data only. Investigations into the IFD method (McArthur et al 2002) undertaken by Environmetrics Australia for the present project corrected a major flaw in this methodology and identified a logical inconsistency in the application of trigger values.

As noted in Fox (2017), a scheme based on only the background data makes no provision for the proposed dredging activity – in effect, only a turbidity signal that is indistinguishable from background can have intensity, frequency, and duration characteristics that honour those obtained from an analysis of background data. Thus, under this scheme and to remain 'compliant', there can be no perturbation of the background signal – in other words, no dredging.

Hydrodynamic modelling undertaken by MetOcean predicted hourly total suspended sediment (TSS) concentrations arising from dredging activities at all Tier 3 monitoring locations using historical meteorological and oceanographic conditions between 2003 and 2013 coupled with anticipated dredging operations. In all, 1,415,868 TSS concentrations were merged with empirical data from baseline monitoring. The steps involved in this process are outlined in Box 2.

Box 2. Steps involved in obtaining total turbidity data.

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.

Step 1 in box 2 requires a model that relates TSS in mg/L to turbidity in NTU. This is examined in section 4.1.

A statistical summary of the modelled surface TSS data is given in Table 4.

It is clear from Table 4 that the predicted contribution to surface turbidity is extremely small with an average concentration of 0.0 mg/L at all sites except SG1 whose average was only marginally higher at 0.14 mg/L. The largest hourly surface TSS concentration of 53.4 mg/L was at SG1 with all other site maxima less than 5 mg/L.

Table 4. Statistical summary of modelled surface TSS data broken for each site.

site	min	Q1	Q2	mean	Q3	max
CH1	0.00	0.00	0.00	0.00	0.00	0.00
CH2	0.00	0.00	0.00	0.00	0.00	0.00
CH3	0.00	0.00	0.00	0.00	0.00	0.24
OS1	0.00	0.00	0.00	0.00	0.00	0.08
OS2	0.00	0.00	0.00	0.00	0.00	0.00
OS3	0.00	0.00	0.00	0.00	0.00	0.04
OS4	0.00	0.00	0.00	0.00	0.00	0.00
OS5	0.00	0.00	0.00	0.00	0.00	0.03
OS6	0.00	0.00	0.00	0.00	0.00	0.08
OS7	0.00	0.00	0.00	0.00	0.00	0.00
SG1	0.00	0.00	0.00	0.14	0.00	53.57
SG2a	0.00	0.00	0.00	0.00	0.00	1.74
SG2b	0.00	0.00	0.00	0.00	0.00	4.48
SG3	0.00	0.00	0.00	0.00	0.00	1.61
UH1	0.00	0.00	0.00	0.00	0.00	1.97
UH2	0.00	0.00	0.00	0.00	0.00	0.83

4.1 TSS-NTU relationship

The harmonisation of modelled TSS concentration data and measured baseline turbidity can only be achieved by using a common scale – either as turbidity units (NTU) or concentrations (mg/L). Because on-going turbidity monitoring is performed autonomously and recorded in NTU, the TSS data will be converted to these units.

During the baseline monitoring period, Vision Environment undertook monthly depth-profiling of the water column at each of the Tier 3 monitoring locations. Several physical and chemical parameters were recorded at the benthos, mid-depth and sub-surface. Importantly, contemporaneous measurements of TSS (mg/L) and turbidity as NTU were obtained and it is these data that allow us to develop a mathematical model relating the two sets of measurements.

A bi-plot of the NTU versus TSS data at each site is shown in Figure 16. Also shown in Figure 6 is a fitted regression line which is forced to pass through the origin. Whether or not a zero or non-zero intercept should be used to describe the NTU-TSS relationship is somewhat academic. There would be a slight improvement in the predictive capability if a non-zero intercept was used, however this was not deemed necessary by virtue of: (i) the intercept(s) are generally very small (typically of the order of 1 -2 NTU) and thus of no practical or ecological significance; and (ii) a zero intercept *in this case* makes more sense as the relationship pertains to the *incremental* impact of dredging. Thus, if no TSS is added by the dredging activity, the increase in turbidity (NTU) must be zero.

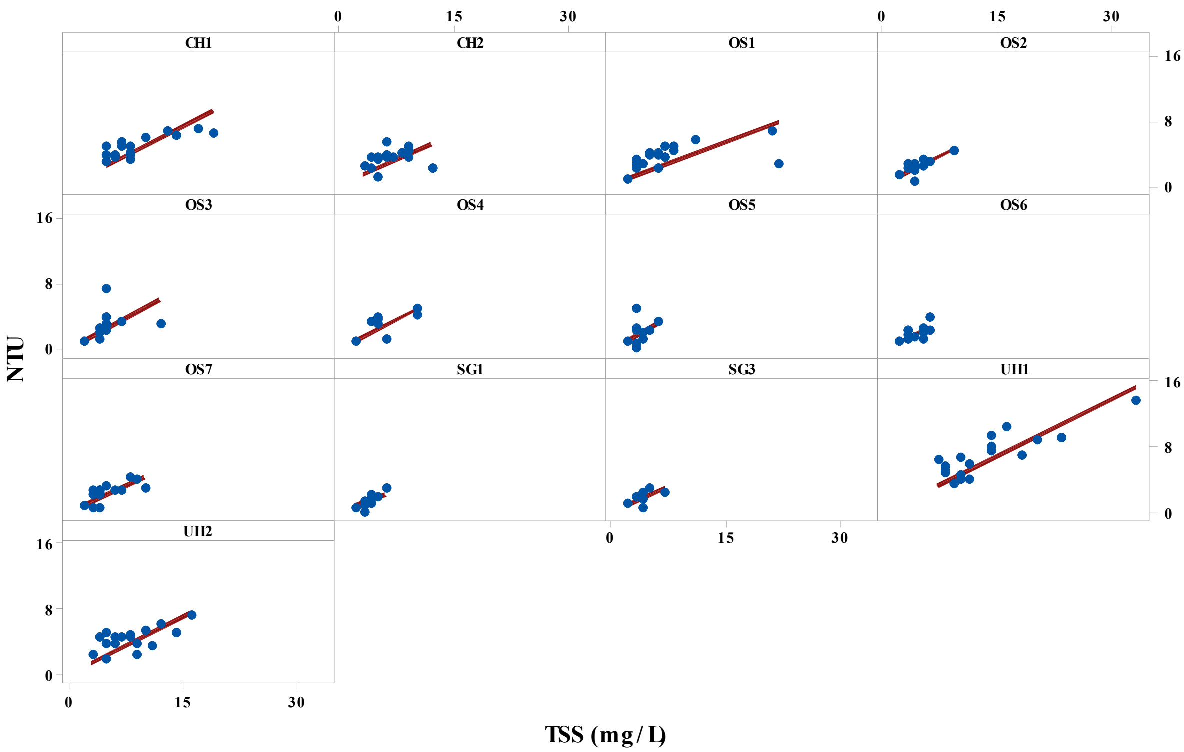


Figure 16. TSS-NTU relationships by site during the baseline monitoring period. Red line is best-fitting regression line through the origin. Note the consistency in regression slopes between sites.

A statistical summary of the TSS-NTU regression analysis is shown in Table 5. The R-squared value shows that this simple model accounts for almost 90% of the total variation in the NTU measurements. Thus, the conversion of modelled TSS (mg/L) to NTU is achieved using the formula: $NTU = 0.4849 \cdot TSS$. Applying this to the results of Table 4 results in a maximum (incremental) turbidity of 26 NTU at SG1 with all other incremental turbidities below 2 NTU.

This result means that trigger values computed from the ***total*** *turbidity (background + dredge) will in this case essentially be equivalent to those computed from the background data alone.*

Table 5. Regression of NTU on TSS. ***Remarks: (i) approximately 90% of the variation in in the NTU data is accounted for by its dependency on TSS; (ii) the estimated slope of this relationship (0.4849) is highly significant; (iii) the lack-of-fit term is significant suggesting additional (non-linear) model terms may lead to a slightly better fit, although this is not deemed necessary for this exercise ; (iv) the variance inflation factor (VIF) is not relevant here since the model contains only a single term.***

Source	DF	Adj SS	Adj MS	F-Value		P-Value
Regression	1	2734.19	2734.19	1456.32		0.000
TSS	1	2734.19	2734.19	1456.32		0.000
Error	185	347.33	1.88			
Lack-of-Fit	94	264.60	2.81	3.10		0.000
Pure Error	91	82.73	0.91			
Total	186	3081.52				
	S	R-sq	R-sq(adj)	R-sq(pred)		
	1.37021	88.73%	88.67%	88.45%		
Term	*Coef*	*SE Coef*	*T-Value*	*P-Value*	*VIF*	
TSS	0.4849	0.0120	40.41	0.000	1.00	

5. DEVELOPMENT OF THE TURBIDITY TRIGGERS

Three levels or tiers of triggering are contemplated for the CDP: Tiers 1 and 2 are for LPC internal use and provide early-warning mechanisms of elevated turbidity. Compliance status during dredging will be assessed using the modified intensity-frequency-duration (m-IFD) approach discussed in Fox (2016).

A compliance alert is 'tripped' if:

(i) the current K-Z smoothed turbidity reading is above the relevant Tier 3 intensity level given in Table 6;

and

(ii) the cumulative time of exceedances defined in (i) during the current 30-day rolling window exceeds the allowable hours given in Table 6.

The Tier 1, 2, and 3 triggers are initially determined as the 80^{th}., 95^{th}., and 99^{th}. percentiles respectively of the *total* turbidity data obtained using the process described in Box 2 above. These preliminary values are then statistically adjusted using Equation (14) in Fox (2016) to account for finite sampling variation. The final set of intensity and duration values to be used for the CDP are given in Table 6.

Table 6. Turbidity intensity values for each site and allowable hours of exceedance in rolling 30-day period. ***NB: Allowable hours for Tiers 1 and 2 are indicative only and non-binding as these are for internal LPC use only.***

Site	Tier 1	Tier 2	Tier 3
CH1	11.6	17.6	28.1
CH2	10.4	15.2	22.7
OS1	9.9	15.1	23.4
OS2	8.9	12.4	17.3
OS3	8.9	14.2	30.6
OS4	Reference Site		
OS5	6.2	11.2	18.3
OS6	7.3	11.5	18.8
OS7	9.2	14.2	22.7
SG1	6.3	9.6	13.9
SG2b	6.9	10.6	20.1
SG3	4.7	7.4	13.1
UH1	15.1	21.4	42.9
UH2	13.0	19.6	30.2
Allowable hours	144	36	7.2

5.1 Performance evaluation

As mentioned at the beginning of this report, an overarching requirement for the Tier 3 triggering mechanism is that it strikes an appropriate balance between the competing risks for the environment and for the project proponent and their contractors. Accordingly, it is appropriate that the mechanism defined by the parameters in Table 6 be evaluated in a 'real-world' environment. Ideally, this would entail trialling the m-IFD method with a second set of baseline data that had not been used as part of the trigger-development process. Given the infeasibility of this strategy, our only recourse is to examine the performance of the methodology using the data already collected. While not perfect, there is nothing inherently wrong with this approach and although lacking independence, it has the potential to highlight data anomalies and uncover operational difficulties. Monitoring of background water quality has continued beyond the initial baseline period and this additional data has also been included in the performance evaluation. This 'extended baseline' data covers the period 1/11/2016 to 1/3/2018 (16 months).

Our assessment commences with a visual inspection of the raw and filtered data relative to the trigger values given in Table 6 (Figures 17 to 20). Overall, the numerical triggers appear to be placed appropriately relative to the filtered data. A more accurate assessment of the actual level of exceedances given in Table 7 shows the overall exceedance rates for Tiers 1, 2, and 3 of 19.5%, 4.8%, and 0.9% respectively are slightly lower than their theoretical values of 20%, 5%, and 1%. Although negligible, we attribute this small difference to the sample-size adjustment referred to in the previous section.

Table 7. Overall exceedance rates of filtered turbidity at each site. First cell entry is baseline monitoring period; second cell entry is extended baseline monitoring period.

	Exceedance rate		
Site	**Tier 1**	**Tier 2**	**Tier 3**
CH1	20.3%	5.1%	1.1%
	19.5%	4.7%	0.9%
CH2	20.5%	5.0%	0.8%
	19.5%	4.7%	0.9%
OS1	17.8%	4.4%	0.9%
	19.4%	4.7%	0.9%
OS2	18.2%	4.6%	0.8%
	20.0%	4.8%	0.9%
OS3	20.1%	5.3%	0.9%
	19.8%	4.8%	0.9%
OS4	Reference only		
OS5	18.6%	4.5%	0.8%
	19.5%	4.7%	0.9%
OS6	21.1%	5.2%	0.8%
	19.5%	4.8%	0.9%
OS7	18.1%	4.6%	0.8%
	19.6%	4.8%	0.9%
SG1	16.9%	4.0%	0.7%
	18.8%	4.6%	0.9%
SG2b	18.2%	4.3%	0.8%
	19.8%	4.8%	0.9%
SG3	18.5%	4.4%	0.8%
	19.5%	4.8%	0.9%
UH1	21.6%	5.4%	1.1%
	19.5%	4.8%	0.9%
UH2	21.8%	5.4%	1.3%
	19.5%	4.7%	0.9%
Average	19.3%	4.8%	0.9%
	19.5%	4.8%	0.9%

The exceedance-rate results of Table 7 only provide a partial analysis of the effectiveness of the m-IFD method.

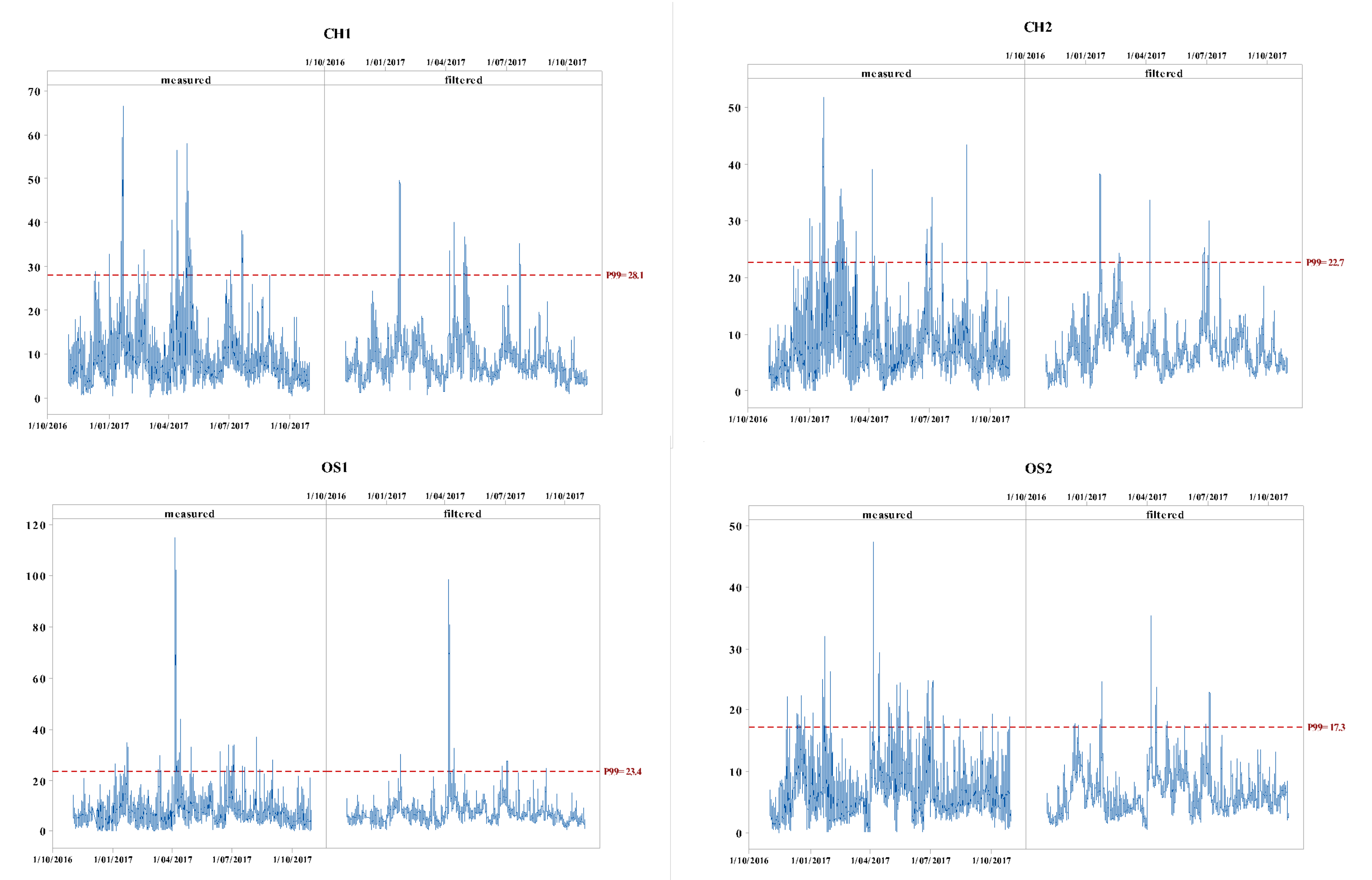


Figure 17. Time-series plot of measured and filtered turbidity data at sites CH1, CH2, OS1, and OS2 with relevant Tier 3 trigger level indicated.

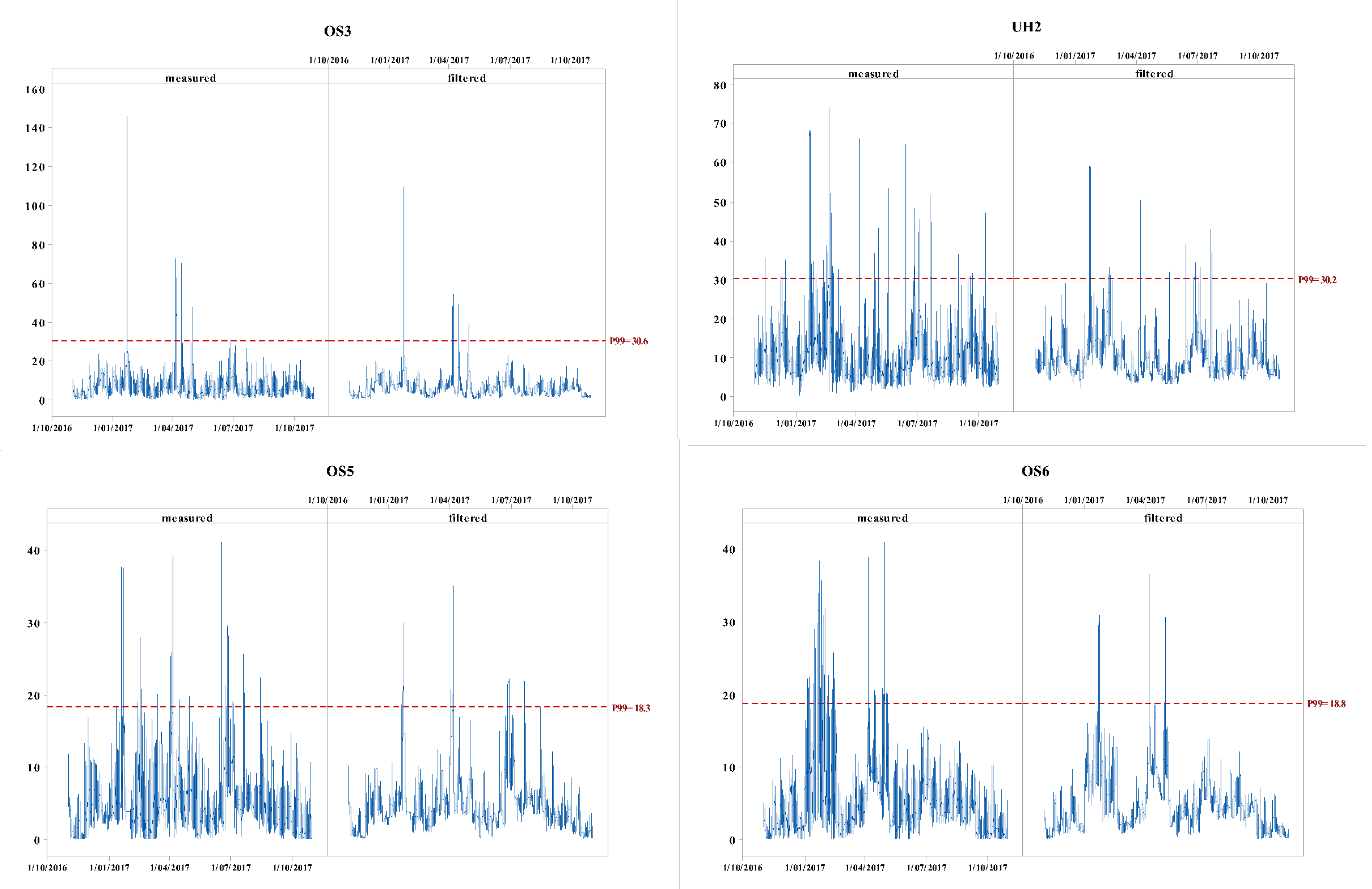


Figure 18. Time-series plot of measured and filtered turbidity data at sites OS3, UH2, OS5, and OS6 with relevant Tier 3 trigger level indicated.

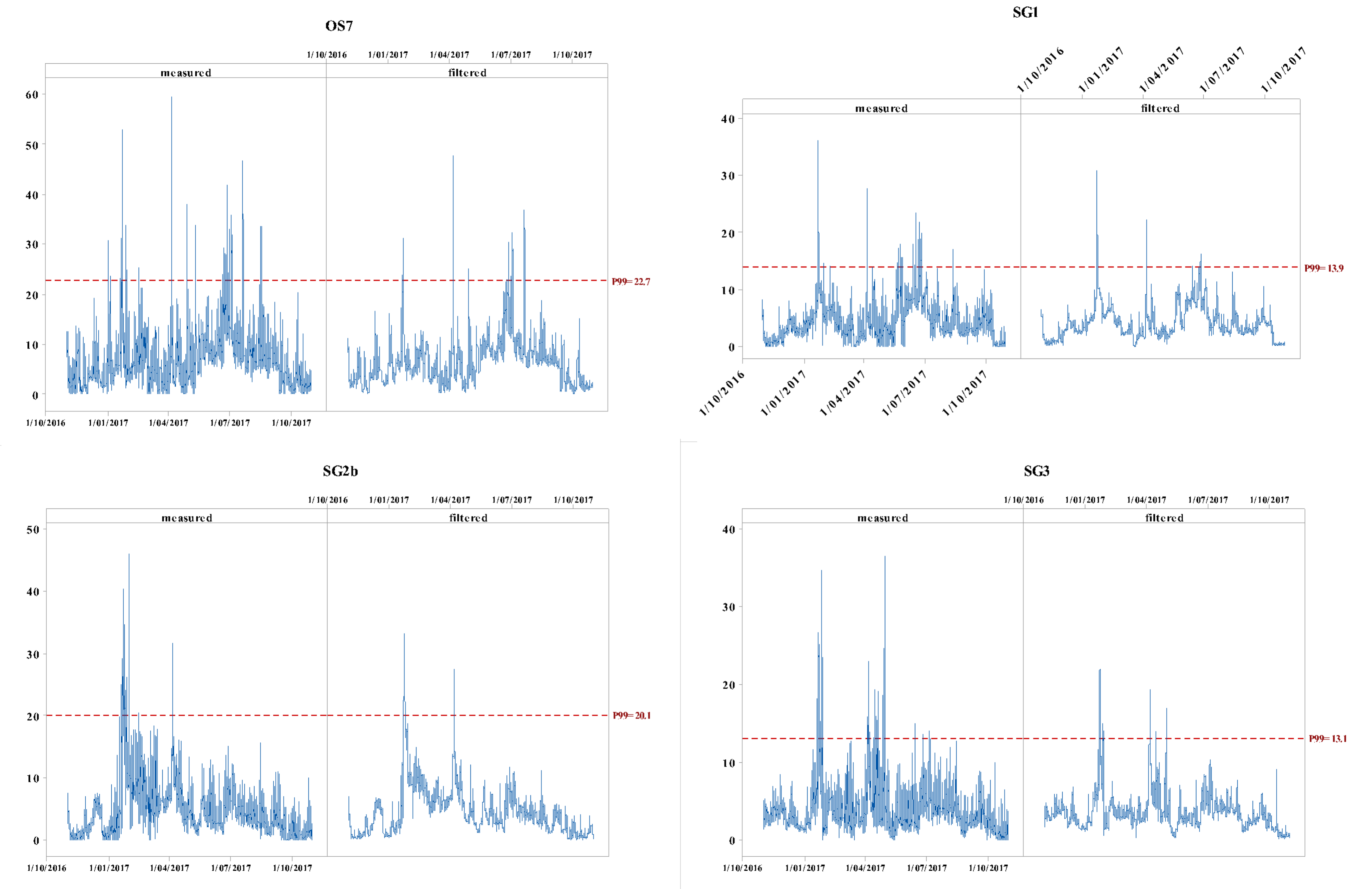


Figure 19. Time-series plot of measured and filtered turbidity data at sites OS7, SG1, SG2b, and SG3 with relevant Tier 3 trigger level indicated.

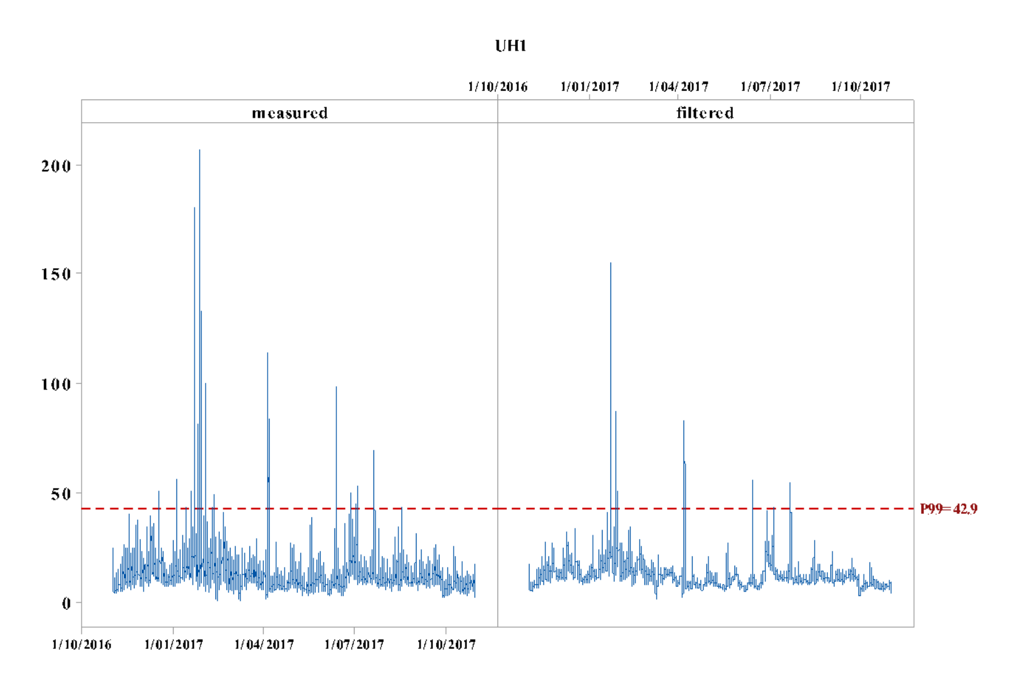


Figure 20. Time-series plot of measured and filtered turbidity data at UH1.

A more comprehensive understanding is obtained from an analysis of the *durations* of exceedances and rates of triggering when both metrics (intensity and duration) are applied to the baseline data (Figures 21 to 33[1]).

There is one figure per site, each comprised of three time-series plots of filtered turbidity data with either a Tier 1, Tier2, or Tier 3 turbidity limit indicated. Portions of the plot shown in green indicate that the turbidity at that time was below the trigger value; blue colouring is used to indicate those times when the turbidity trigger was exceeded but not the allowable hours; while red indicates those times when both turbidity and allowable hours were exceeded. Also shown above the horizontal axis is a red bar which depicts the length of continuous time that when the turbidity trigger and the allowable hours were exceeded.

With respect to Figures 21 to 33 several general observations may be made:

- Considerable triggering and exceedance of 'allowable' hours occurs at Tiers 1 and 2. As an early warning device, this is to be expected and as previously mentioned, this information is for LPC's internal use only;
- The duration of a Tier 3 alert is often 30 days (the length of the moving assessment window) although durations as small as half a day (OS5) to 55 days (SG3) were observed;
- The length of the exceedance duration is highly dependent on the characteristics of the turbidity signal during the 30-day assessment window. Exceedance patterns that are more spread out across the assessment time-frame will tend to take longer to 'clear'.

[1] Important note: These figures use the terminology 'compliant' and 'non-compliant'. This should not be interpreted in the regulatory sense. The term 'non-compliant' is used here when two events have occurred: (i) the intensity level or trigger value has been exceeded *and* the total number of allowable exceedance hours in a 30-day window extending back in time from any point on the horizontal axis has been exceeded.

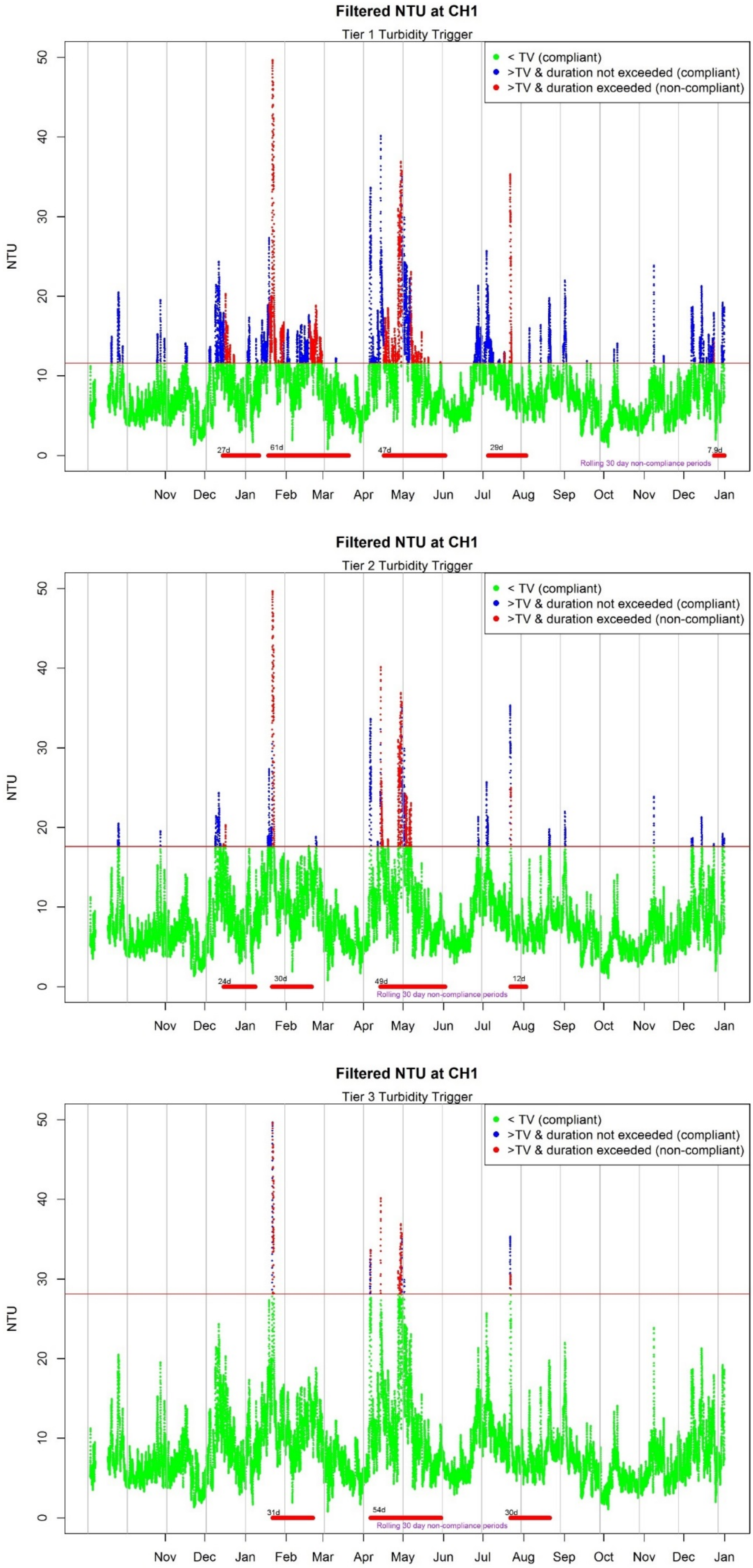


Figure 21. Compliance alerting during extended baseline monitoring period at CH1.

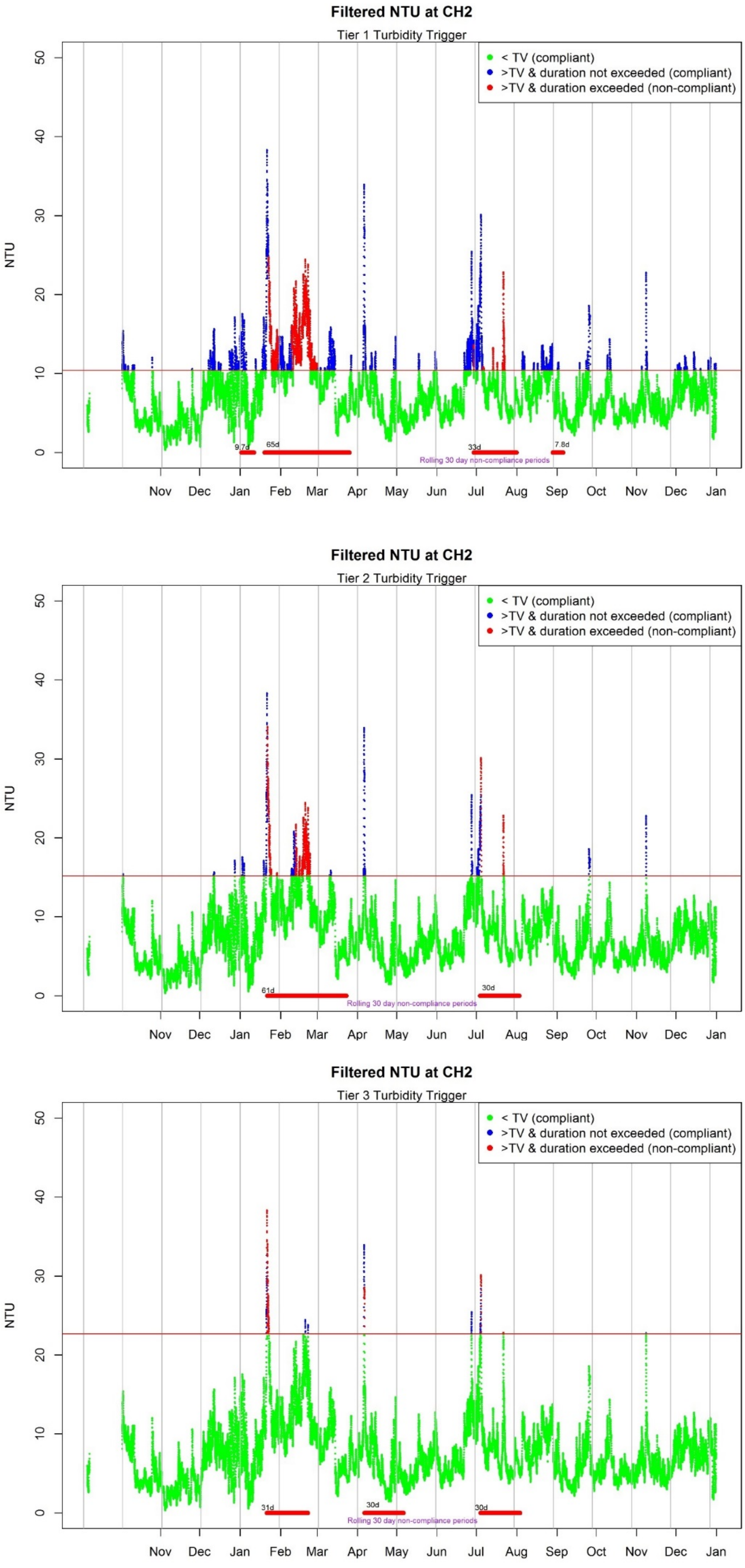


Figure 22. Compliance alerting during extended baseline monitoring period at CH2.

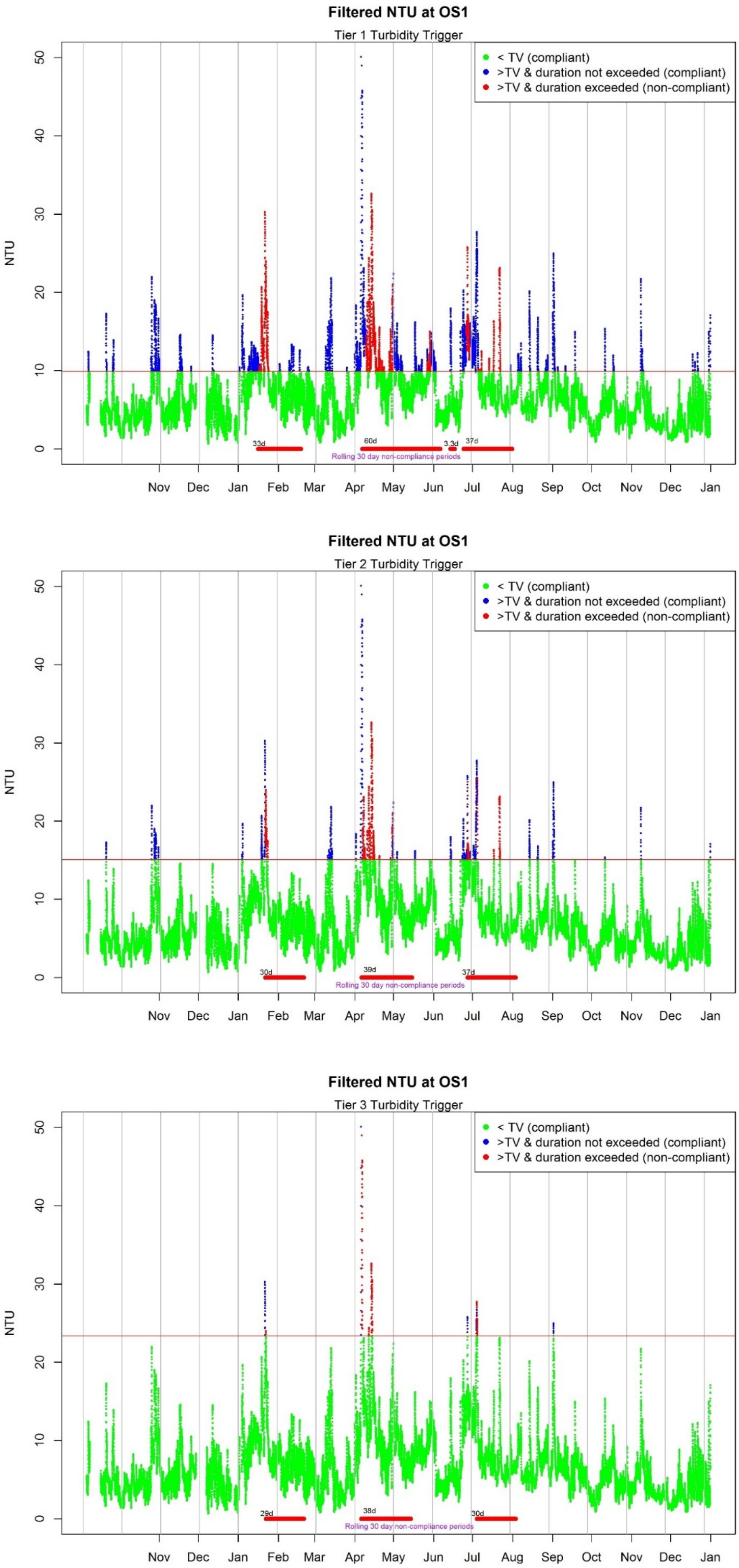
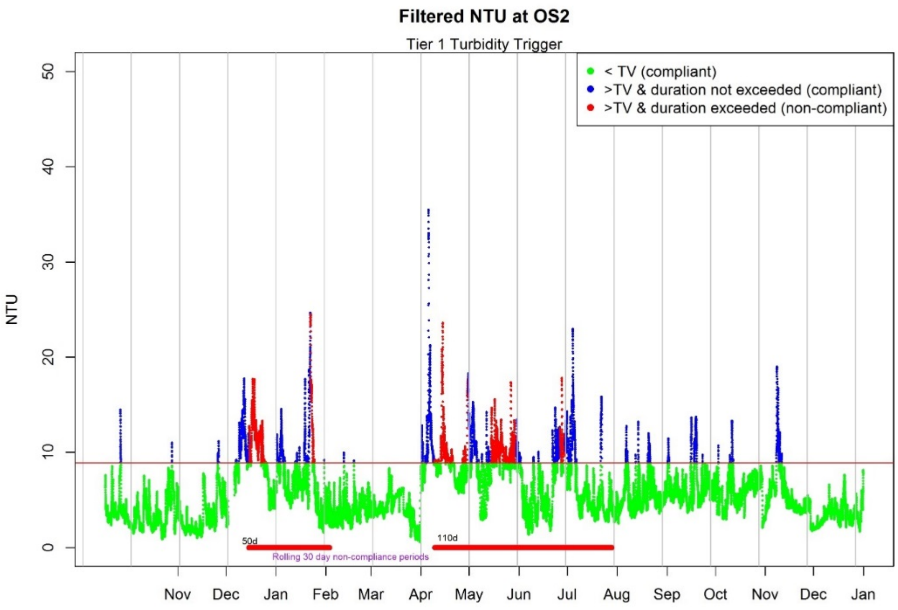
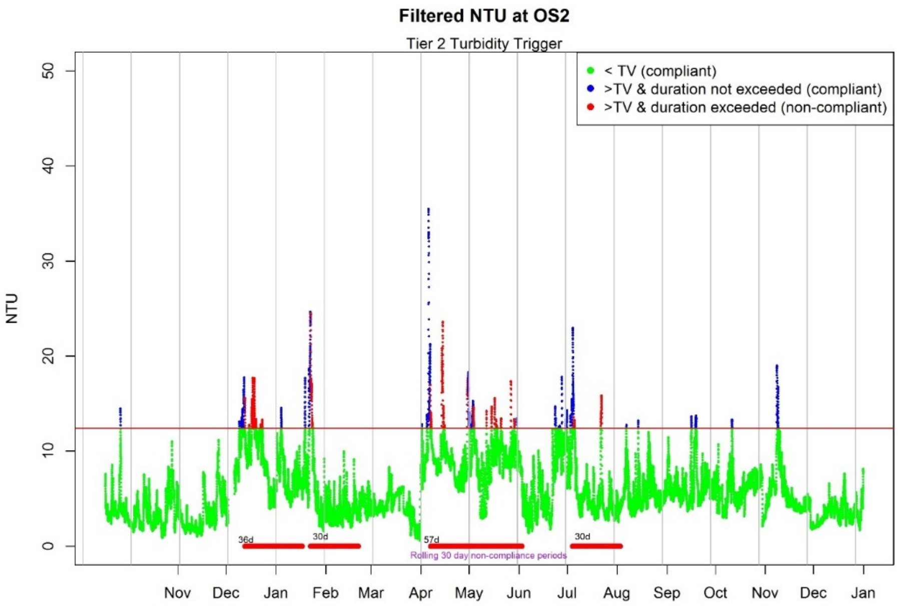


Figure 23. Compliance alerting during extended baseline monitoring period at OS1.





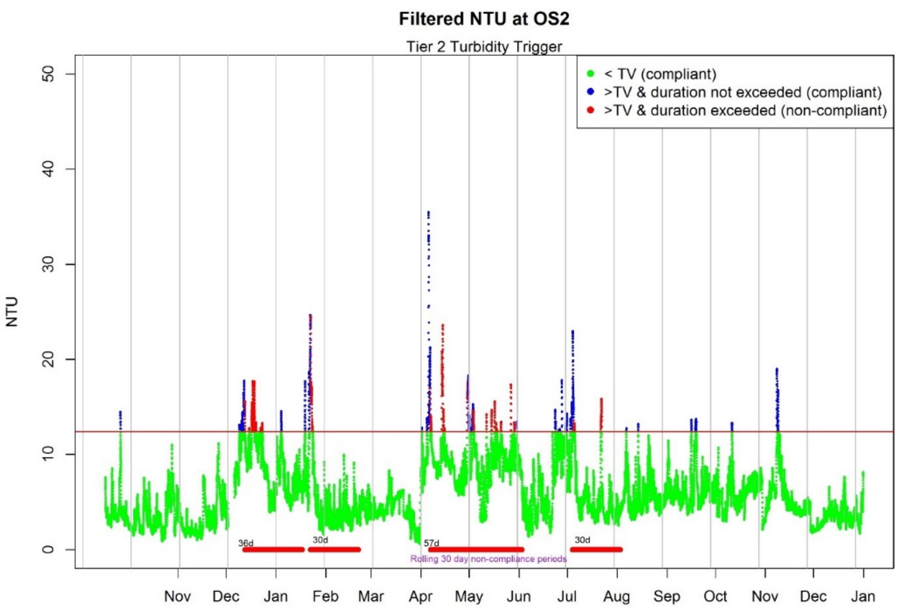


Figure 24. Compliance alerting during extended baseline monitoring period at OS2.

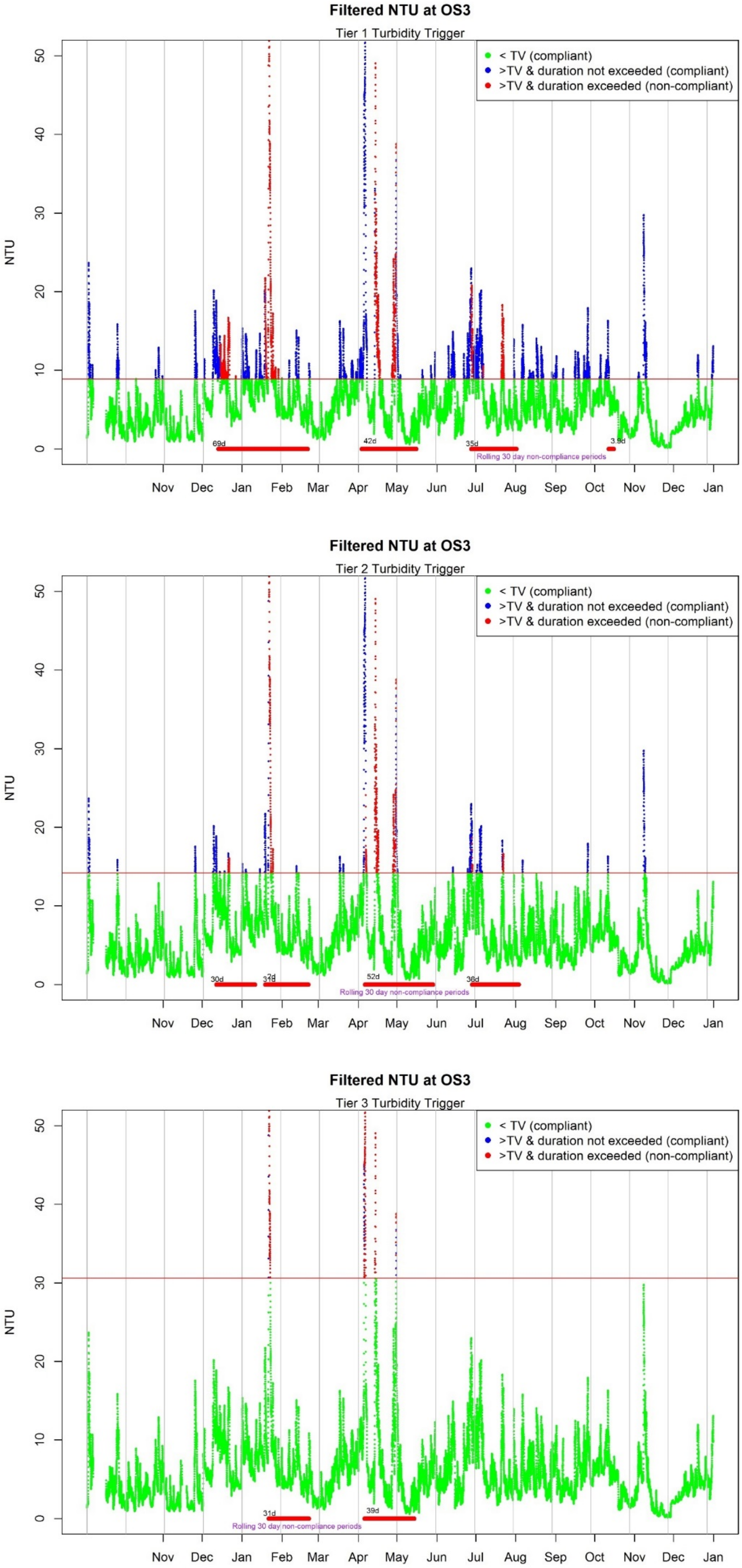


Figure 25. Compliance alerting during extended baseline monitoring period at OS3.

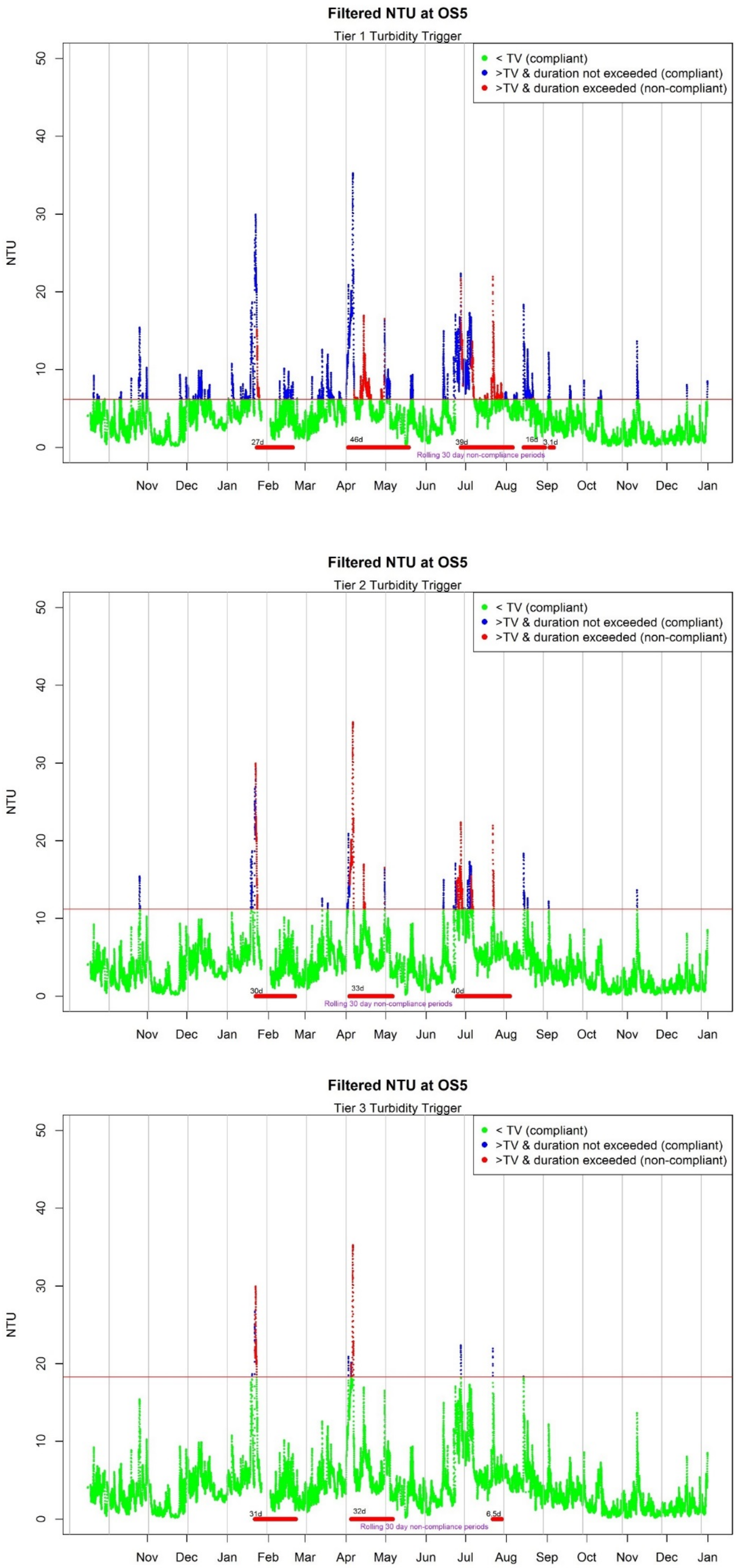


Figure 26. Compliance alerting during extended baseline monitoring period at OS5.

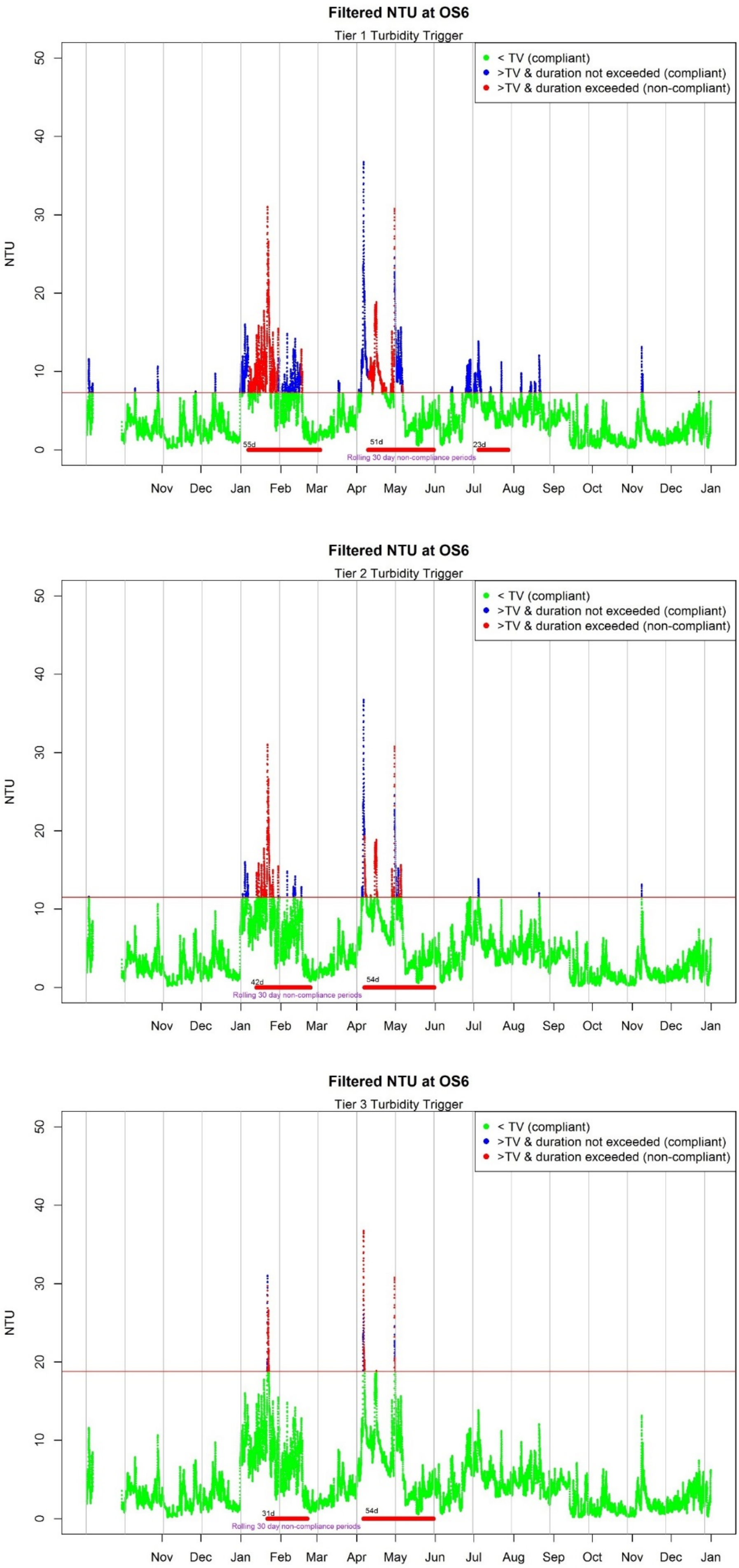


Figure 27. Compliance alerting during extended baseline monitoring period at OS6.

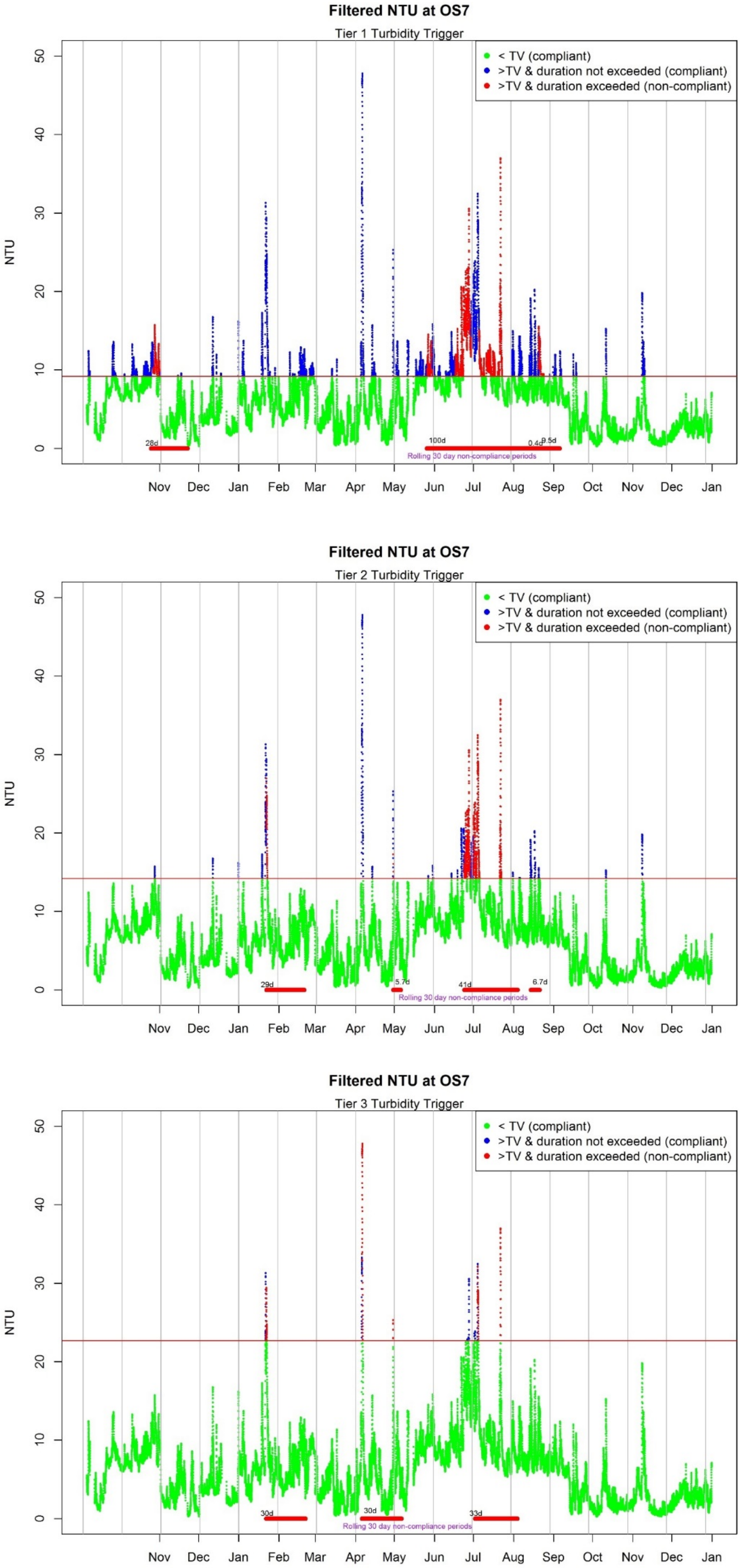


Figure 28. Compliance alerting during extended baseline monitoring period at OS7.

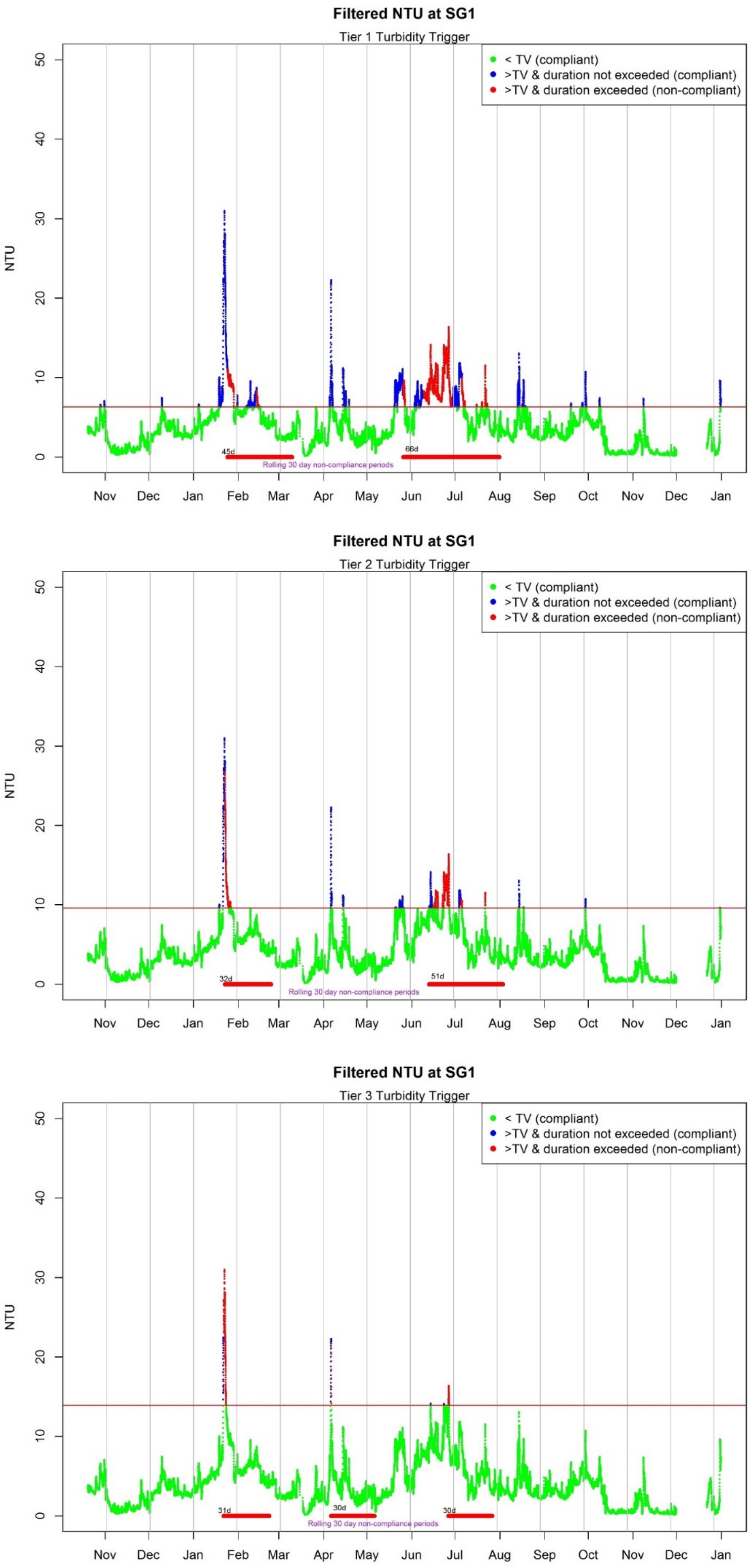


Figure 29. Compliance alerting during extended baseline monitoring period at SG1.

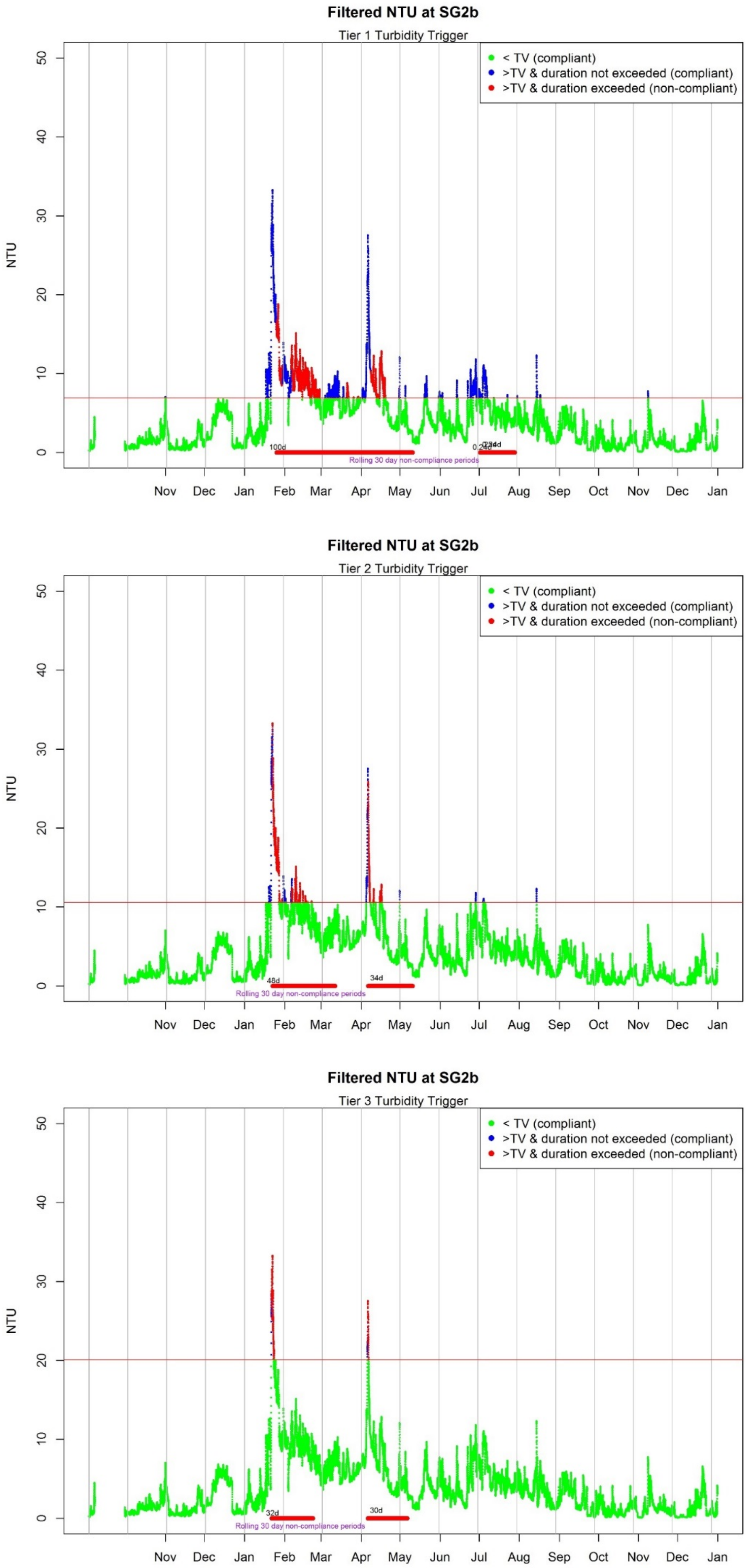


Figure 30. Compliance alerting during extended baseline monitoring period at SG2b.

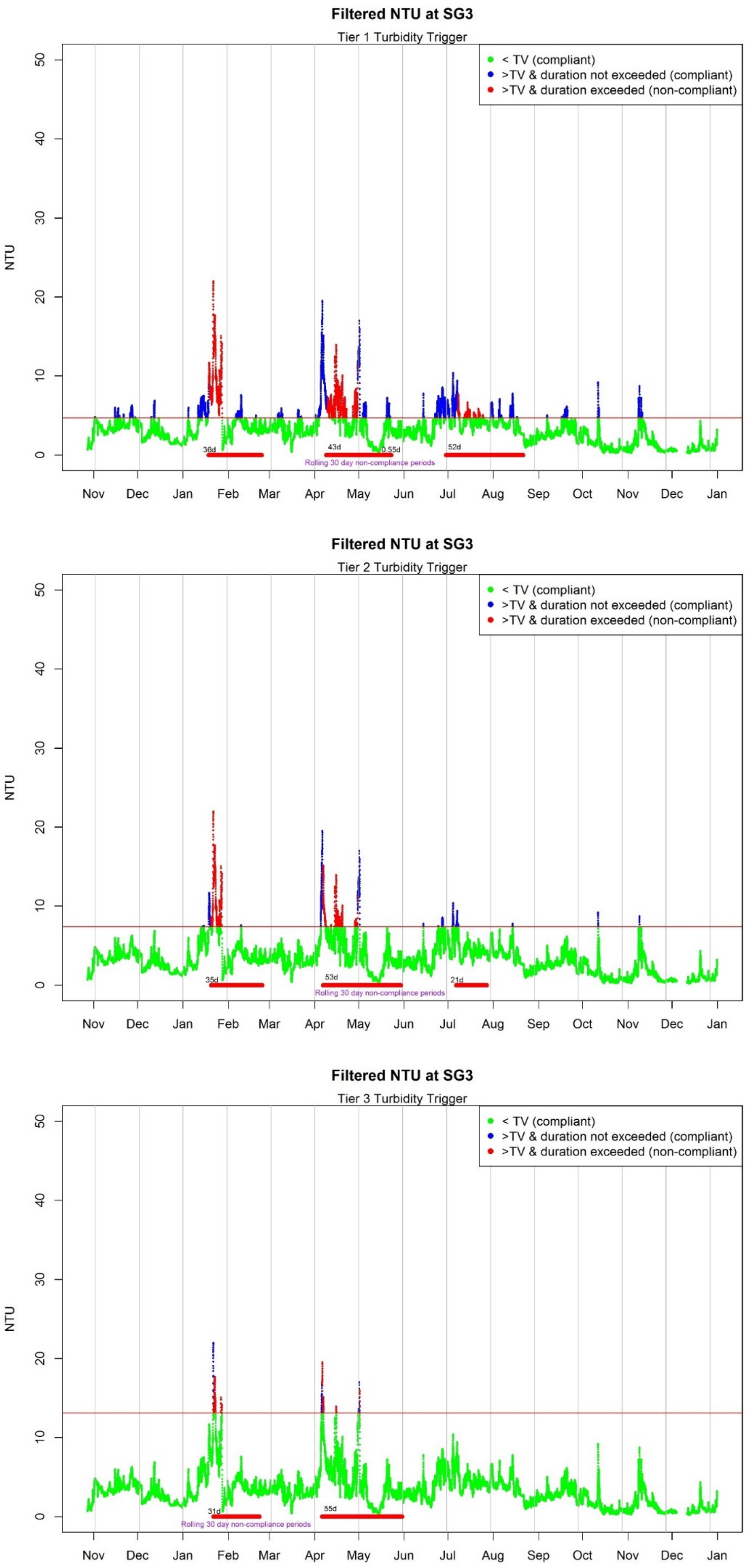


Figure 31. Compliance alerting during extended baseline monitoring period at SG3.

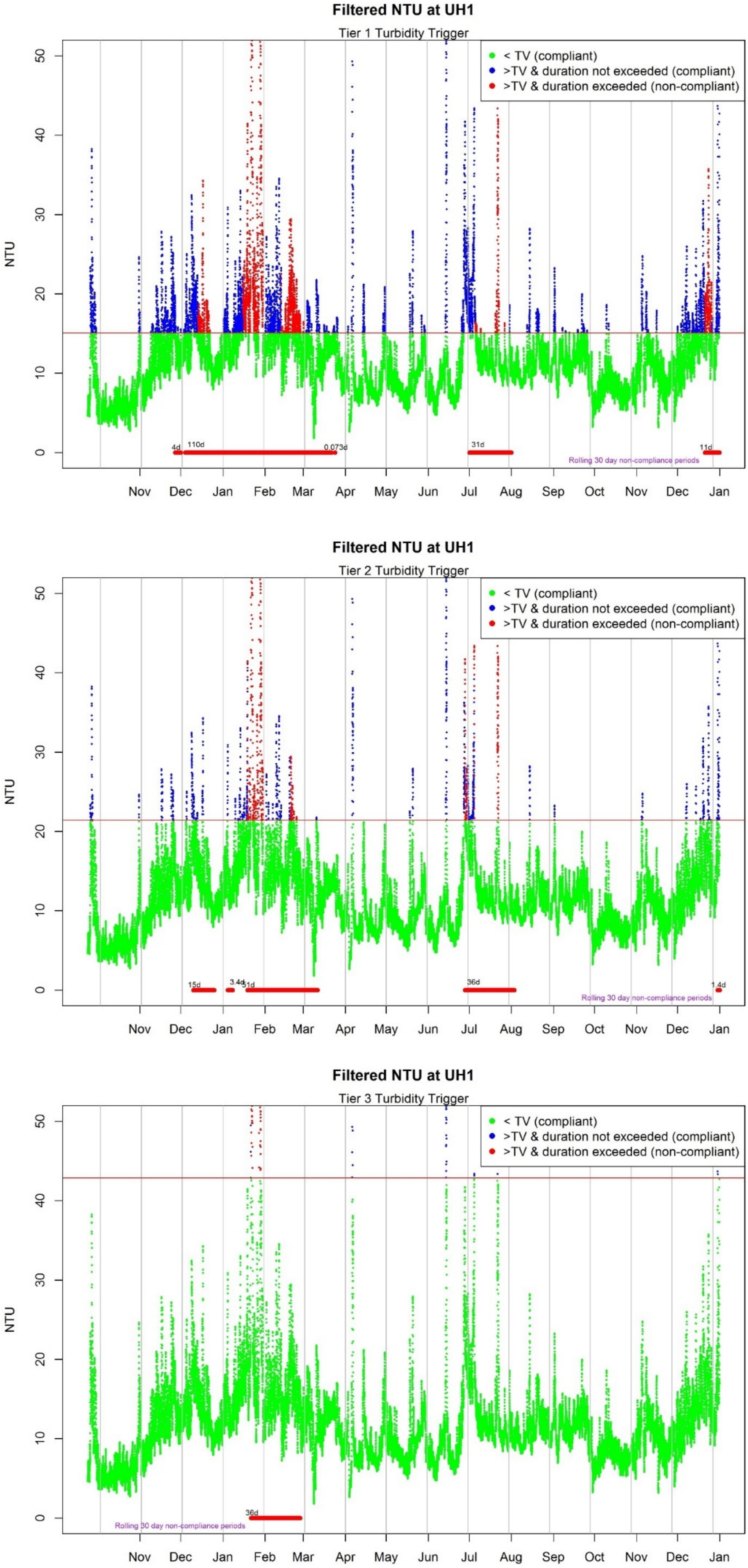
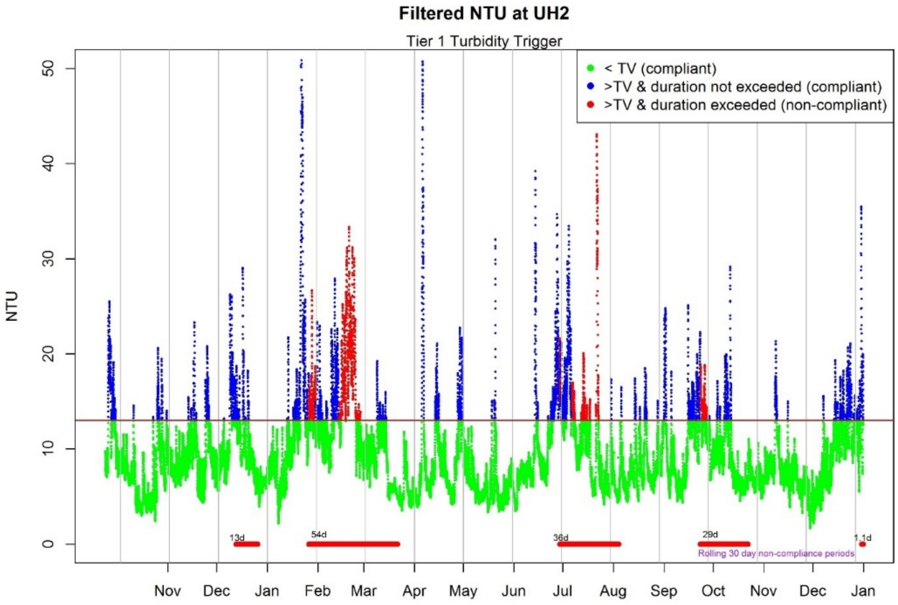
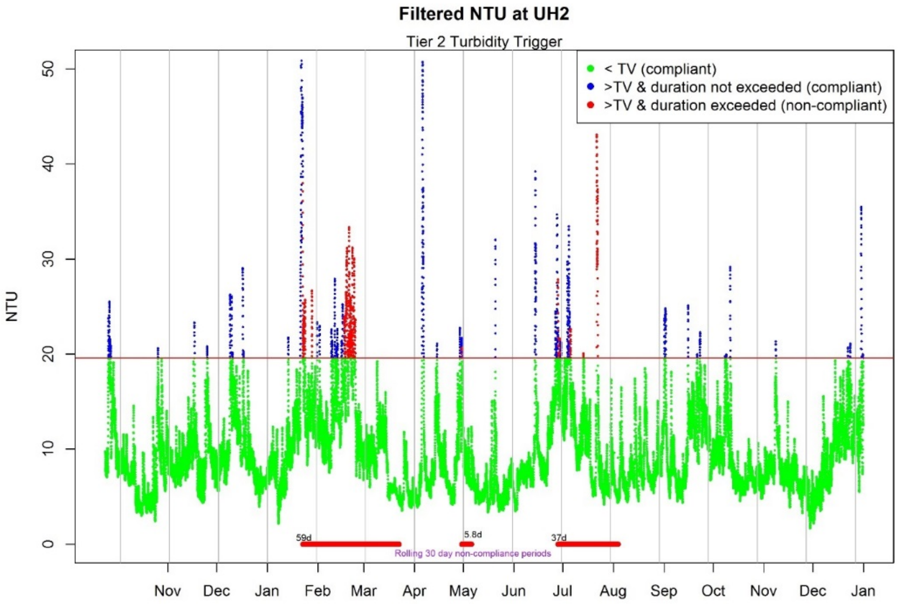


Figure 32. Compliance alerting during extended baseline monitoring period at UH1.





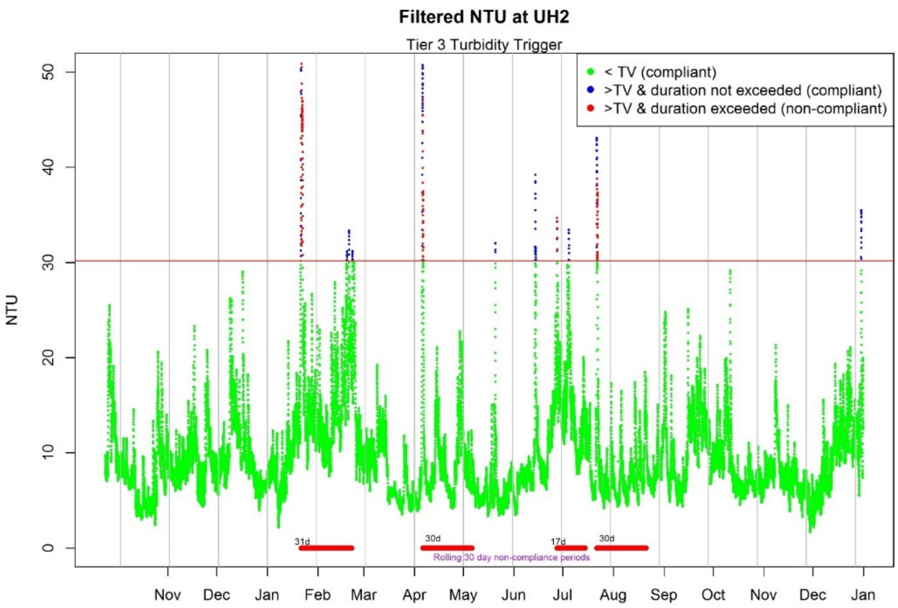


Figure 33. Compliance alerting during extended baseline monitoring period at UH2.

6. References

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