

University of Southampton School of Ocean and Earth Science

**Quantifying the morphological behaviour of the Lymington  
estuary using volumetric estimates of sediment transport to assess  
the potential for saltmarsh restoration**



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## **Abstract**

The Solent has a large portion of saltmarsh that has been in decline for over 100 years particularly in the town of Lymington in the West Solent. The Supply of sediment to these marshes offers a potential explanation for the observed changes but only a single sediment budget has been conducted to date. Following the methods set out by the previous budget, an updated sediment budget was synthesised, and the state of the marshes was analysed using LiDAR to create a detailed baseline of the present marsh state in the presence of new management interventions. The sediment budget has not been significantly altered by the management interventions and remains comparable to the previous budget. The saltmarshes are not accelerating past the previous estimates of erosion in the Solent but further, more rigorous monitoring is required to draw more detailed conclusions.

## **1. Introduction**

The Solent is home to a large network of Saltmarshes with most of these natural habitats located on the western coastline of the Solent between Hurst Spit and Beaulieu (NFDC, 2017). Historically, the retreat of these marshes has been of interest with the rates of erosion listed at 3.2m a year between 1781 to 1968 (Pontee, 2004) or 4m a year between 1907 and 1975 and 7m per year between 1975 and 1993 (Ke and Collins, 2002) and more recently 3m a year (NFDC, 2017). The erosion of the saltmarshes is expected to continue the release fine sediments into the Solent as retreat continues (NFDC, 2017).

The hydrodynamic environment in the West Solent favours the depletion of sediments stored in the marshes and therefore these stores are transferred into suspended load (NFDC, 2017). This trend is likely to continue and predicted to intensify with the increasing threat of sea level rise (NFDC, 2017). NASA predicts that under climate scenario SSP3-7.0 that

Bournemouth and Portsmouth will observe a sea level rise of 0.63m and 0.64m respectively by 2100 (NASA, 2021).

Much of the low-lying grazing land between Lymington and Keyhaven was reclaimed in the 1700 and 1800s and has been protected by seawalls since, totalling around 10.6km of embankments and seawalls (Beresford and Shipp, 2023), (NFDC, 2017). These areas are at increasing risk of coastal squeeze where these anthropogenic structures prevent the natural landward transgression of coastal habitats in response to rising sea levels and therefore, leading to their degradation (GOV.UK, 2021).

The saltmarshes in and around Lymington provide significant environmental services, such as providing wild bird habitats, human services such as recreational enjoyment and flood protection (Serato de Castro Silva, 2014). Despite the importance of these habitats, they have been rapidly eroding since the 1920s and more recently there has been emphasis on preserving these environments with the plethora of legal protections and special designations for these environments driving projects to recharge or recreate these environments (Serato de Castro Silva, 2014).

To aid this there has been significant effort to remap the extent of Saltmarshes in the UK to update the extend from 2006-2009 to 2016-2019 in which there was an observed increase in extent of 7% countrywide (Environment Agency, 2022). The Solent and South Downs observed a net gain of 1.7% overall in saltmarsh extent, though much of this gain was attributed to the new Medmerry managed realignment project in the Eastern Solent. Without these projects, the region observed a net loss of 2.6% much of which was located in the Solent waterbodies specifically (Environment Agency, 2022). Despite this, the Solent is home to the largest portion of upper saltmarsh environment with almost 50% of it being upper saltmarsh environment (Environment Agency, 2022). Historically, a large part of the saltmarsh decline has been land reclamations and the dieback of spartina though other

detrimental effects include dredging activities, cabling activities, inappropriate grazing practices, historical landfill activities, embanking and other engineering work (Environment Agency, 2022, Serato de Castro Silva, 2014). The sediment supply to the marsh is important as this will dictate whether these environments can keep up with sea-level rise (Environment Agency, 2022).

Due to the number of assets behind coastal defences in Lymington and the complex legal obligations associated with the sites, there is significant drive to maintain and restore these habitats. Managed realignment schemes such as Medmerry are an unsuitable option for this site and therefore it has been subject to experimentation with beneficial placement of dredged sediments.

There are currently three marshes of interest in Lymington; Boiler Marsh, Cockleshell Marsh and Pylewell Marsh. Many of the experiments to date have been conducted on the Boiler marsh.

*Table 1 : Names, Locations, years and volumes of the schemes undertaken in Lymington to date modified from (ABPMer, 2023a)*

Scheme	Years	Marsh	Volume (m <sup>3</sup> )
Wightlink	2012	Boiler Marsh	1,330
Wightlink	2013	Boiler Marsh	3,120
Yacht Haven	2012-13	Unnamed	2,000
L/2014/00396/2	2014-2021	Boiler Marsh	40,000

The 2013 Yacht Haven scheme was in response to rock armour construction. No more phases of the LHC project for the new breakwater have been constructed since 2014 and are not predicted to be needed until 2029-2032. (Lymington Harbour Commission, 2019). There are proposals to trial further bottom placement by Solent forum on the Pylewell and Cockleshell

marshes which is currently still in the licencing phase which is due to conclude in 2024. In addition to these projects, there is also ongoing consultation to rewrite the Shoreline management plan for the coastline between Hurst and Lyminster in 2026.

It is vital to understand how these changes have impacted the movements, supplies and sinks of sediments to assess their impact upon the marshes and future consequences for the system. This can be done with a Sediment budget to quantify sources, sinks and pathways within a system.

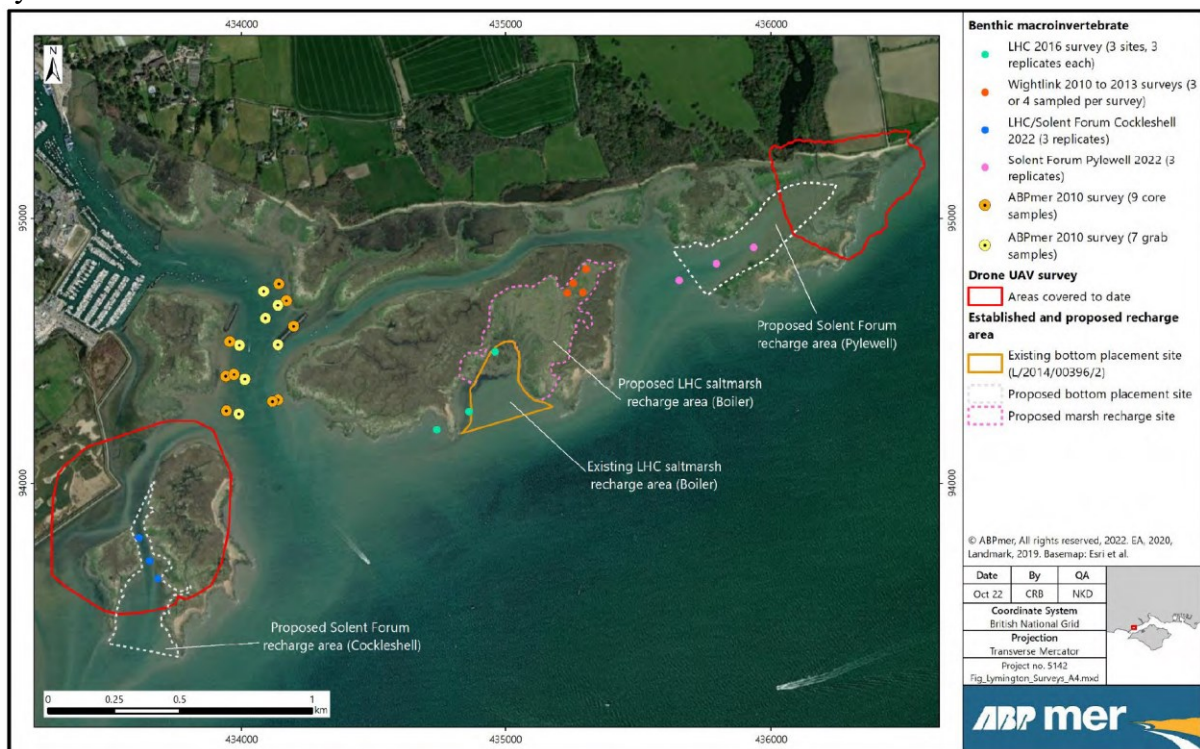


Figure 1: Existing and proposed marsh recharge sites in Lyminster taken from (ABPmer, 2023a)

Therefore, it is the aim of this dissertation to undertake a new sediment budget analysis to inform current changes since the previous budget for 2006-2012 to inform future management decisions and ongoing projects. To accomplish this the following objectives were defined and met.

- Quantify volumetric estimates using the histogram method and an interpolation method throughout the estuary between 2016 and 2021
- Compare the differences between the two inputs using the same sources, sinks and pathways as the previous budget
- Undertake a detailed analysis of the most recent changes to the saltmarshes with available LiDAR data
- Provide an updated sediment budget

## **2 Lymington Background**

Saltmarshes are some of the rarest and most threatened environments in the UK and have suffered from various threats such as pollution, land reclamation and erosion as well as hydrodynamics and land use changes (Möller and Spencer, 2002), (Baily and Inkpen, 2013). The long-term conservation of these environments requires an understanding on how these areas develop and trends in spatial and temporal behaviour (Baily and Inkpen, 2013), (Ladd, 2021). For example, Ke and Collins, 2002 suggest that erosion of the Lymington marshes is due to a change in coastal morphology of the area, a sediment deficit in the Solent combined with the ebb dominance of the Lymington estuary and the evolution of *Spartina* marshes. In addition, Pontee, 2004 expands this idea by stating saltmarshes are at risk of erosion by fracturing because of the evolution of creek networks and erosion from wave action on the saltmarsh edges. This erosion has been a significant problem since the 1960s (WOLTERS et al., 2005) and has continued into the present day. It is suggested that all saltmarsh between Lymington and Keyhaven will be lost under all climate scenarios by 2080 (Foster et al., 2013). The speed at which the saltmarshes can change depends upon the balance of vertical accretion, infilling, healthy vegetation growth, lateral progradation, surface degradation and landward progression (Möller and Spencer, 2002). Key controls of that balance could be changes in the tidal regime as well as wind-wave climate, vegetation and soil forming

processes, relative sea-level changes and the sediment supply (Möller and Spencer, 2002). Though it has been more recently suggested that lateral extent changes of saltmarshes cannot simply be quantified with the changes in sea level in the last 150 years and instead that sediment supply plays a much more crucial role in the erosion of saltmarshes (Ladd et al., 2019). They also suggested that the effects of spartina colonisation was limited, contrary to Ke and Collins, 2002.

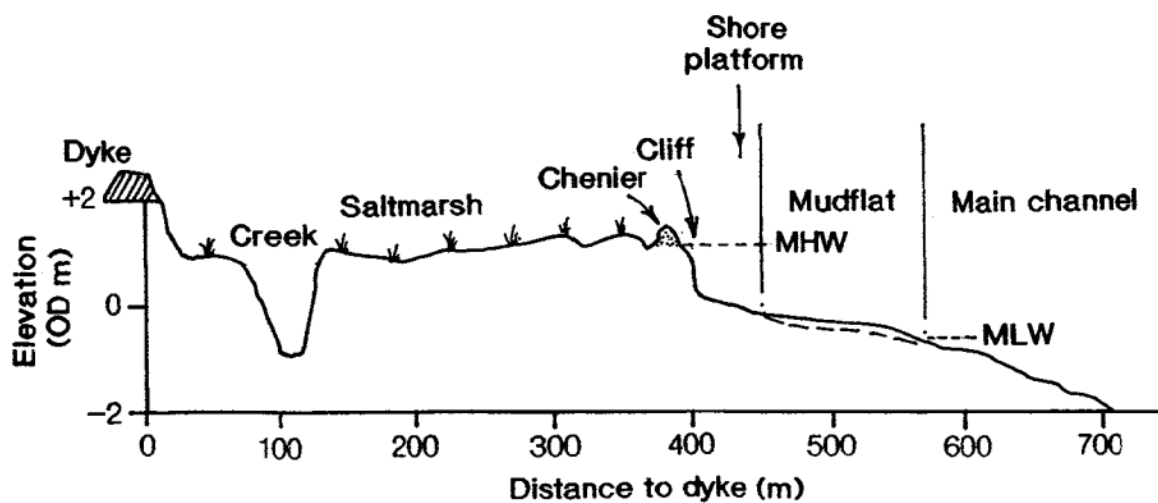


Figure 2: The general structure of muddy coastlines in the West Solent taken from (Ke and Collins, 2002).

The restoration of these environments has several benefits including but not limited to environmental, such as reinstating habitats for bird species and grass species specialised to the marsh environment. (Foster et al., 2013). They can also reduce the need for the construction of additional coastal defences and increase an area's resilience to coastal flooding and future changes (Foster et al., 2013), (Möller and Spencer, 2002), (WOLTERS et al., 2005), as well as carbon sequestration (Ladd, 2021). Beneficial use of dredged sediment is likely to become an important process in the maintenance and resilience of saltmarshes in future, particularly where managed realignment is not a viable option. (Ladd, 2021).

The sediment supply to a marsh could be accounted for with a sediment budget which involves the summing of sources, sinks and transport pathways within a system alongside a detailed understanding of the hydrodynamics and movements of sediments to do so with accuracy (Serato de Castro Silva, 2014). The sediment supply to the marshes can be altered by two management schemes there are already examples of in the Solent known as Managed realignment in Medmerry and beneficial use of dredged sediment in Lymington (ABPMer, 2023a), (ABPMer, 2023b), (Environment Agency, 2012), (ABPMer 2020). Beneficial placement is the centre of trials in Lymington with the four most up to date projects detailed in table 1. Beneficial use of dredged sediment has grown in use over the previous 30 years and has been used before to create or restore mudflats and saltmarshes on existing marshes/mudflats or near where they have been previously (Foster et al., 2013). There are three methods that could be used in beneficial placement which are 1) direct placement on to the area to increase the elevation or lateral extent. 2) placement in the subtidal zone at a single or multiple locations relative to the area of recharge to allow natural processes to redistribute the sediment. 3) direct placement into proposed realignment sites prior to breaching the coastal barrier (Foster et al., 2013). In Lymington, there has been both schemes using direct placement and subtidal placement, the longest running scheme in Lymington under MMO licence L/2014/00396/2 uses subtidal placement to create a sacrificial bund and the other three projects listed in table 1 used direct placement of sediment to halt the erosion of a creek threatening to destabilise the marsh though was never aimed to address wider saltmarsh degradation (Foster et al., 2013), (ABPMer, 2023a), (ABPMer, 2023b). Schemes can also vary in size from a few thousand m<sup>3</sup>/year like Lymington up to many million m<sup>3</sup>/year in Mississippi (Spearman and Benson, 2023). There are conflicting statements as to how the sediment supply has altered in the Solent in relation to the decline in Saltmarshes. Ladd et al, 2019 state there is no evidence to suggest that suspended sediment fluxes to the UK have

changed since 1974 or that marine sediment sources have been depleted in the previous 50 years while Ke and Collins 2002 suggest that there is a deficit in the Solent. Therefore, it is important to attempt to quantify whether this is the case. Though no research to date has unequivocally identified the source of the saltmarsh erosion (Foster et al., 2013).

Sediment budgets are important tools in determining the effects of dredging and land claim on erosion where sufficient sediment availability leads to increased accretion in front of the marsh (Wolters et al., 2005). The current understanding is that a positive sediment budget promotes accretion and therefore the survival of the marsh while a lack of sediment leads to the degradation of the marsh (PannoZZo et al., 2021). The state of the marshes could be in part accounted for with a sediment budget.

At Lymington Ke and Collins 2002 suggested that the sediment exported from the system amounted to around 154,000 m<sup>3</sup>/year while the volume lost from the marshes alone amounted to 38,000 m<sup>3</sup>/year. They also noted that despite the lateral erosion, the upper marsh was continuing to accrete vertically at a rate of between 2 and 5mm per year (Ke and Collins, 2002). Whereas Serato de Castro Silva, 2014 predicted that the sources and sinks in the estuary amount to between 130,000 and 115,000 m<sup>3</sup>/year from Black and Veatch, 2013.

### **2.1 The last budget (2014)**

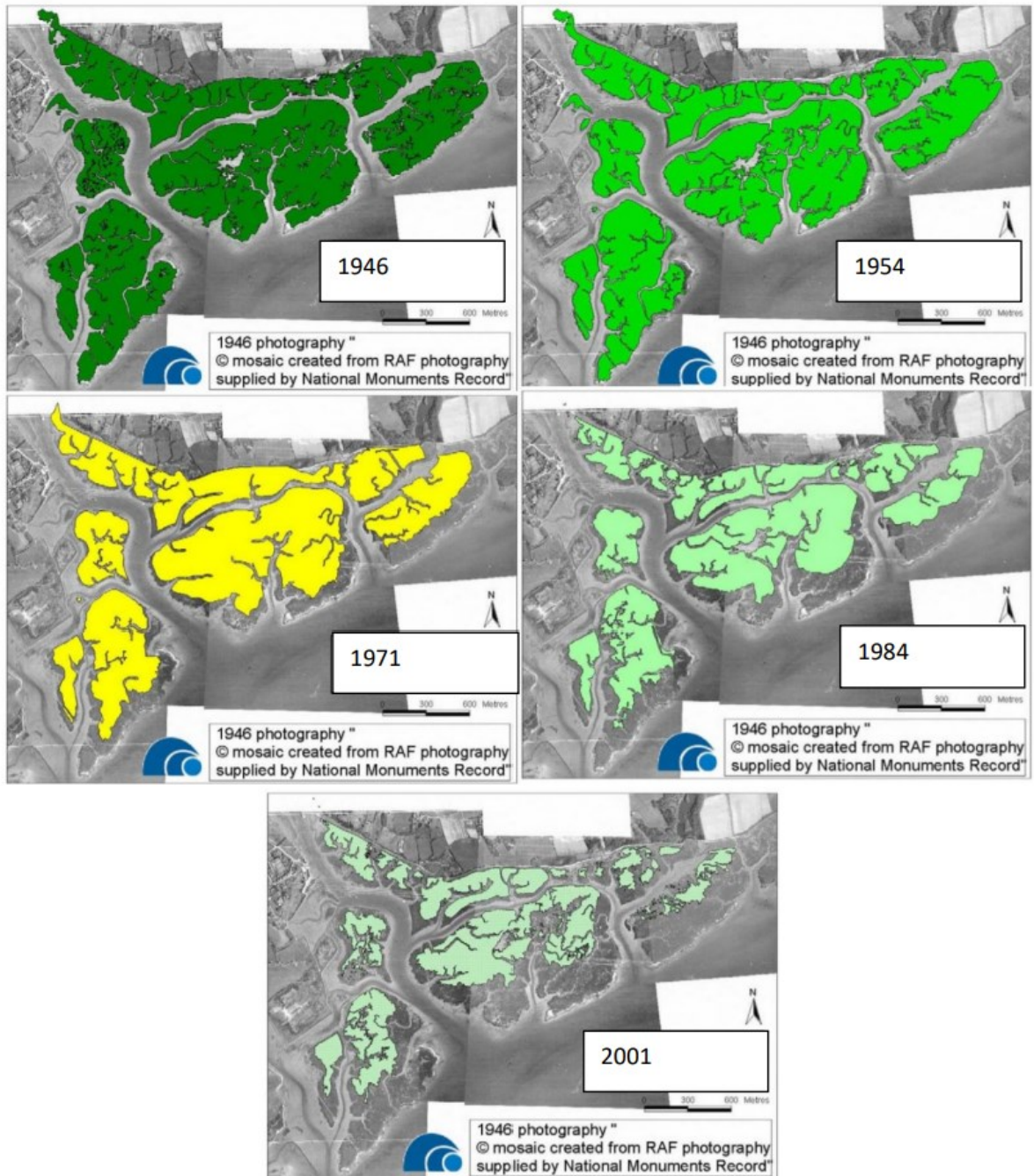
Serato de Castro Silva in 2014, aimed to quantify the movements of the sediments within the estuary to provide possible explanation for saltmarsh loss and to inform future interventions. Prior to (Serato de Castro Silva, 2014), Black and Veatch (2013) stated “no formal sediment budget has been calculated for the Lymington estuary, and there is insufficient existing data on hydrodynamics and sediment movement to do so with any reliability”. Serato de Castro Silva, 2014 however, provided an accurate sediment budget and sources of uncertainty as well as estimating the filtering efficiency, sedimentation rates and better identifying the sources and

sinks of sediment in the Lymington estuary. They suggested the sediment is of local origin being imported from further offshore and the former drowned saltmarshes (Serato de Castro Silva, 2014). They used a combination of bathymetry of the main channel and shallow water bathymetry to quantify the budget using a combination of estimates of shoreline and saltmarsh erosion and littoral drift. These estimates were combined with a histogram and interpolation analysis of the volumetric changes in the channel with the dredging volumes provided by the LHC (Serato de Castro Silva, 2014). They found between 80,000 and 200,000 m<sup>3</sup>/year were exported depending upon the scenario between 2008 to 2012 and 20,000 m<sup>3</sup> is lost between 2012 and 2014 , varying between 10,000 and 80,000 m<sup>3</sup>/year dependent on the chosen input.

## **2.2 The Site**

Lymington is managed by the New Forest District council (NFDC) and is located on the South coast of England and is home to 15,845 people (Parish.uk , 2021). The town has a rich history dating back to the 6<sup>th</sup> century and was once an important port town until the construction of a dam in 1731. This bridge exacerbated the silting of the harbour and the denial of its demolition led to the die out of the port and associated activities. (LHC, 2011). In 1830, the first paddle steamer travelled between Lymington and Yarmouth, and has increased in size multiple times to reach its current capacity of 65 cars and 359 passengers per ferry in 2009 fulfilled by 3 ferries (Wight Link, 2024). The Wightlink ferries have been the subject of controversy and the subject of a trial placement scheme. The Town also has a rich recreational history with 3 marinas, Berthon, Yacht haven and Fortuna and a large yacht club. It has also been home to a large network of Saltmarshes which began eroding around 1781 (Ke and Collins, 2002) with rates identified ranging between 3 and 7m a year (Ke and Collins, 2002) the extent of the erosion can be observed in figure 2. This significant habitat loss has been of great concern particularly as it shows no signs of stopping in the future with

no intervention and figure 4 shows the most up to date extent of the marshes in the present day.



**Figure 50.** Saltmarsh extent at Lymington River Estuary (Cope *et al.*, 2008).

(2008 Channel Coastal Observatory, © New Forest District Council, reproduced with permission)

*Figure 3: Historical Saltmarsh extent form 1946 to 2001 taken from (Parry and Hendy, 2022).*



Figure 4: The extent and classifications of saltmarshes in Lymington between 2016 and 2019 with data taken from (Environment Agency, 2022)

## 2.3 Lymington's Hydrodynamics

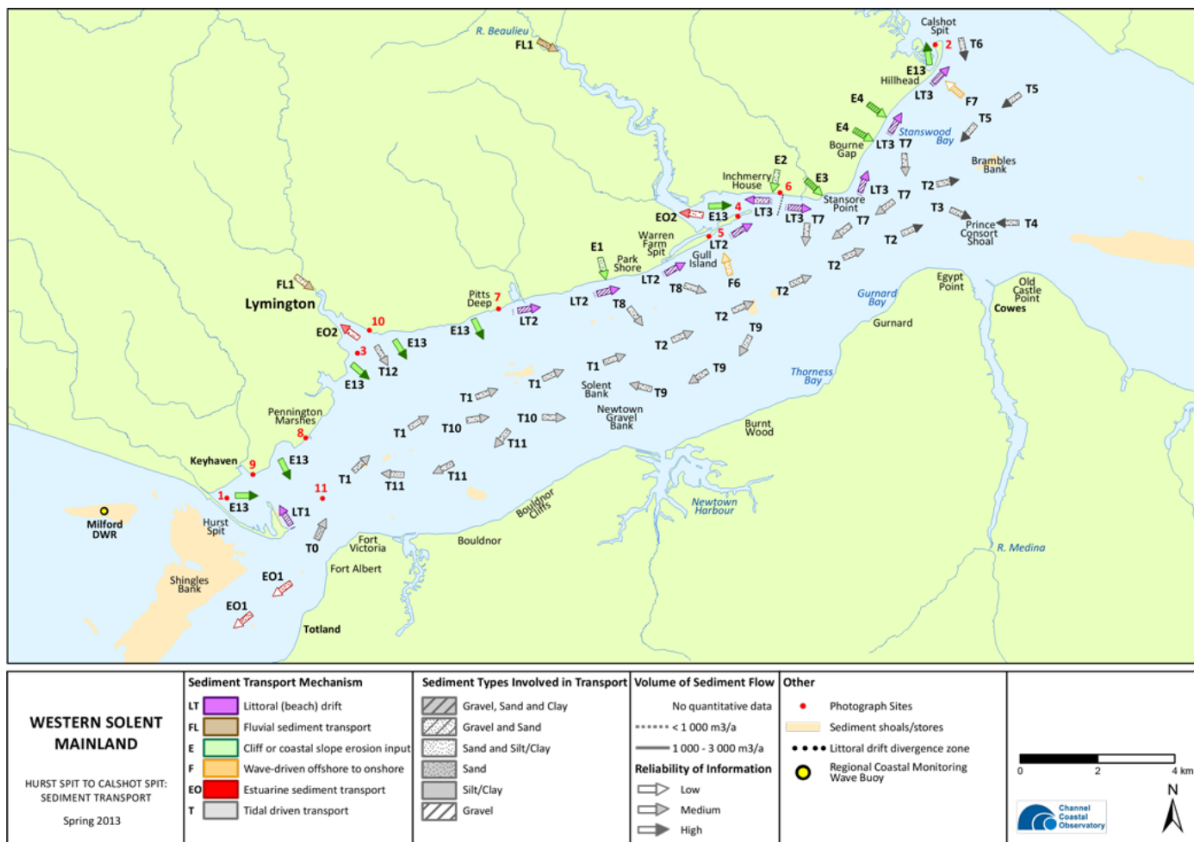


Figure 5: Sediment movements identified in the SCOPAC sediment transport study STS area 17 taken from (NFDC, 2017)

Lymington is located along the West Solent which is made up by the tidal channel with Hurst Narrows on western boundary and the Brambles Bank on the Eastern boundary and is one of the two major tributaries in the area (NFDC, 2017). The average width of the channel stands at 4.5km but the narrowest section is at Hurst Narrows standing at 1.48km in width (NFDC, 2017). The depth of the channel varies from 20m deep on its eastern side to 60m at Hurst Narrows but is on average 10-15m deep (NFDC, 2017).

The West Solent experienced prevailing winds from the southwest and south between 1996 and 2012 and an average 10% significant wave height exceedance of 1.31m at Milford on Sea

The West Solent is provided significant protection by Hurst spit and the Isle of Wight and is

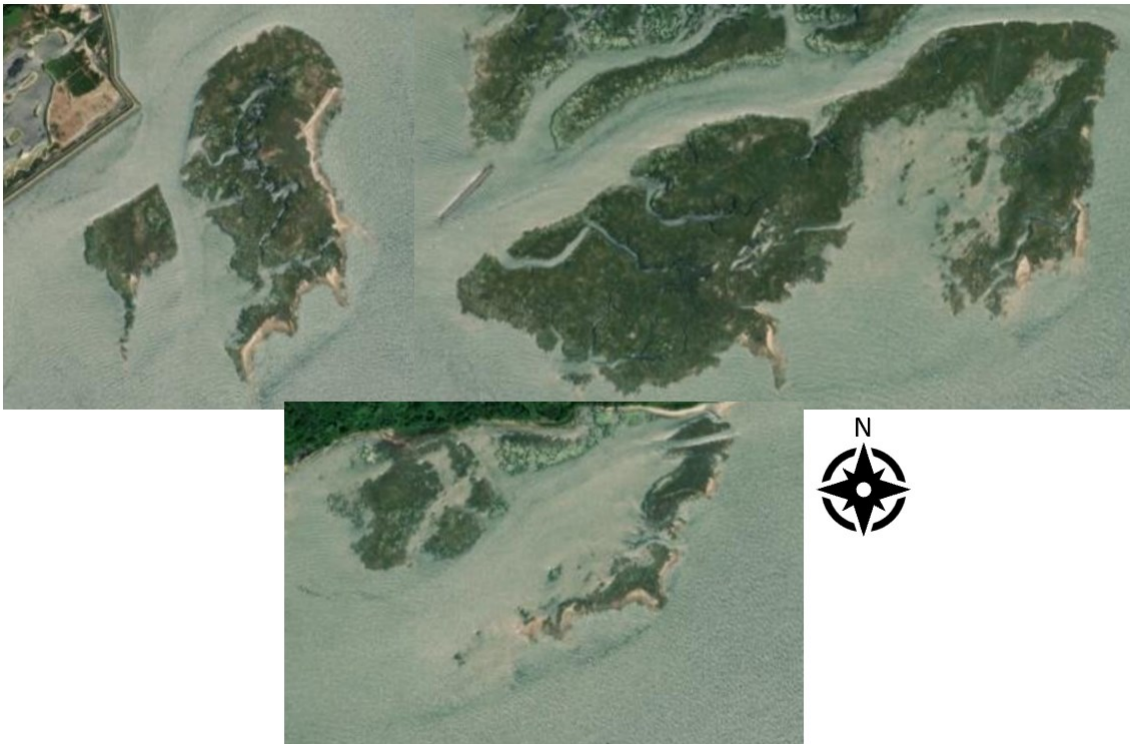
therefore, mostly low energy and fetch limited with significant wave heights lying between 0.3m and 0.8m (NFDC, 2017). Lymington itself had an average significant wave height exceedance of 0.38m between 2003 and 2008 with an average wind direction of 196° (South by West) from 2017-2022 (CCO, 2022). Gales at Lymington vary from 18.1 to 25.5 mph gusting between 22.7 – 31.5mph between 2017 and 2022, (CCO) Lymington experienced a maximum wave height of 1.44m between 2003 and 2008 (CCO, 2022). It has been suggested the lower Lymington estuary has a wave climate that is dominated by easterly fetch and the shoreline from Keyhaven to Pitts Deep is becoming more energetic due to the erosion of mudflats and saltmarshes providing protection to the shoreline. The tidal range of the West Solent is small, however the water movements are sizeable as the range varies considerably across the coastline varying from 2m at Hurst Point, 2.1m in Lymington and 3.9m at Calshot on spring tides. (CCO, 2022, SCOPAC, 2017). The protection provided by the Isle of Wight combined with a gently shelving offshore and nearshore combined with intertidal gradients prevents rapid tidal flows near the shore allowing for the accumulation of clay and silt and hence the formation of mudflats and saltmarshes (SCOPAC, 2017).

#### **2.4 Lymington's sediments**

The Solent today is what remains of the drowned river valley for the ancient Solent river that flowed eastward through south Hampshire and Dorset which was flooded in the Holocene during the Flandrian marine transgression (Algan et al., 1994, Allen and Gibbard, 1993, Ke and Collins, 2002). The Solent in the present day extends from Hurst Spit to Pagham harbour and includes the northern coastline of the Isle of Wight (Foster et al., 2013).

Lymington itself mostly comprises of muddy coastline with some evidence of sand in the form of small patches of sand on the shoreline as well as sandy cheniers on the seaward edges of the saltmarsh system. The cheniers are around 10-20m in width and 0.4-0.9m in height (Ke

and Collins, 2002). Lymington exhibits tidal asymmetry due to the shortened period of the ebb flow and is therefore more rapid. The low wave energy environment of the West Solent results in fine grain sediment transported on ebb tides with the main pathways lying in the main channel and along the saltmarsh edges (NFDC, 2017). Hence, the transport of coarser bedload sediment is likely to be in a net seaward direction (NFDC, 2017). The transport of fine sediments into Lymington is likely to happen on the flood tide (NFDC, 2017). Due to the presence of dams, weirs and the causeway in the Lymington River, the potential for fluvial input from the river is severely reduced and therefore the sediments accumulated on the mudflats and saltmarshes are supplied from the Solent with minimal contribution of coarse sediments from the river (NFDC, 2017). The frontage between Hurst Spit and Lymington is defended by approximately 10.6km of sea walls and embankments (Beresford and Shipp, 2023) though low-lying cliffs are capable of supplying sediment in a restricted capacity as well as active coastal erosion in some places, though the frontage is more likely to be a store of sediment than a source. Littoral drift is not a major process in the West Solent due to the protection offered by Hurst Spit and the Isle of Wight which cases the limited fetch conditions and is therefore only present in the more exposed areas of the West Solent, further to the east of Lymington (NFDC, 2017). The fine-grained sediment was confirmed by 2013 aerial imagery and observation that fine grained sediment enters the West Solent from Christchurch bay to the west of Hurst Narrows, particularly on flood tides and marine sediments, as well as suspended clay sediments originating from cliff erosion, are drawn into the Solent this way (NFDC, 2017) The main channel of the Lymington River - contrary to the silt-clay composition of its banks – is made up of gravel and sand, this indicates that shear stress is of a sufficient level to re-entrain fine sediment during the low tides, though some is trapped in the marinas and mooring areas and some fines are deposited in areas of the Lymington estuary mouth (NFDC, 2017).



*Figure 6: evidence of sandy cheniers at the three named marshes using ArcGIS pro basemap*

## **2.5 Changes since the last budget in 2014**

Since the work of (Serato de Castro Silva, 2014). There have been significant changes in the legislation of the area and the physical engineering structures and interventions.

The legislative changes retain many of the legal obligations prior to the UK's exit from the EU in 2020 but made alterations to those responsible for meeting these obligations, as well as adding more sites to the UK protected site network (DEFRA, 2021). The preservation of the saltmarshes in Lymington contributes to the Environment Agency's Regional Habitat Compensation Program which is the Government's agreed mechanism to deliver strategic habitat compensation for flood and erosion risk management to fulfil its obligations to the habitats regulations. Obligations to conventions such as RAMSAR remain unchanged and these legislation changes became active on the first of January 2021 following the end of the Brexit transition period on December 31<sup>st</sup> 2020 (DEFRA, 2021). In addition to the legislative changes, there has been an additional phase of the breakwater construction.

The first phase was completed at the end of 2010 and the second phase was completed in 2014 and therefore its potential impacts of phase 2 have not been explored. There are plans for up to 6 phases of construction (LHC, 2019). There have also been other significant events starting with the valentine's day storms of 2014 which caused flooding along the coastline and required parts of the Lymington Town Quay area to have water pumped out (McKinney, 2023). The 2014 storm also caused the loss of 100,000 tonnes of shingle from Hurst Spit and a height reduction of 7m (English Heritage, n.d.). In addition, a further storm in 2021 which caused the overtopping of sea defences and localised flooding (McKinney, 2023). The 2021 storm also caused the collapse of the 19<sup>th</sup> century east wing of Hurst Castle due to the undercutting of foundations and the counterscarp wall originally built to define a shingle ditch but now constitutes an important part of the castle's sea defences (English Heritage, n.d.).

## **2.6 Sediment Budget**

A sediment budget is an account of sediment sources and sinks within a given system over time to provide a conceptual understanding of sediment distribution in the system (Kana, 1995).

Budgets can be conducted on several scales and have three main components. These components are the sediment cells, sediment sources and sediment sinks with the sources and sinks relative to a given cell., the concept of conservation of mass is applied and can therefore be calculated with equation 1

$$\sum Q_{source} - Q_{sink} - \Delta V + P - R = Residual \quad \text{Equation 1}$$

where  $Q_{source}$  is The cell's input

$Q_{\text{sink}}$  is the cell's output

V is the volume change within the cell

P is the placement into a cell

R is the removal from a cell

and Residual = zero for a balanced cell.

(Mcgillet al , 2022), (Roberts and Brooks, 2018)

### **3 Methodology**

For repeatability and comparability, the method below follows closely the approach laid out by Serato de Castro Silva in 2014. This accounts for sources, sinks and pathways of sediment based on existing understanding as well as volume changes using available data.

#### **3.1 Bathymetric data**

*Table 1: The features of all the bathymetric data used in the budget analysis where CCO is the Channel Coastal Observatory, LHC is the Lyminster Harbour Commissioners, ODN is Ordnance data Newlyn and CD is Chart Datum (CD is 1.98m below ODN). (CCO, 2024).*

Year	Survey	Data Type	Company	Provider	Datum
2016 January	J1124	Multibeam & Single Beam	Shoreline Surveys LTD	LHC	CD
2017 January	J1243_03 & J1243_04	Multibeam & Single Beam	Shoreline Surveys LTD	LHC	CD
2017	CCO 2017207	LiDAR	CCO	CCO	ODN
2018 January	J1392	Multibeam & Single Beam	Shoreline Surveys LTD	LHC	CD
2018 October	J1505_SBES	Single beam	Shoreline Surveys LTD	LHC	CD
2019 September	J1644	Multibeam & Single beam	Shoreline Surveys LTD	LHC	CD
2020 January	J1705	Multibeam & Single beam	Shoreline Surveys LTD	LHC	CD
2020 September	J1836_SBES	Single beam	Shoreline Surveys LTD	LHC	CD
2020	CCO 20200312	LiDAR	CCO	CCO	ODN
2021 September	J1965	Multibeam & Single beam	Shoreline Surveys LTD	LHC	CD
2021 January	J1881_SBES	Single Beam	Shoreline Surveys LTD	LHC	CD
2021	CCO 2021101	LiDAR	CCO	CCO	ODN
2022 October	J2114_SBES	Single Beam	Shoreline Surveys LTD	LHC	CD
2022 October	J2114_MBES	Multibeam	Shoreline Surveys LTD	LHC	CD

For all years of bathymetry data Real Time Kinematic (RTK) positioning was used to make tidal corrections and all surveys but J1392 and J2114 used a GPS with Trimble VRS NOW Virtual tide gauge alongside the RTK which were already applied to the data prior to analysis.

The data were all first imported into ArcGIS pro and rasterised with the “topo to raster tool” using the suggested cell sizes from the data properties except where the suggested sizes were more than 300, where the suggested size of a similar raster was used instead. They were then resampled into the 12 and 3m resolutions ensure they matched the resolution of the lowest resolution dataset for the analysis and additionally to the resolution set out with the resolution tests below. These datasets were then clipped to the cell boundaries and stored in a geodatabase for further analysis.

### **3.2 Conceptual Budget**

This analysis builds upon the previous budget developed by Serato de Castro Silva in 2014 and therefore the conceptual understanding of the budget was taken from the final budget given in their analysis and the same pathways and cells were used in this analysis.

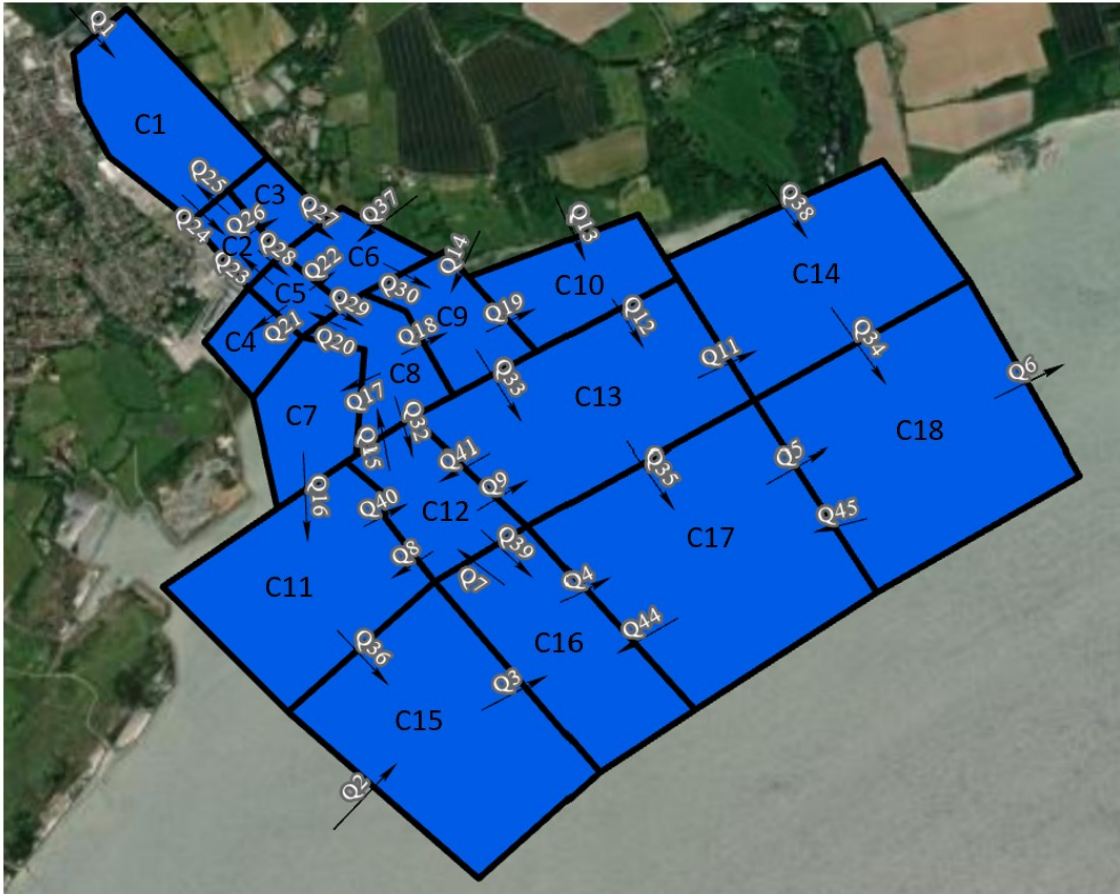


Figure 7: The sediment cells (labelled C followed by the cell number) and the flux pathways (labelled Q followed by the flux number) used in the analysis modified from (Serato de Castro Silva, 2014)

### **3.3 Data Coverage and Time step**

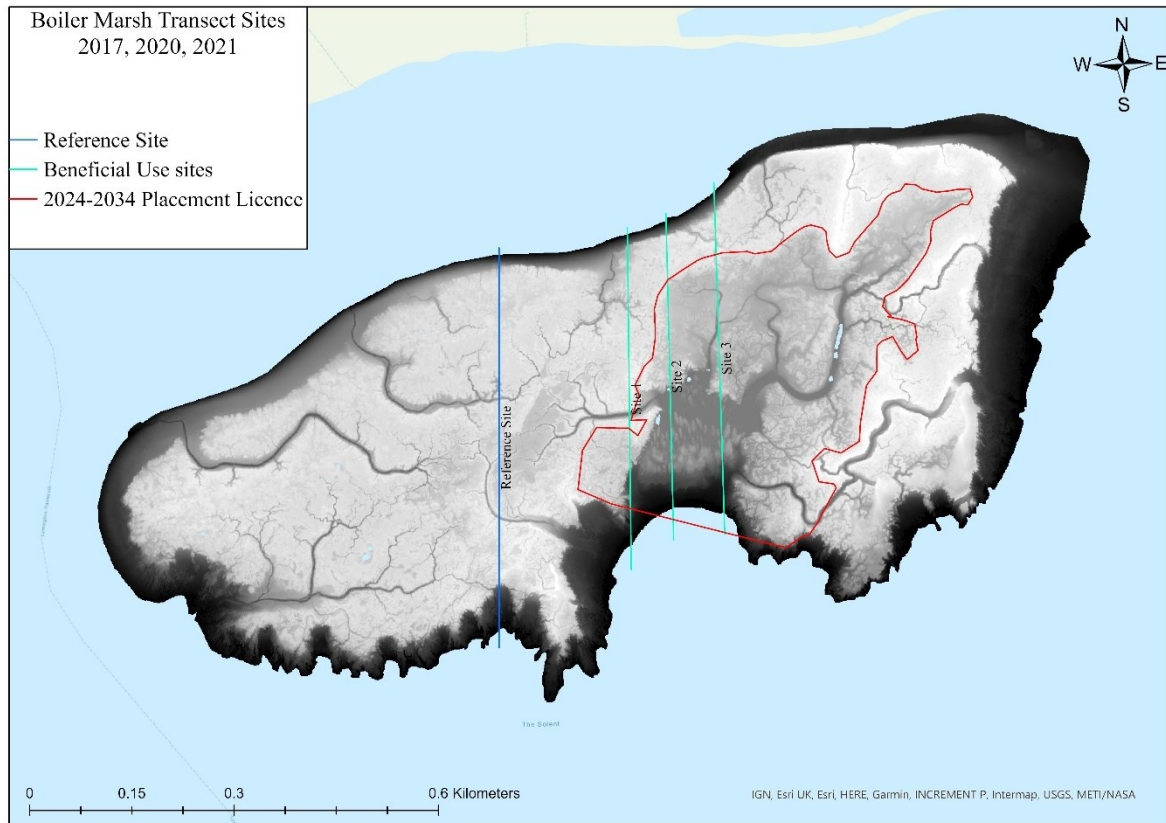
To ensure an accurate comparison, years of bathymetry with low data coverage were discarded to avoid extrapolating a small amount of data over a large area. Therefore, the years 2017, 2020 and 2022 were discarded as they only covered cells 8, 12 and 13 in 2017, cells 2, 5 and 13 in 2020 and cells 1 and 13 in 2022. While this results in an uneven timestep for the analysis, it is not uncommon to conduct an analysis with an uneven timestep (e.g. Sarreta et al., 2010). Therefore, the timesteps of 2016-2018, 2018-2019 and 2019-2021 were used in this study. For the bathymetric data, cells 13 and 17 were discarded in favour of LiDAR estimates for the Saltmarsh erosion due to the uneven coverage of the bathymetry over this

area which did not align with the budget timesteps. The LiDAR was not combined with the bathymetry data and instead used to estimate the volume changes in the shallower cells like the use of the CCO bathymetry to cover shallower cells by (Serato de Castro Silva, 2014) particularly where the timesteps did not align with the chosen time steps to maximise bathymetry coverage. The LiDAR data required a transformation from ODN (Ordnance Data Newlyn) to bring it in line with the bathymetry data in CD (Chart Datum) and therefore a transformation of -1.98m was applied using the raster calculator before the LiDAR was also clipped to the cell boundaries used for the bathymetry data.

### **3.4 Sensitivity analysis of data sub-sampling resolution**

To establish the best resolution to preserve the detail of the saltmarshes in the LiDAR data, a series of tests were conducted in Boiler Marsh detailed below.

A polygon was drawn around the Boiler Marsh using all three years of LiDAR data as a reference and then this polygon was used with the extract by mask tool to isolate the marsh from the rest of the data. Then four transect lines were drawn in ArcGIS based upon the 2024 to 2034 MMO License area reference MLA/2023/00052 (this is larger than the one contained in MLA/2014/0259/1). The transects consisted of one reference site adjacent to the placement area and 3 sites within the placement area.



*Figure 8: The boiler marsh transect sites taken using (MMO, 2023) and (CCO, 2024)*

A stack profile was then extracted using the transect lines and exported as a text file to be imported into MATLAB. The stack profiles were then used to create transect plots for the marsh across all three years (code available in appendix)

The data was then resampled using the resample tool with the cubic resampling technique set to the new cell sizes. The stack profiles were then conducted again using the same lines and the same code block. The tests were done at 1m, 2m, 3m and 5m resolutions.

For the structure of Pylewell and Cockleshell marshes, a polygon was drawn around the marshes and the LiDAR data at 1m resolution were clipped to the polygon. A transect was then drawn at a site approximately in the middle of the marsh irrespective of the Solent Forum placement areas. A stack profile was then performed and exported as a text file to be imported into MATLAB.

### **3.5.1 Volume estimates- Interpolation**

For the volume estimates for sediment budget two methods were applied, the first was an IDW (Inverse Distance Weighted) interpolation which has been used by many including (Serato de Castro Silva, 2014), (Sarretta et al., 2010)

The IDW was applied to the clipped data by converting the clipped data to a point field and applying the IDW tool to the point field. The IDW tool with the geostatistical analysis also conducts a cross validation analysis.

*Table 2: The parameters used for the IDW analysis for all sets of volumetric estimates conducted in ArcGIS pro.*

Parameter	Value
Cell Size	1
Power	2
Search Neighbourhood	Standard
Min Neighbours	10
Max Neighbours	15
Sector Type	4

The selected parameters are based upon the k-fold analysis conducted by Serato de Castro Silva, 2014 and the IDW interpolation.

The IDW was selected because the IDW 3D tool in ArcGIS makes no assumptions about the distribution or trends of the data and the interpolated values will pass through the measured values exactly. (esri, n.d a) The predictions are based upon a weighted average of the points within the search neighbourhood of the point where the prediction is being made (esri, n.d a) IDW assumes that the points closer together are more alike than those further apart and the values closer to the prediction have more weight applied to them than those further away, in addition the maximum and minimum recorded points can only be recorded at that location (esri, n.d a).

The cross-validation results generated three values. The count, which is the number of points that have values in the cross validation, the mean error which measures the modal bias and the closer to zero this value is, the more accurate with a positive value indicating a tendency to over predict and a negative result is the inverse (esri, n.d b). The final value generated is the root mean square error which is the average square of the cross-validation errors, this statistic should be as small as possible as this is the average difference between the predicted values and the measured values (esri, n.d b).

The cross-validation values were recorded contained in table 7 , and the scatter plots of the mean error and root mean square error were generated.

The IDW rasters were then subtracted from each other with the earlier of the two years taken from the later using the minus tool and the resulting raster was converted to a point field to generate an attribute table. The statistics were then generated, and the sum of all the points was recorded in table 8.

### **3.5.2 Volume Estimates-Histogram analysis**

The second of the two methods is the histogram analysis method first proposed by Carl Amos in a Lymington monitoring report and has since been used by many including (Serato de Castro Silva, 2014) (Townend, 2010; Sarretta *et al.*, 2010)

The histogram method works on the assumption that the bathymetric survey data is a valid subset of the total possible bathymetric values that inform the morphology of the estuary. (Serato de Castro Silva, 2014). Therefore, it is not distorted by bathymetric lines or by some sampled regions of the data. (Serato de Castro Silva, 2014).

The methods applied herein, again follow those set out in (Serato de Castro Silva, 2014).

First the clipped cells were converted to point fields and exported to text files for import into MATLAB. To ensure that the two years are comparable, the depths and spatial extent must be equalised. The spatial extent had already been clipped to the cell boundaries in an earlier step and therefore the depths had to be clipped for further analysis. The maximum of the two minimum depths and the minimum of the two maximum depths as per equations 2 and 3 taken from (Serato de Castro Silva, 2014) were then set as the thresholds for the analysis using MATLAB and the code block contained in the appendix.

$$Min_{depth} = \min (max\ depth_x, max\ depth_y) \quad \text{Equation 2}$$

$$Max_{depth} = \max (min\ depth_x, min\ depth_y) \quad \text{Equation 3}$$

The values were then limited using these thresholds using the code block contained in the appendix. The values were then imported back into ArcGIS pro and a histogram was generated using the equalised values using 50 classes following Serato de Castro Silva (2014). The histograms were exported to excel as tables where a normalised depth was applied using the excel code block also contained in the appendix.

Once in excel, a normalised frequency was applied to the depth which accounts for the values in a given class ( $\#_{d,class}$ ) and the total measures in the survey (total count) using equation 4 taken from (Serato de Castro Silva, 2014).

$$NF_{d,yr} = \frac{\#_{d,class}}{Total\ count} \quad \text{Equation 4}$$

( $NF_{d,yr}$ ) was then multiplied by the bin centre of the class ( $d_d$ ) which gives a weighted depth for that class. This was applied for every single year and then the difference between the two years was calculated by taking the difference then summing. This sum was then multiplied by the cell area for a total volume for the cell using equation 5 from (Serato de Castro Silva, 2014) to give the total volume change of the cell.

$$Volume = Area \times \sum(NF_{d2,yr2} d_{d2}) - (NF_{d1,yr1} d_{d1}) \quad \text{Equation 5}$$

### **3.6 Dredging and Placement Values**

Dredging and placement values as well as the schedule and locations were provided by the LHC (Lyminster Harbour Commissioners).

*Table 3: Modified from (ABP Mer, 2023a), (ABP Mer, 2023b) showing the dredging volumes per year and the type of dredging.*

Year	Annual Volume (tonnes)	Dredging Type
2016	23,926 / 6,664	Maintenance / Capital
2017	20,211 / 328	Maintenance / Capital
2018	25,783	Maintenance
2019	26,439	Maintenance
2020	24,308	Maintenance
2021	20,976	Maintenance

Disposal volumes were taken from the report provided by the LHC and cross referenced with the MMO public register and the dredging schedule to infer specific volumes for locations given in table The exact placement values in table 4 were assigned to Cell 13 for this analysis but do encroach slightly on cell 17.

*Table 4: Modified from (ABP Mer, 2023a), (ABP Mer, 2023b) showing the disposal volumes per year on Boiler Marsh and the licence reference*

Years	Disposal Quantity (wet metric tonnes)	MMO Licence reference
2016 (Nov to Dec)	9,942	L/2014/00084/6
2017/18 (Nov to Jan)	9,286	L/2014/00396/2
2018 (Nov to Dec)	6,446	
2019/20 (Nov to Feb)	8,959	
2020/21 (Nov to Mar)	9,942	
2021/22 (Nov to Mar)	8,124	

### **3.7 Sediment Budget**

The SBAS 2020 tool box for ArcGIS pro (US Army Corp of Engineers, 2020) was used to conduct the sediment budget analysis using the same cells and fluxes set out by (Serato de Castro Silva, 2014) inclusive of the two additional fluxes identified in the final sediment budget not present in their conceptual budget.

Three budget alternatives were set out with two conditions for each year Labelled A, B and C. The three alternatives were set out as 2016-2018, 2018-2019 and 2019-2021 timesteps. The scenarios for each were the calculated volumes combined with the average values calculated from the available LiDAR data per year using all the available LiDAR data, due to the absence of CCO bathymetry data for the entire study period multiplied by the timestep duration in years. Then the second scenario was in absence of dredging. Rather than estimate the erosion of the saltmarshes as Serato de Castro Silva (2014) did, the actual volumes from the LiDAR data clipped to the cell boundaries of 11, 13 and 14 were used and averaged per year and then multiplied by the duration of the timestep in years. The LiDAR was able to provide data for all areas where there was an absence of bathymetry except for cells 4, 15, 17 and 18. The actual values directly from the LiDAR were used for cells 6, 9, 10 and 14 instead of estimating shoreline erosion as the clipped cells do contain the shoreline as well as the erosion of the additional unnamed marshes therefore the actual values from the LiDAR were used in all cases where LiDAR was the only data coverage for a cell.

*Table 5: The name and description of the sediment budget alternatives explored using (US Army Corp of Engineers, 2020)*

Alternative	Description
1A	2016-2018 inclusive of shallow averages, dredging and placement using IDW values
2A	2016-2018 inclusive of shallow averages and placement only using IDW values
1B	2018-2019 inclusive of shallow averages, dredging and placement using IDW values
2B	2018-2019 inclusive of shallow averages and placement only using IDW values
1C	2019-2021 inclusive of shallow averages, dredging and placement using IDW values
2C	2019-2021 inclusive of shallow averages and placement only using IDW values
1D	2016-2018 inclusive of shallow averages, dredging and placement using Histogram values
1E	2018-2019 inclusive of shallow averages, dredging and placement using Histogram values
1F	2019-2021 inclusive of shallow averages, dredging and placement using Histogram values

For the littoral drift estimate, NFDC, 2017 suggests that the process of littoral drift is not significant on this stretch of coastline though data from the NCERM project (Environment Agency, 2022) was employed to establish the rate of erosion for the coastline between Hurst Spit and cell 15. however, the rate to the 5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup> percentile confidence on both long and short timescales was listed as zero, therefore the estimate given by Serato de Castro Silva, (2014) of 24,000m<sup>3</sup> per two years was used as this is unlikely to have changed significantly between the end of their budget in 2014 and the start of this one in 2016.

Shoreline erosion on the eastern side of the estuary is given as 8m, 6m and 4m to the 5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup> percentile confidence level for the period of 0-20 years. Therefore, it can be suggested that 0.2m per year is an appropriate estimate for the period 2018-2021 which has increased from the estimate given in (Serato de Castro Silva, 2014) and (Posford Duvivier, 1999) Therefore, this was used to estimate fluxes Q37, Q14, Q13 and Q38

The CERC and (Kamphuis, 2002) equation contained in the appendix were used to double check the littoral drift estimate of (Serato de Castro Silva, 2014).

Riverine inputs of sediment are also thought to be low with the sediment concentration lying between 5 and 10 mg/L (Zhu, 2014) and the combined input of Bartley Water, Beaulieu River, Dark Water, Avon Water and Lymington River was estimated to amount to 411m<sup>3</sup> per year of fine sediments (NFDC, 2017). Therefore, the riverine input was set to zero for all scenarios due to the small volume likely to be trapped by the regulated tidal exchange scheme above cell 1.

## 4. Results

### 4.1 Resolution tests and saltmarshes

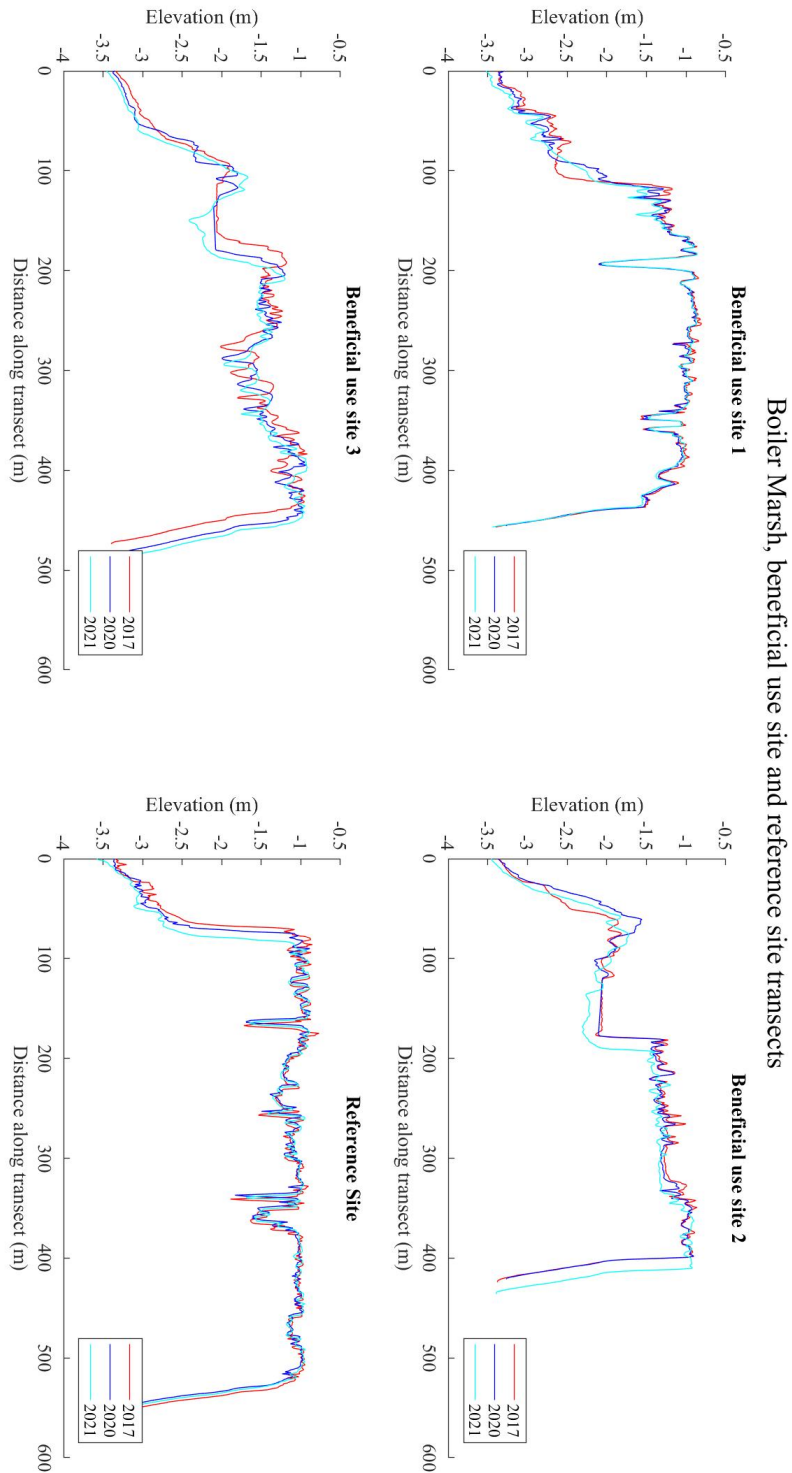


Figure 9: A graph of the stack profile transect across boiler marsh at 1m resolution with 2017 in red, 2020 in blue and 2021 in cyan using (CCO, 2024) data

The results of the 1m resolution from the unaltered LiDAR are given by Figure 9 at the reference and beneficial use sites. The beneficial use site 1 shows the most conformity to the reference site and sites 2 and 3 showing deviation from the reference site at both the upper and lower marsh, there is more activity at the sacrificial bund created at these sites, with the sacrificial bund not present in beneficial use site 1, likely due to the transect being the furthest away from the MMO licence area for L/2014/00396/2 and sites two and 3 being much closer. There is also evidence of creek structures at the reference site and the beneficial use site, which are not obvious in sites 2 and 3. Site 3 shows a dip in the upper marsh where the other three sites display a much flatter trend on the upper marsh. At sites 2 and three the marsh appears to be transgressing landward with its maximum landward extent occurring in 2021, at the reference site the maximum landward extent is displayed in 2017 and transgresses slightly seaward in 2020 and 2021. At the beneficial site 1 the maximum landward extent is at the same location in all three years and shows little change behind the first creek structure with the most activity at the front of the marsh. The elevation of the marsh structure below the marsh cliff changes significantly but the location of the cliff does not change. The top of the cliff structure is reduced in elevation with its lowest height displayed in 2021. At the reference site, there is less change on the lower marsh and the top of the marsh cliff, however, the location of cliff is progressing landward with its most landward location displayed by 2021. Sites 2 and 3 appear to have a more sloping marsh cliff structure than site 1 and the reference site. Site 3 shows the most activity in all years and appears to be progressing landward at the fastest rate.

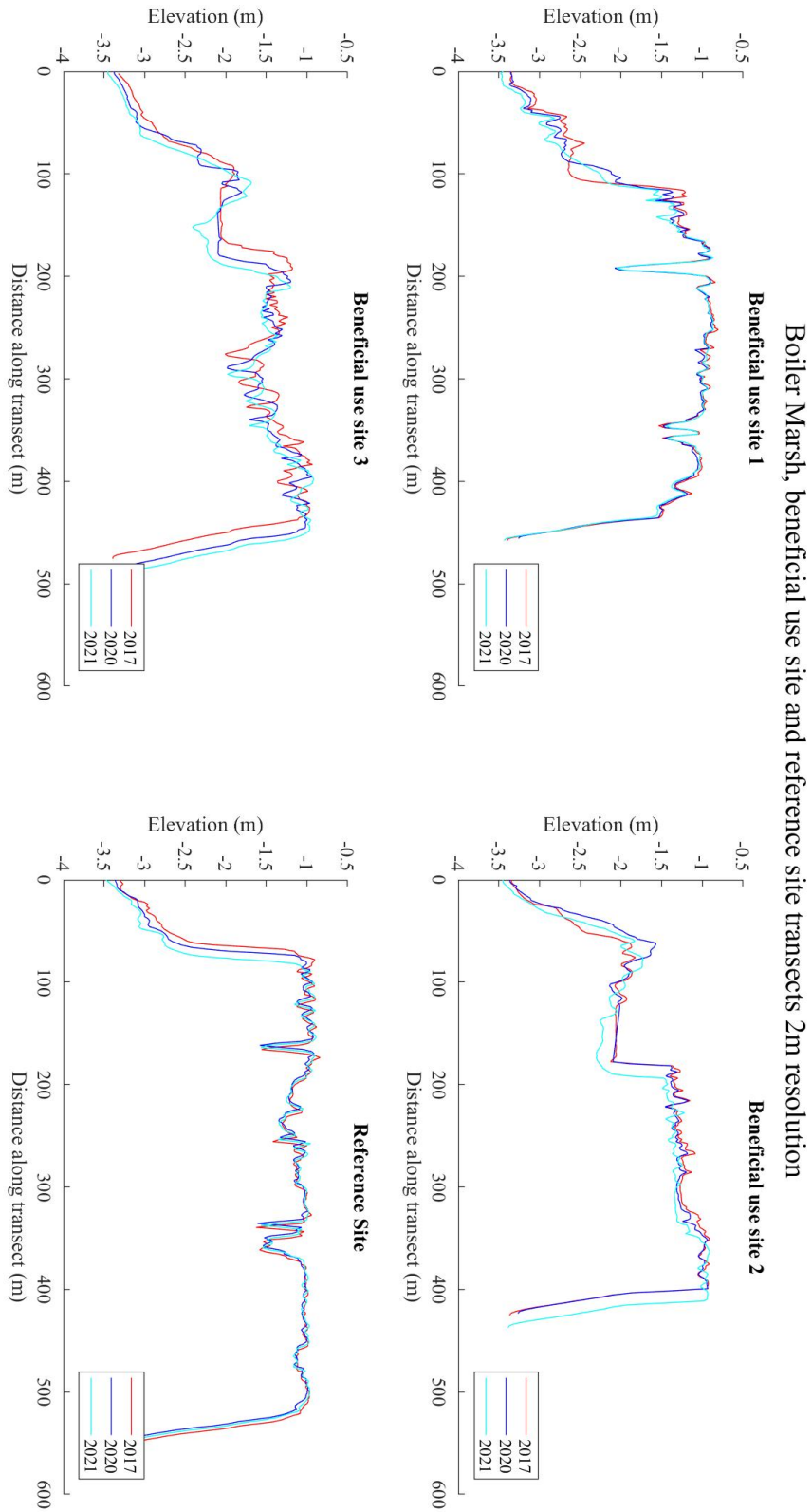


Figure 10: the 2m resolution transects across boiler marsh with 2017 in red, 2020 in blue and 2021 in cyan using (CCO, 2024) data

The 2m resolution transects display the same trends as the 1m transects but loses some of the finer details on the upper marsh and the structure in front of the marsh cliff. The creek locations and depths are still well preserved at 2m of resolution and the activity at the bottom of the marsh cliff is also well preserved.

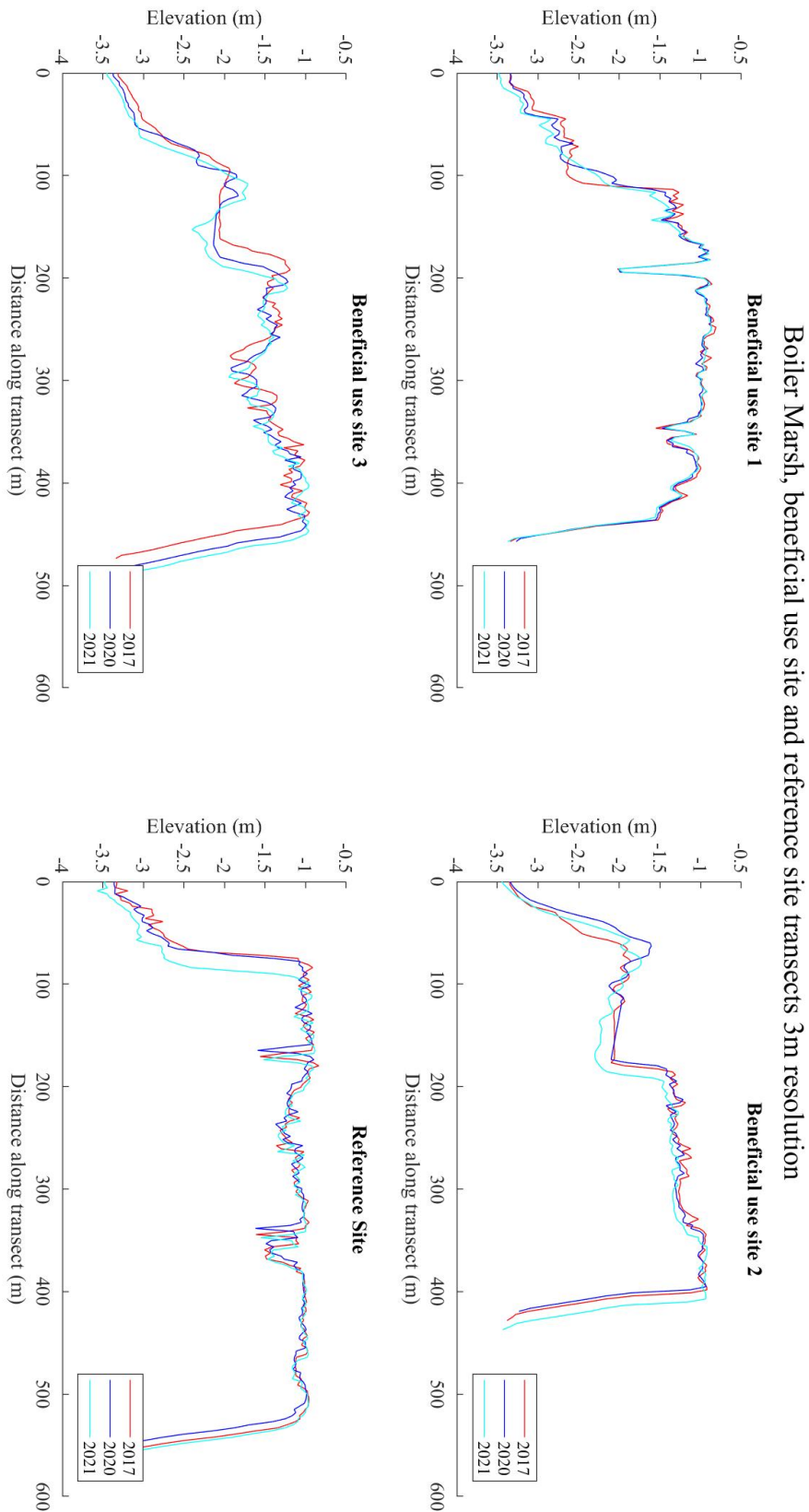


Figure 11: the 3m resolution transects across boiler marsh with 2017 in red, 2020 in blue and 2021 in cyan using (CCO, 2024) data

At 3m the structures from the previous two resolutions as well as the activity remain well preserved but more of the smaller scale variations are still lost but largely does not affect the appearance of the trends displayed. It does however suggest that the maximum landward extent of the reference site is now 2021 and 2017 instead of just 2017 like the previous two resolutions.

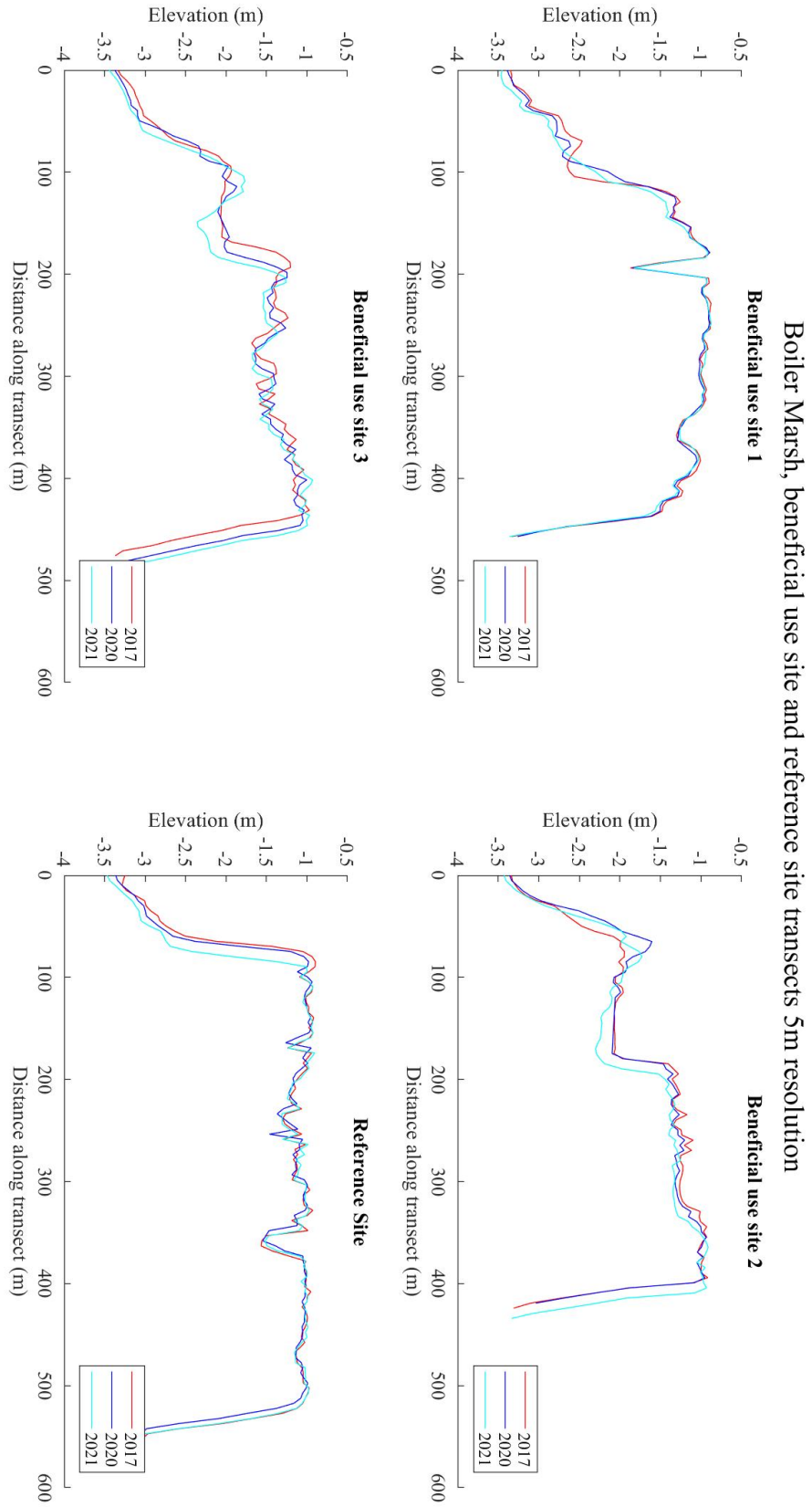


Figure 12: the 5m resolution transects across boiler marsh with 2017 in red, 2020 in blue and 2021 in cyan using (CCO, 2024) data

At 5m the structures of the creek toward the landward extend of the marsh at site 1 is completely erased and the appearance of some of the creeks in the reference site are reduced and some have also been erased. At site 3 the variations have been significantly smoothed and the dip shown in the higher resolutions is also reduced in depth though the locations and shapes of the sacrificial bund remain mostly unaltered but significantly smoothed out. Much of the activity below the marsh cliffs is lost however the landward transgression of the marsh is also unaltered except for at the reference site where the maximum landward extent now appears as 2020 and 2021 instead of 2017. Therefore, for the budget analysis a 3m resolution will be compared alongside a 12m resolution to establish whether there is significant difference between the two resolutions to preserve as much of the saltmarsh change as possible.

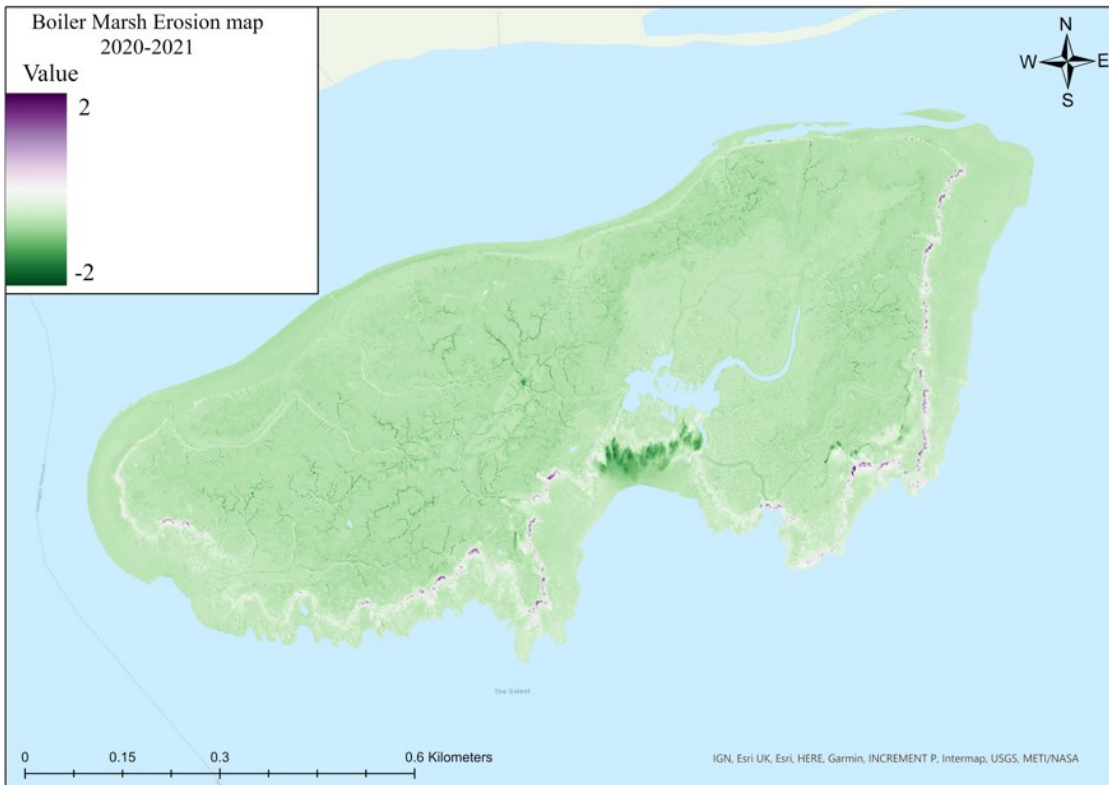
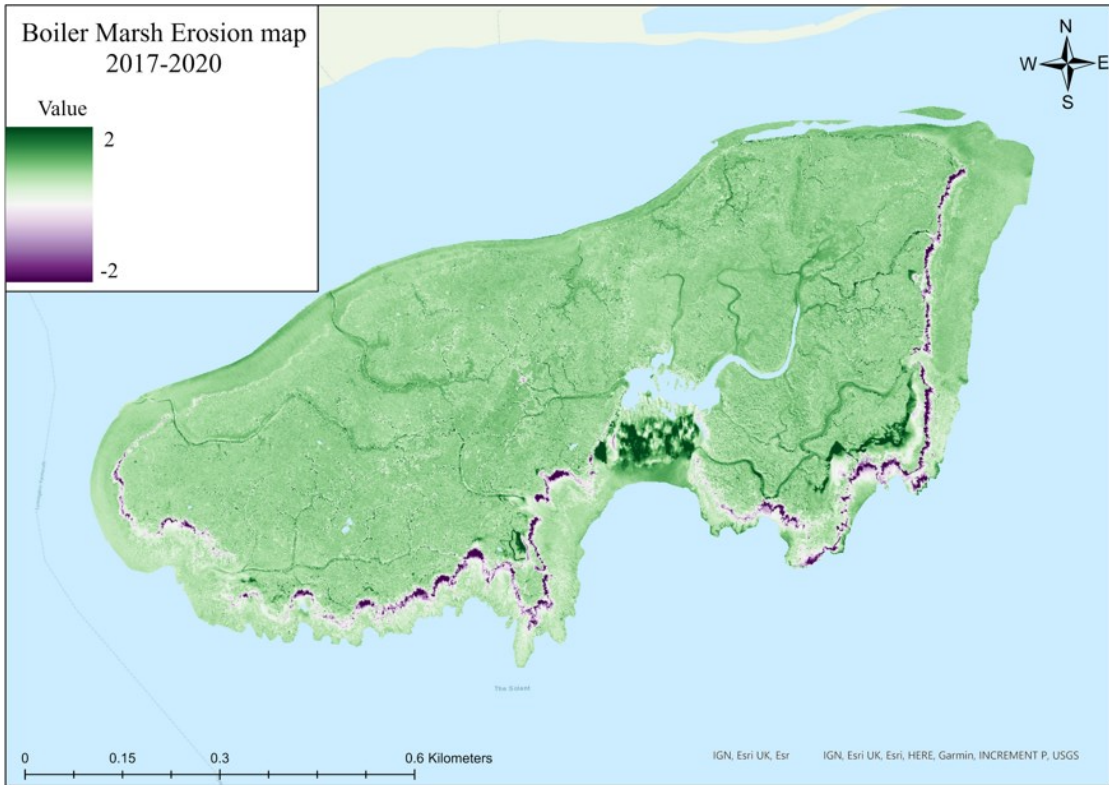


Figure 13: displaying the locations and volumes of erosion (in meters) in 1m resolution from the CCO LiDAR where negative values represent erosion for Boiler marsh using (CCO, 2024) data

At the seaward extent of the marsh there is significant erosion at the marsh cliffs interrupted by the accretion shown at the beneficial placement site. There is also significant erosion on the eastern extent of the marsh and to a lesser extent on the western edge of the marsh. Much of the upper marsh shows a mix of low erosion or accretion with the accretion focused around the creek system of the marsh and the western extent of the beneficial placement site

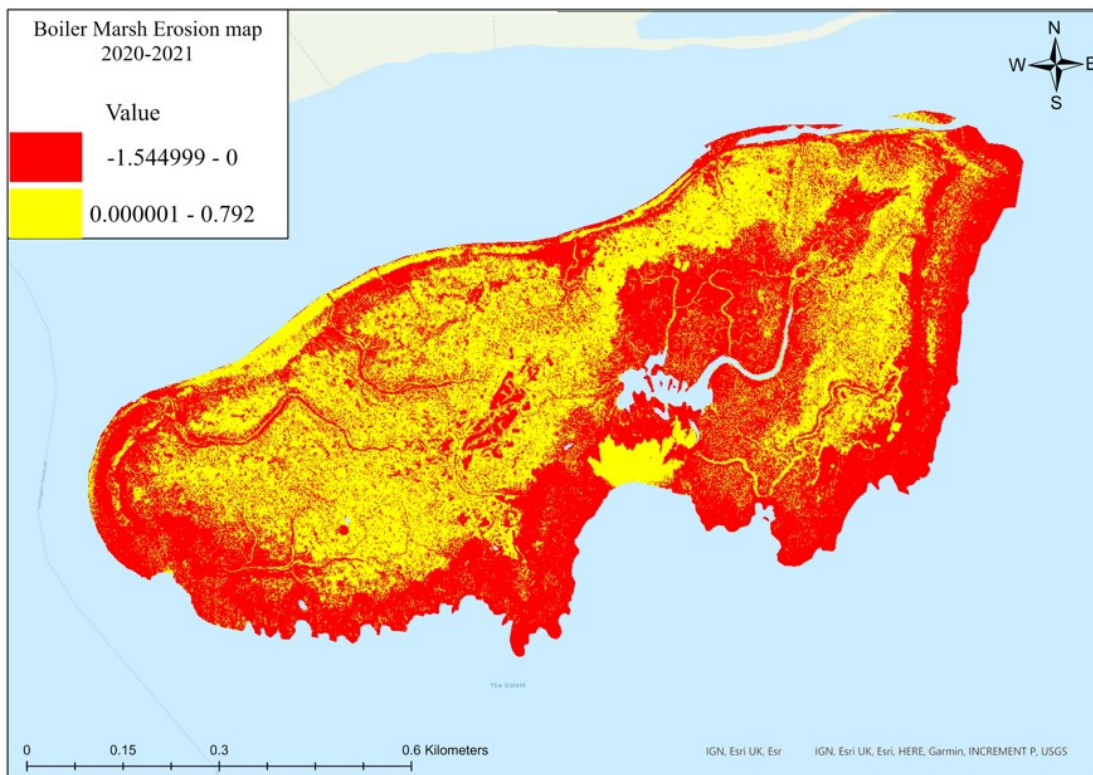
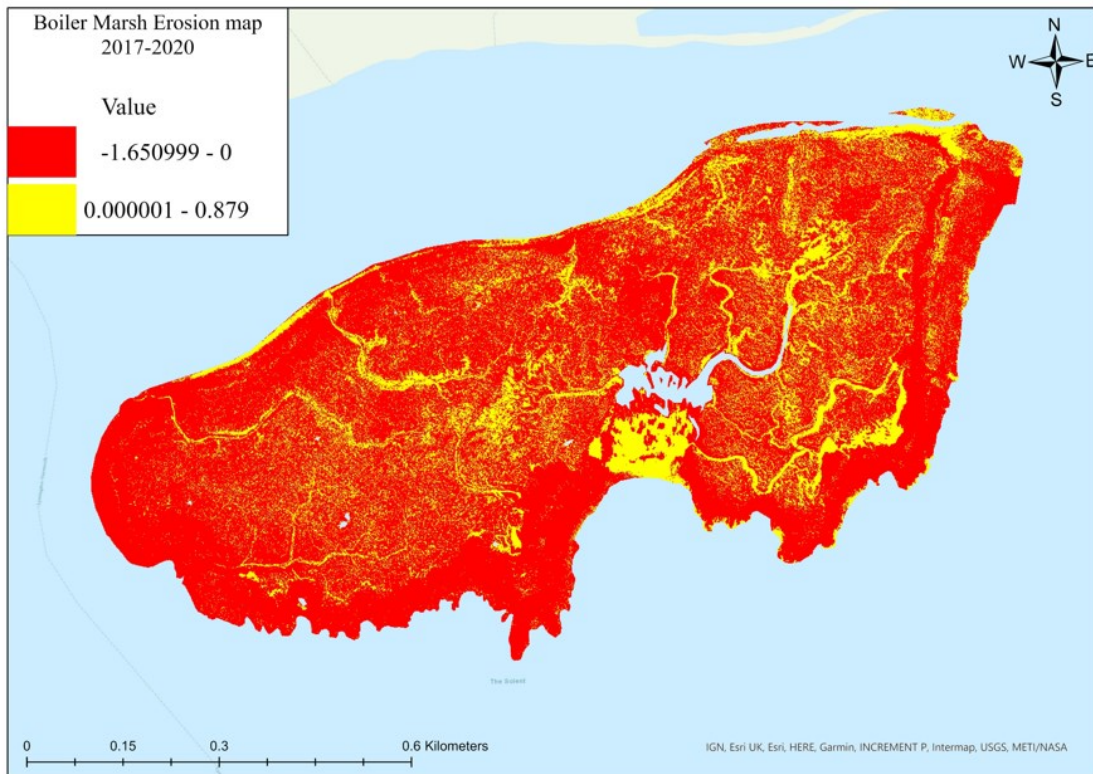


Figure 14: displaying the locations and volumes of erosion (in meters) and accretion in 1m resolution classified by red for erosion and yellow for accretion generated using using (CCO, 2024) data

The areas of erosion and accretion are better shown by the class maps of figure 13 in which it is immediately obvious that there is widespread erosion across the whole marsh between 2017 and 2020 with areas of accretion confined closely to the creek network and crucially, there has been some erosion in parts of the beneficial use placement area as well as in the Wightlink scheme location. 2020 to 2021 displays a far less dramatic picture yet much of the marsh edges are still eroding significantly. It can also be suggested that the accretion in the landward extent of the marsh can be attributed to the landward transgression of the marsh shown by the transects rather than accretion, and there is accretion on the creek network but erosion immediately adjacent to them as well as less erosion from the upper marsh platform.

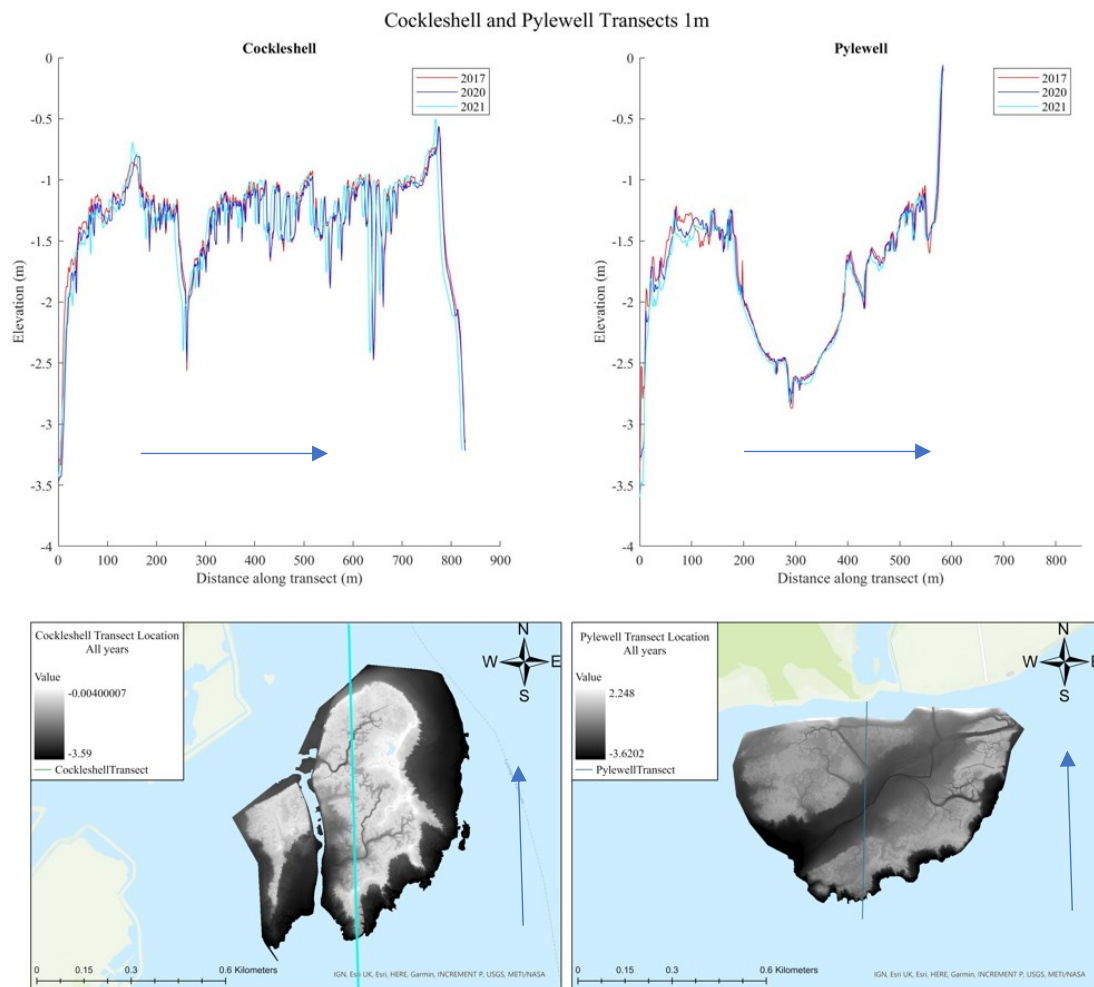


Figure 15: The Cockleshell and Pylewell 1m transects and locations using using (CCO, 2024) data with blue arrows indicating transec direction

Cockleshell and Pylewell behave much like the reference site at boiler marsh and appears to show steady erosion of the marsh as well as infilling of the creek networks throughout the marsh which is notable due to the erosional tendency of creek networks. While the frontal marsh erosion is present, landward transgression of these two marshes appears absent but there is still infilling of the creek networks.

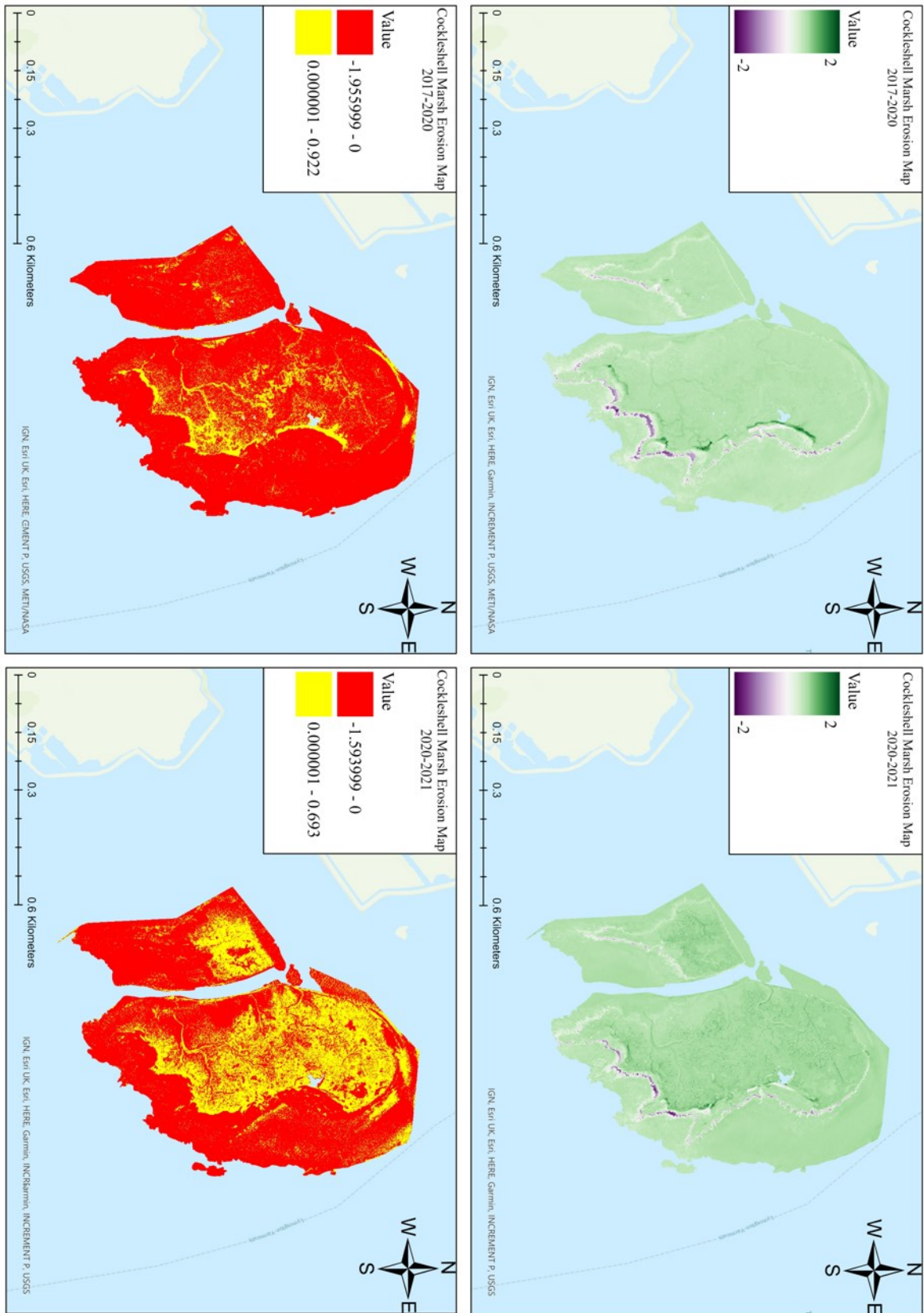


Figure 16: Cockleshell erosion maps by volume (in meters) and by class where red is erosion and yellow is accretion using using (CCO, 2024) data

Cockleshell marsh has significant erosion on its southern edge and some on its eastern extent with areas of significant accretion directly behind the erosion front. Again, much of the accretion is centred on the creek networks and the upper marsh. The erosion in both time periods is extremely pronounced on the seaward extents of the marsh.

The class maps display the true extent of the erosional areas and much like Boiler marsh they are extremely pronounced in the larger of the two timesteps and the lower marsh being subject to erosion at all times.

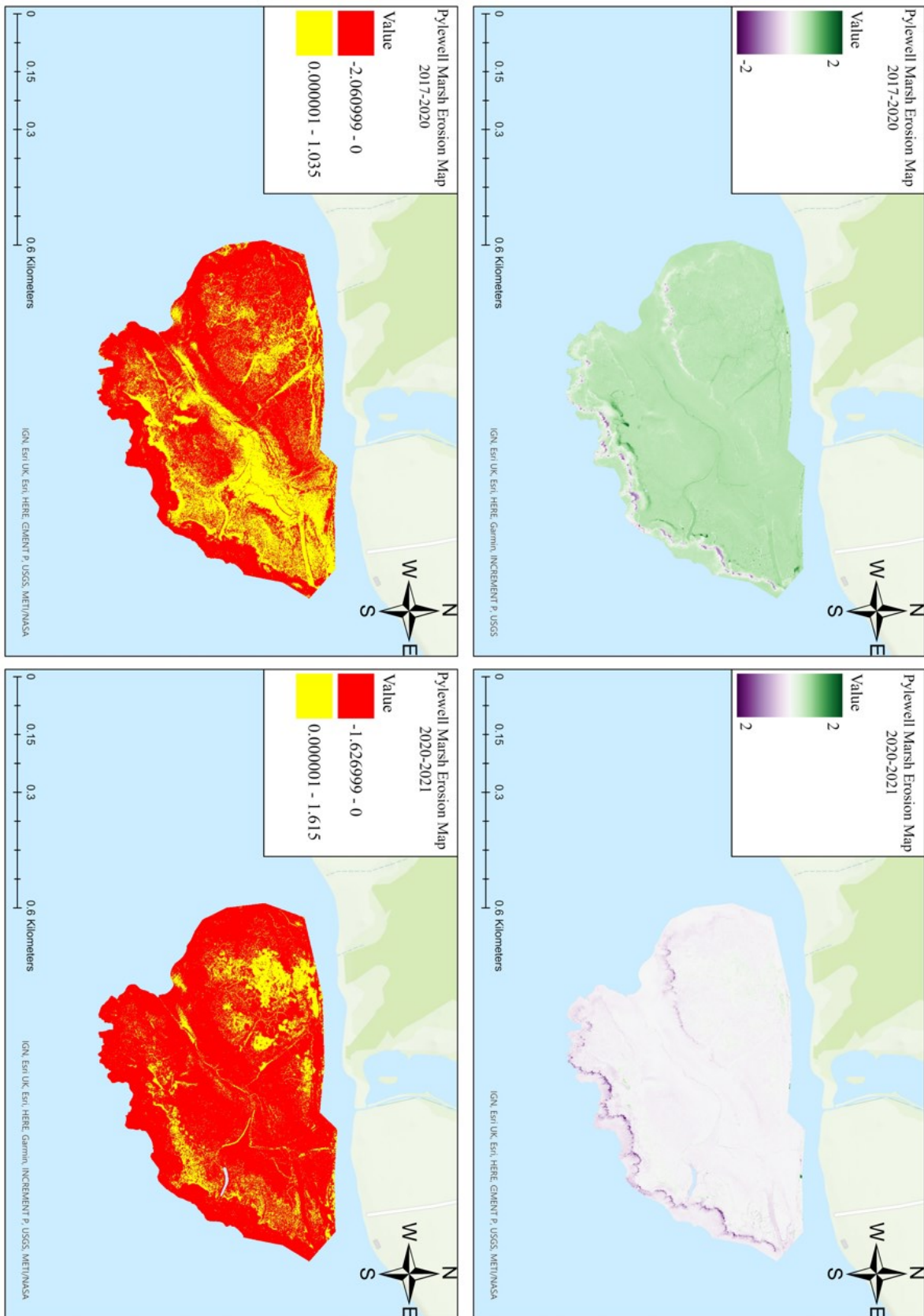


Figure 17: Pylewell erosion maps by volume (in meters) and by class where red is erosion and yellow is accretion from the LiDAR data

Much like Cockleshell and Boiler marshes, there is significant erosion on the seaward extent of the marsh and accretion in the creek systems. However, opposite to Boiler and Cockleshell, Pylewell shows greater accretion in the longer timestep than the shorter which is also mirrored in the total volumes lost in the time periods.

*Table 6: volumes lost from the marsh per LiDAR timestep*

Marsh name and years	Volume change (m <sup>3</sup> )
Boiler 2017-2020	-30,624
Cockleshell 2017-2020	-32,208
Pylewell 2017-2020	-14,964
Boiler 2020-2021	-10,883
Cockleshell 2020-2021	-15,129
Pylewell 2020-2021	-20,559

#### **4.2 Interpolation and Histogram volumes**

*Table 7: The results from the IDW cross validation for both resolutions*

Year	Cell	Mean Error (m <sup>3</sup> ) (3m resolution)	RMSE (m <sup>3</sup> ) (3m resolution)	Mean Error (12m resolution)	RMSE (12m resolution)
2016	1	0.010	0.216	0.043	0.543
2018		0.010	0.269	0.044	0.629
2019		0.009	0.284	0.044	0.649
2021		0.009	0.263	0.036	0.522
2016	2	0.007	0.199	0.039	0.622
2018		0.009	0.241	0.050	0.678
2019		0.007	0.219	0.042	0.677
2021		0.005	0.237	0.040	0.656
2016	5	0.005	0.180	0.023	0.596
2018		0.005	0.198	0.018	0.611
2019		0.005	0.203	0.015	0.602
2021		0.003	0.202	0.022	0.596
2016	8	0.004	0.145	0.010	0.566
2018		0.004	0.179	0.009	0.577
2019		0.004	0.177	0.011	0.577
2021		0.002	0.157	0.009	0.581
2016	12	0.002	0.122	0.003	0.507
2018		0.003	0.185	0.004	0.523
2019		0.002	0.172	0.004	0.508
2021		0.002	0.166	0.004	0.521
2016	16	0.001	0.058	0.003	0.242
2018		0.001	0.066	0.003	0.241
2019		0.001	0.067	0.003	0.239
2021		0.001	0.067	0.003	0.240

The results of the cross validation are consistent with a high level of accuracy for the interpolated values, particularly for the 3m resolution. The cells closest to the seaward boundary have the lowest maximum error values which is consistent with the agreement observed in table 8.

*Table 8: The volume changes calculated with the Histogram and IDW methods at both resolutions.*

Cell	Resolution (m)	Years	Volume (m <sup>3</sup> ) Histogram	Volume (m <sup>3</sup> ) IDW
1	3	2016-2018	23383	-23186
	12		12128	-784
	3	2018-2019	48242	16792
	12		56627	21293
	3	2019-2021	-47940	27465
	12		-69949	8375
2	3	2016-2018	5640	-31192
	12		3141	-14360
	3	2018-2019	-4329	-10496
	12		14250	-23797
	3	2019-2021	-24646	14954
	12		1707	14435
5	3	2016-2018	-4914	-7335
	12		-8183	-8164
	3	2018-2019	-1903	103
	12		-8093	-6536
	3	2019-2021	2721	-7215
	12		6114	3465
8	3	2016-2018	6866	2168
	12		-11111	2115
	3	2018-2019	13335	15679
	12		5300	5500
	3	2019-2021	12571	-37661
	12		19249	-31702
12	3	2016-2018	14050	-18615
	12		-3409	-19124
	3	2018-2019	25388	56267
	12		24397	56720
	3	2019-2021	-27786	-25200
	12		-15708	-24139
16	3	2016-2018	6430	-13447
	12		7984	-11035
	3	2018-2019	118900	125000
	12		43553	112621
	3	2019-2021	-55190	-77770
	12		-22413	-71154

The different methods have a different level of agreement between the resolutions. The methods display different patterns of accretion and erosion per cell. There are more consistent patterns in the two year timestep than the single year and the later years 2019-2020 show a greater accretional pattern compared to the 2016-2018 timestep and the 2018-2019 step favours an accretional pattern with some variation.

*Table 9: named marsh cell volume changes from the LiDAR*

Cell	Resolution (m)	Average volume per year (m <sup>3</sup> )
11	1	-12387
	3	-1145
	12	-83
13	1	-8845
	3	-1098
	12	-29
14	1	-11324
	3	-1218
	12	-77

The cells containing named marshes were analysed using the LiDAR data at the original and the two analysed resolutions. For the volume changes, the original value was used as this was more representative of the marsh activity. The yearly estimated volume however is based upon uneven timesteps due data availability.

*Table 10: volume changes in the cells where there was no bathymetry data*

Cell	Average volume per year (m <sup>3</sup> )
3	-1098
6	-1623
7	-1254
9	-2137
10	-214

The original resolution was used once again for the cells where only Lidar coverage was available. The values were based on an uneven timestep once again, resulting in the small value for Cell 10 which had a greater tendency to flick between erosion and accretion.

*Table 11: the predictions of the marsh frontal and edge erosion and their flux pathways*

Marsh Area	Pathway name	Length of front (m)	Erosion rate (unit)	Volume per year (m <sup>3</sup> )
Boiler Marsh (South)	Q35	1340	1.6	2144
<u>Pylewell</u> Marsh (South)	Q34	801	1.84	1473
Cockleshell Marsh (South)	Q36	890	1.77	1575
Boiler Marsh (East)	Q11	490	1.6	748
<u>Pylewell</u> Marsh (East)	Q34	390	1.84	717
Cockleshell Marsh (East)	Q40	490	1.77	867
Boiler Marsh (West)	Q41	341	1.6	545.6

These predictions were based on a 1m wide erosion front and fell below the predictions of (Serato de Castro Silva, 2014). Likely because they were based upon a single width of erosion front when it has been shown above to be variable across the marsh front.

*Table 12: The predictions of the shoreline erosion value with data taken from the NCERM 2018 dataset*

Cell Boundary	Pathway name	Boundary Length (m)	Erosion rate (m/yr)	Volume per year (m <sup>3</sup> )
6	Q37	460	0.2	92
9	Q14	204		40.8
10	Q13	956		191.2
14	Q38	1046		209.2

The values are much larger than those used by (Serato de Castro Silva, 2014) by an order of magnitude. As these were the most up to date values available. There may be an issue with the estimates in the previous budget as these values should not have changed so significantly in the 2 years between the end of the last budget and the start of this one as the previous values were almost undetectable.

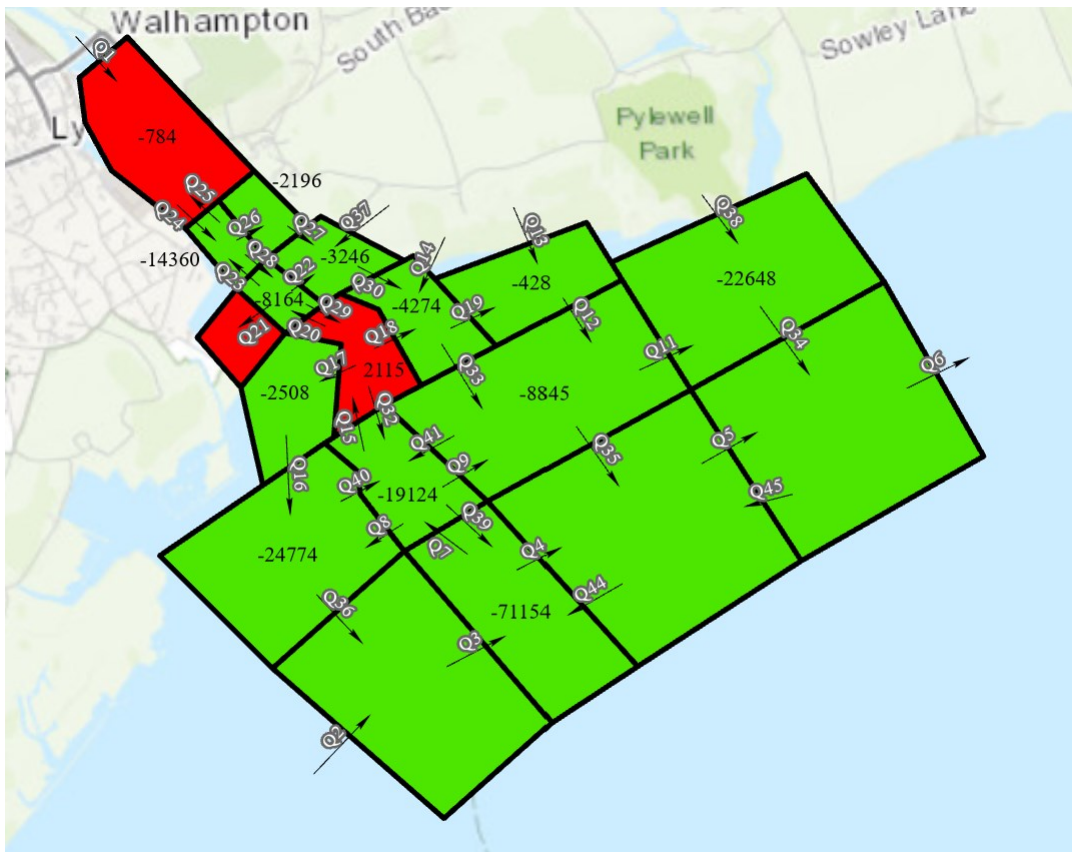


Figure 17: Alternative 1A unbalanced

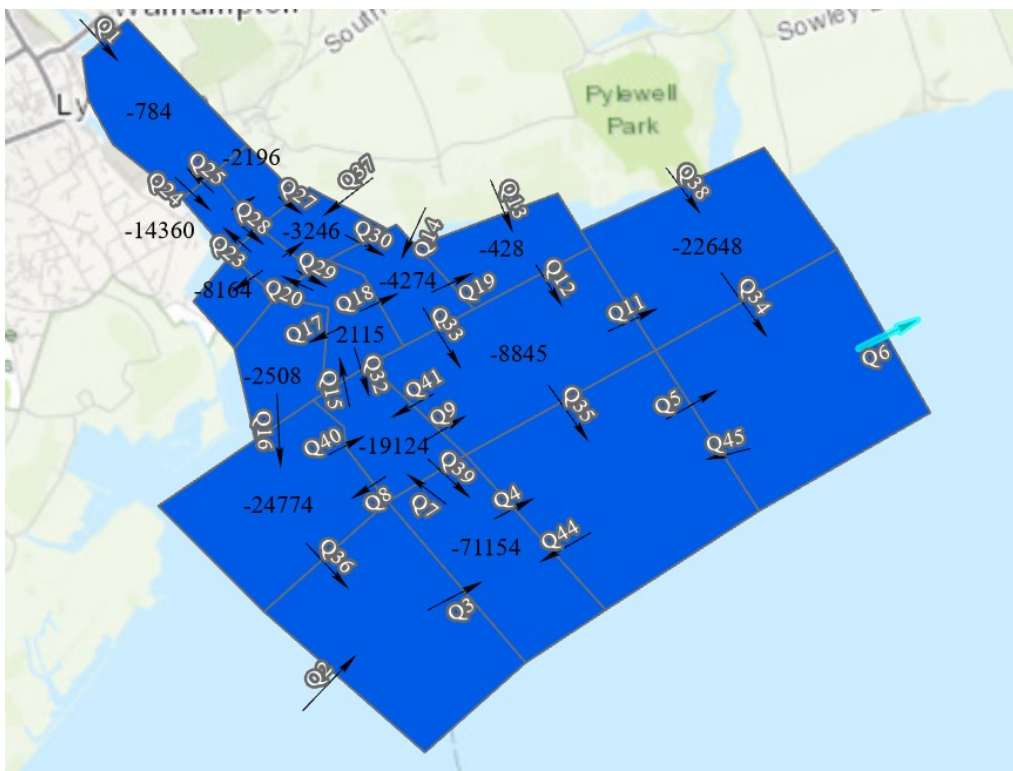


Figure 18: Alternative 1A fully balanced

The sediment budgets for most alternatives were able to be fully balanced for a sensible export volume for the size of the system and are similar to that predicted by the last budget.

*Table 13: Alternatives and their respective export volumes when fully balanced or for 1&2B and 1E, as close to balanced as possible.*

Alternative name	Export Volume m <sup>3</sup>
1A	173161.4
2A	131217.4
1B	-155082.8
2B	-114385.8
1C	161412.4
2C	203550.4
1D	44856.4
1E	-125466.8
1F	92497.4

Alternatives 1B, 2B and 1E were not able to be balanced with the single year timestep displaying a consistent and significant deficit similar between the interpolation and histogram methods. The export volumes are smaller for the Histogram method and are more consistent with the later estimate for 2012 – 2014 from the last budget where as the IDW methods are more consistent with the earlier budget years. This is including the placement of sediment which does not have appeared to have significantly altered the export volumes therefore is likely retained in the system.

## **5 Discussion**

### **5.1 Histogram vs IDW**

Serato de Castro Silva, 2014 suggested more investigation into the accuracy of interpolation methods and Histogram analysis methods which has been conducted as in table 8. The differences between the histogram values and the interpolation values in cell 12 mirror the disagreements observed by (Serato de Castro Silva, 2014). However, to assess whether this was down to the methods or the cell selection, both methods were applied to all cells in the

main channel. There is no pattern of agreement between the two estimates at all 6 cells of the navigation channel for every year and for both resolutions. However, the histogram method is consistently smaller than the IDW method. Therefore, I suggest a reanalysis of the data for a more detailed comparison of the two methods and their outputs.

## 5.2 Resolution

The resolution tests between the Histogram and the IDW displayed different levels of agreement at different points of the navigation channel. The IDW analysis showed a much higher level of agreement in the seaward extent of the navigation channel between the two estimates, likely where the interpolation method uses a model to predict data and there is less small scale variation due to the general trend of import of sediment into the wider system and its larger geographical area, they are also likely to be more energetic due to the lack of meanders and the proximity to the rest of the Solent and the lack of defences in the lower estuary. The histogram method however displays more agreement in the upper estuary, perhaps due to the use of real data as opposed to that of predictions from a model (esri, n.d a) and the trends generally for greater accretion in the first two cells of the estuary. Therefore, there is a trade-off to be made in the resolution of datasets collected for more accuracy for a macro and micro budget analysis. From the results presented in table 8 a histogram analysis is more suitable for a micro budget where the resolutions in the upper estuary have high levels of agreement and IDW is more suitable for a macro budget on a larger scale where there is a higher level of agreement in the larger seaward cells and shows agreement for a larger number of cells. Interpolation analysis remains a popular option for sediment budgets with an excellent example being (Serrata et al, 2010) where a TIN was applied for a reasonable estimate. Therefore, the budgets were predominantly balanced using the IDW values at the 12m resolution as suggested by (Roberts and Brooks, 2018). Therefore I propose additional analysis of the two methods with future datasets.

### 5.3 Comparison to the last budget

The export volumes of alternatives 1A of 173,161 m<sup>3</sup> and 1C of 161,412.4 m<sup>3</sup> are comparable to the volumes established by Serato de Castro Silva, (2014) as they lie between their estimates of 108,363 m<sup>3</sup> and 79,375 m<sup>3</sup> per year as they are 86,883.7 m<sup>3</sup> and 80,706.2 m<sup>3</sup> respectively. However, these are IDW values where Serato de Castro Silva, (2014) used the histogram method. Using the histogram methods alternatives 1D and 1F remain comparable to Serato de Castro Silva, (2014) where the 22,428.2 m<sup>3</sup> of alternative 1D falls just shy of their 22,909 m<sup>3</sup> between 2012 and 2014. The 46,248.7 m<sup>3</sup> of alternative 1F falls between that of Serato de Castro Silva's 79,375 m<sup>3</sup> and 22,909 m<sup>3</sup>. However, despite this, these estimates fall short of those predicted prior to the previous analysis of 154,000 m<sup>3</sup>/year (Ke and Collins, 2002) and 130,000 to 115,000 m<sup>3</sup>/year. The Histogram estimates lie well below the estimated 38,000 m<sup>3</sup>/year Ke and Collins estimated to come from saltmarsh erosion alone.

While the initial volumes are comparable, the volumes where there is a lack of dredging, show some contradiction. The difference between alternatives 1C and 2C was 42,138 m<sup>3</sup> equating to an additional export of 21,069 m<sup>3</sup>/year which is slightly less than the dredging volumes per year for that period. The unbalanced alternatives 1B and 2B display a difference of 40,697m<sup>3</sup> which is significantly higher than the dredged volume per year for this period, but this alternative remains unbalanced. However, the difference between 1A and 2A is -41,944 m<sup>3</sup> suggesting a deficit of 20,972 m<sup>3</sup>/year for that period compared to when dredging is occurring. This only partially supports the suggestion by Serato de Castro Silva, (2014) that the dredging creates an influx of sediment to the estuary and would need further investigation through more years of budget analysis.

There was a total of three alternatives that were not able to be balanced which were alternatives 1B, 2B and 1E, each with a deficit per year ranging from -114,385.8 to -

155,082.8 m<sup>3</sup>. The one thing in common with these timesteps is that they are all the single year timestep. Prior to this budget there has only been two-year steps formally investigated which have all resulted in comparable budgets, but the single year budget is consistently in deficit. This suggests that there is further investigation needed on smaller timesteps as this may suggest that there are cycles of erosion and accretion that may not be accounted for in the larger timestep. This was not able to be further investigated due to gaps in the data provided by the LHC.

The placement volumes do not appear to have significantly altered the sediment budget and appears to remain in the system.

The erosion of the Saltmarsh was likely underestimated in this study as the width of the erosional front was taken as 1m when it has been shown to vary between 1.3m up to 8m in a single area and therefore the export of sediment from the system could be higher. The littoral drift may also have been underestimated as both the CERC and the Kamphuis 2002 formula generated much more significant estimates than that used. (CERC, 1998), (Shanas and Sanil Kumar, 2014)

CERC estimated 650325 m<sup>3</sup>/year for the 4km of coastline and Kamphuis predicted 2411360 m<sup>3</sup>/year for the 4km of coastline. These estimates are based upon a sandy coastline rather than a mixed, predominantly muddy coastline and therefore are not representative of the actual values of littoral drift for this area as it is stated to not be an important process in this stretch of the Solent (NFDC, 2017)

#### **5.4 Impacts on the marshes**

There is evidence for some landward transgression of the marshes, however the shape and magnitude of this change is strange as the marsh appears to have transgressed landward by around 10m while maintaining its shape which is highly unusual. This could hint some issues

with the registration of this area of the dataset as much of the dataset is similar with changes of around 4m at the reference site over the three-year timestep. The shape at the front of the marsh has eroded significantly in beneficial site 3 losing 12m in the 3-year timestep equating to a loss of 4m a year and losing 6m in the single year. Whereas at the reference site lost 4m in the 3-year timestep equating to 1.3m a year and 8m in the single year timestep. This greatly varies between sites at the marsh and is only partially consistent with the estimates made by (Pontee, 2004), (Ke and Collins 2002) and (NFDC, 2007). One suggestion for this could be an increase in storminess. Though few studies have been conducted into the combined impacts of increased storminess and sea level rise on saltmarshes, there is evidence to suggest that saltmarsh stability may be impacted by rising sea level (Pannoazzo et al., 2021). In the UK and Ireland between 2015 to 2023, there was 11, 5, 10, 8, 7, 7, 7 and named storms with 10 in 2024 at the time of writing (Met Office, 2019). Leonardi et al., 2018 further suggest that impacts in the saltmarshes are more complex due to the increased potential for sediment deposition linked to storm intensity, stating instead that storm frequency is a more important factor for long term accretion. The cheniers elsewhere in the Solent have been linked to increased scour and erosion (Quaresma et al., 2007). From the LiDAR analysis there are areas of accretion behind the cheniers where the chenier is migrating landward with the marsh erosion. There is some evidence to suggest they are present in the transects but the satellite imagery and erosion maps present clear evidence for their existence. However, the trends of storms in the area would benefit from further analysis to better link the changes in erosion patterns linked to the cheniers as the patten in named storms does not present any definitive evidence to suggest an increase in storminess during the study period.

The LiDAR also presents an area of Pylewell marsh where there is an erosion front and a lack of chenier. the LiDAR is also a Digital Terrain model which eliminates the Marsh canopy as a source of error. This area is more impacted by the state of the tide due to the lack of sandy

sediment supply accreting on the more seaward extent of the marsh. (Neumann, 2014) conducted analysis on the hydrodynamics of the Lymington estuary which identified two types of tide in the inner and outer estuary. In the inner estuary it was shown to be a standing tide which would explain the general pattern of accretion in the marinas requiring dredging and offers a potential explanation for how the saltmarshes were initially formed as they favour a standing tide (Neumann, 2014). However, further out it was shown to be a progressive tide which favours the erosion of the marshes and explains the erosion of the seaward extents of the marsh with and without the cheniers (Neumann, 2014). It was also stated that sea level rise pushes the trend for a progressive tide further into the estuary which would require more long-term monitoring to establish the impacts upon the saltmarshes in the future. The increasing sea-level, movement of the progressive tides and the potential for increased storminess presents a dim future for the marshes requiring more extensive LiDAR analysis to assess the damage.

## **6 Conclusions**

The volumetric estimates showed a large difference between the analysis method, however, the trends remained largely the same and also remained comparable to the previous sediment budget. The IDW analysis method showed cross validation statistics consistent with a high level of confidence, particularly with the 3m resolution dataset. Despite this, more comparison between the two methods is required.

The budgets remain comparable to the previous budgets despite the changes in the system, but further monitoring will be required when the new projects are approved later in 2024.

There is significant variation in the marsh structure in the available LiDAR data showing large variations in the rates of erosion, particularly at the beneficial placement site requiring more extensive monitoring for more accurate assessment of marsh state.

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## Appendix

### Code blocks

Resolution tests

```
clear all
ben= readtable("Ben5mres.csv")

ben = table2array(ben)

b1_2017 = ben(:,[1 2]);
b2_2017 = ben(:,[3 4]);
b3_2017 = ben(:,[5 6]);
b1_2020 = ben(:,[8 9]);
b2_2020 = ben(:,[10 11]);
b3_2020 = ben(:,[12 13]);
b1_2021 = ben(:,[15 16]);
b2_2021 = ben(:,[17 18]);
b3_2021 = ben(:,[19 20]);

ref = readtable("Ref5mres.csv");
ref = table2array(ref);

ref2017 = ref(:,[1 2]);
ref2020 = ref(:,[3 4]);
ref2021 = ref(:,[5 6]);

figure()
hold on
ax=gca;
ax.FontName = 'Times New Roman';
sgt = sgttitle('Boiler Marsh, beneficial use site and reference site transects 5m
resolution');
sgt.FontName = 'Times New Roman';
subplot(2,2,1)
hold on
t1 = title('Beneficial use site 1')
t1.FontName = 'Times New Roman';
ax1=gca;
ax1.FontName = 'Times New Roman';
plot(b1_2017(:,1),b1_2017(:,2),'r')
hold on
plot(b1_2020(:,1),b1_2020(:,2),'b')
hold on
plot(b1_2021(:,1),b1_2021(:,2),'c')
hold on
ylim([-4 -0.5])
xlim([0 600])
xlabel('Distance along transect (m)')
ylabel('Elevation (m)')
legend('2017','2020','2021','Location','southeast')
```

```

subplot(2,2,2)
hold on
t2 = title('Beneficial use site 2')
t2.FontName = 'Times New Roman';
ax2=gca;
ax2.FontName = 'Times New Roman';
plot(b2_2017(:,1),b2_2017(:,2), 'r')
hold on
plot(b2_2020(:,1),b2_2020(:,2), 'b')
hold on
plot(b2_2021(:,1),b2_2021(:,2), 'c')
hold on
ylim([-4 -0.5])
xlim([0 600])
xlabel('Distance along transect (m)')
ylabel('Elevation (m)')
legend('2017', '2020', '2021', 'Location', 'southeast')
subplot(2,2,3)
hold on
t3 = title('Beneficial use site 3')
t3.FontName = 'Times New Roman';
ax3=gca;
ax3.FontName = 'Times New Roman';
plot(b3_2017(:,1),b3_2017(:,2), 'r')
hold on
plot(b3_2020(:,1),b3_2020(:,2), 'b')
hold on
plot(b3_2021(:,1),b3_2021(:,2), 'c')
hold on
ylim([-4 -0.5])
xlim([0 600])
xlabel('Distance along transect (m)')
ylabel('Elevation (m)')
legend('2017', '2020', '2021', 'Location', 'southeast')
subplot(2,2,4)
hold on
t4 = title('Reference Site')
t4.FontName = 'Times New Roman';
ax4=gca;
ax4.FontName = 'Times New Roman';
plot(ref2017(:,1),ref2017(:,2), 'r')
hold on
plot(ref2020(:,1),ref2020(:,2), 'b')
hold on
plot(ref2021(:,1),ref2021(:,2), 'c')
hold on
ylim([-4 -0.5])
xlim([0 600])
xlabel('Distance along transect (m)')
ylabel('Elevation (m)')
legend('2017', '2020', '2021', 'Location', 'southeast')

```

Histogram generation

```

clear all
% Create a sample table
T = readtable("ArcGIS export name.txt");

```

```

% Set values greater than the threshold to NaN in column ' Table Variable Name'
threshold1 = minimum depth value;
logical_index = T.Table Variable Name < threshold1;
T. Table Variable Name (logical_index) = NaN;

%Display the table output to verify

disp(T);

threshold2 = maximum depth value;
logical_index = T. Table Variable Name > threshold2;
T. Table Variable Name (logical_index) = NaN;

disp(T);

% Write the new output table with the desired export name and export for reimport
to ArcGIS for histogram analysis

writetable(T,'Nan New ArcGIS input for histogram name','Delimiter',' ')
type('Nan New ArcGIS input for histogram name.txt')

```

Excel commands

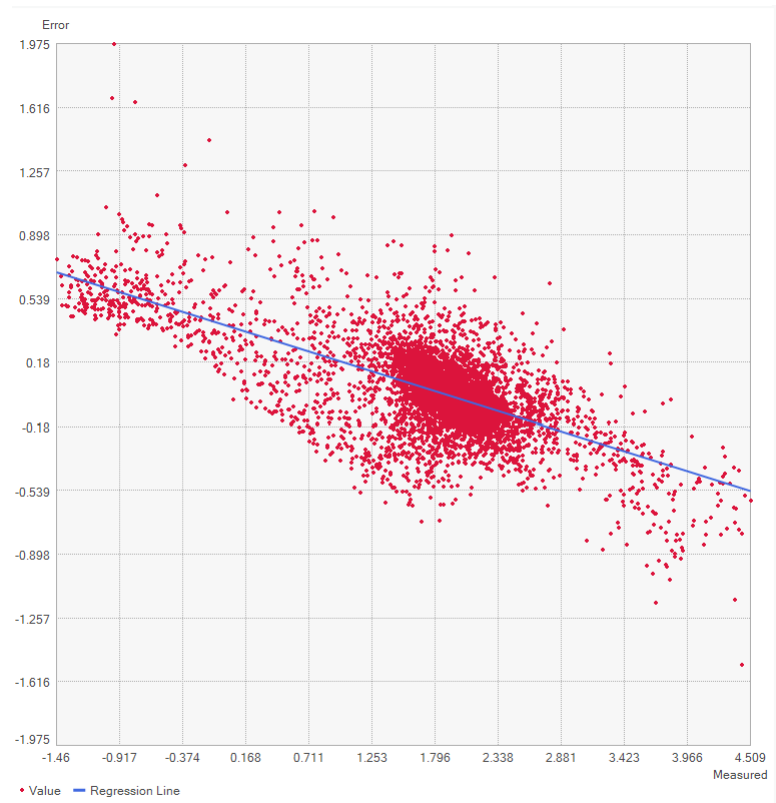
= (Cell with class count / total cell count) \* (Minimum class boundary + half the class width value)

= (SUM(Column containing  $NF_{d1,yr1}$ ) - (SUM(column containing  $NF_{d2,yr2}$ ))

= cell containing the total change \* Cell area

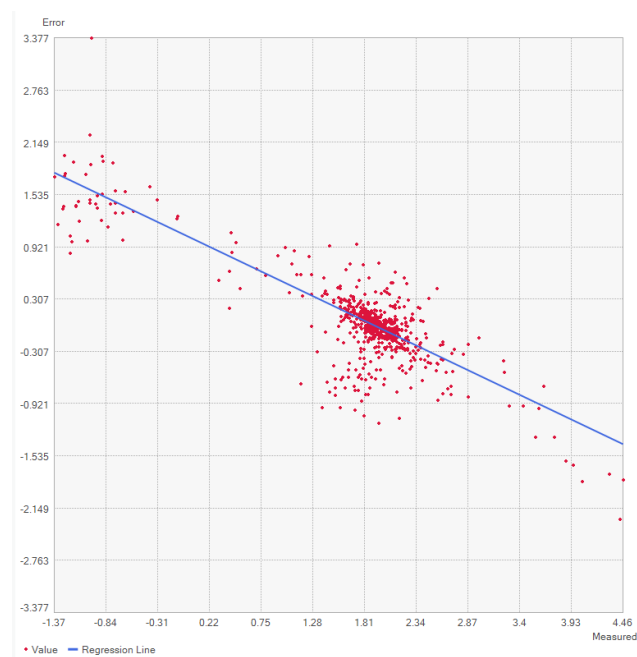
## IDW Cross validation

Cell 1 – 2016 3m



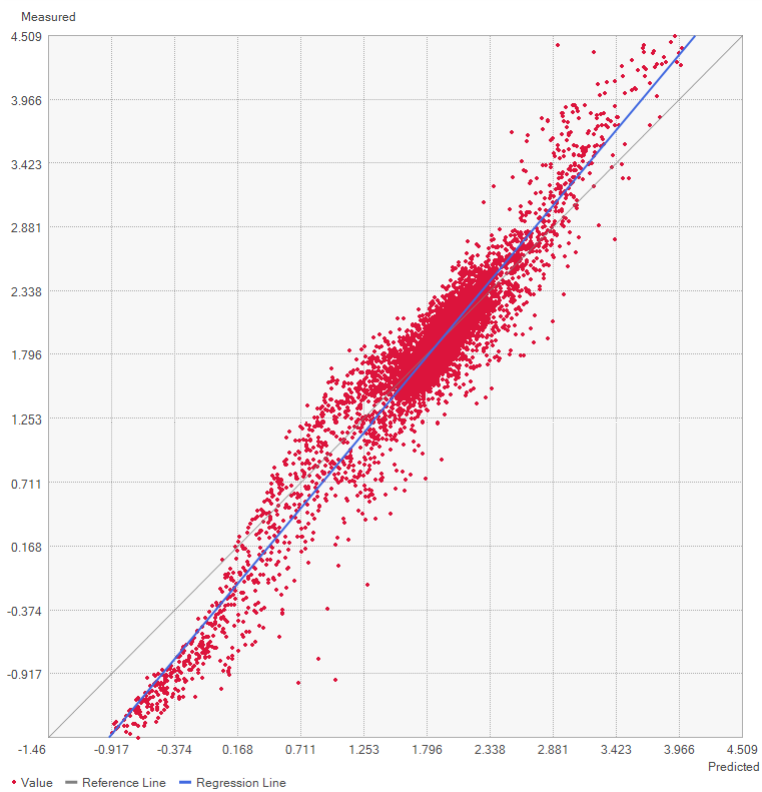
Regression function:  $-0.20563340541126 * x + 0.38629355172885$

Cell 1 – 2016 12m



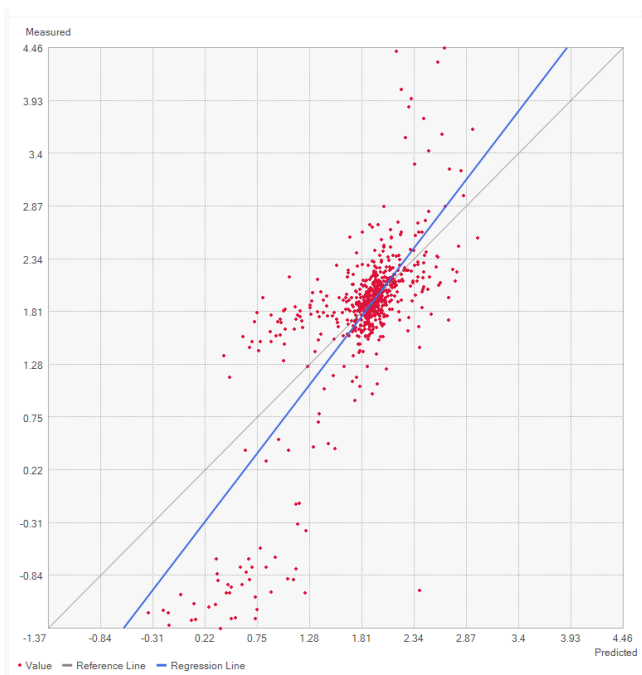
Regression function:  $-0.547178012716952 * x + 1.042792238143$

## C1 – 2016 3m



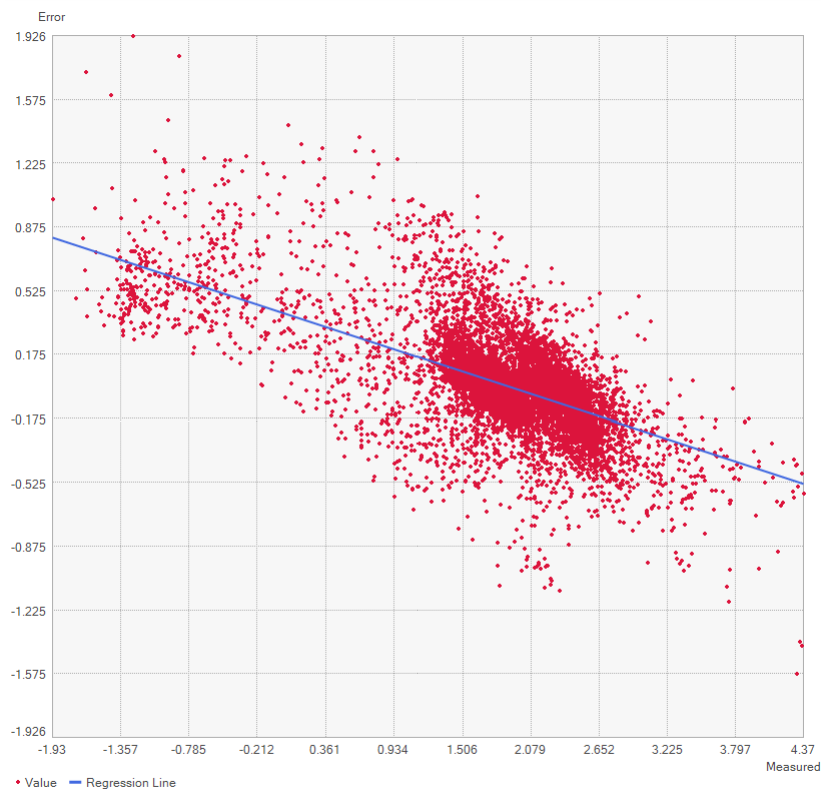
Regression function:  $1.18379727939898 * x + -0.34666746064181$

## C1 – 2016 12m



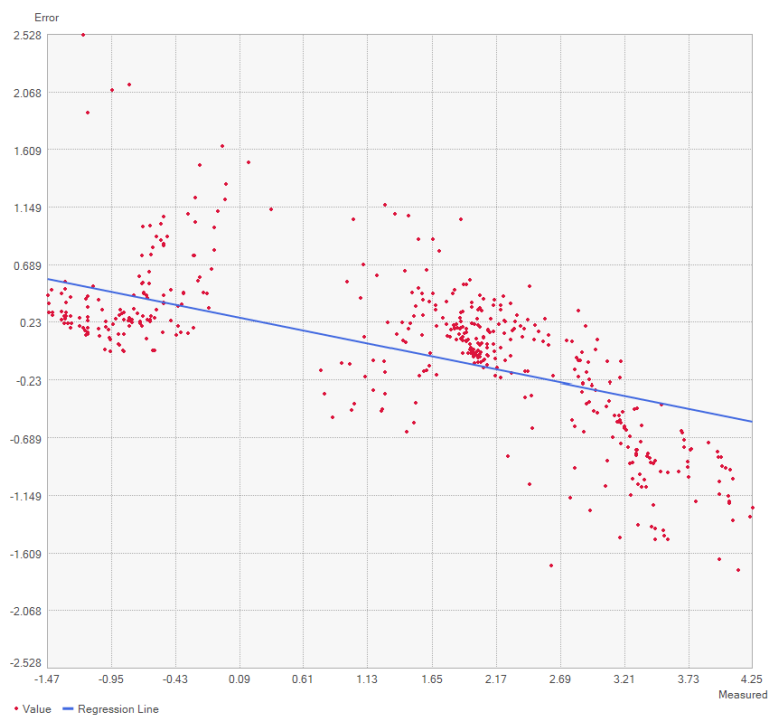
Regression function:  $1.29624262314277 * x + -0.58218957344958$

### C1 – 2018 3m



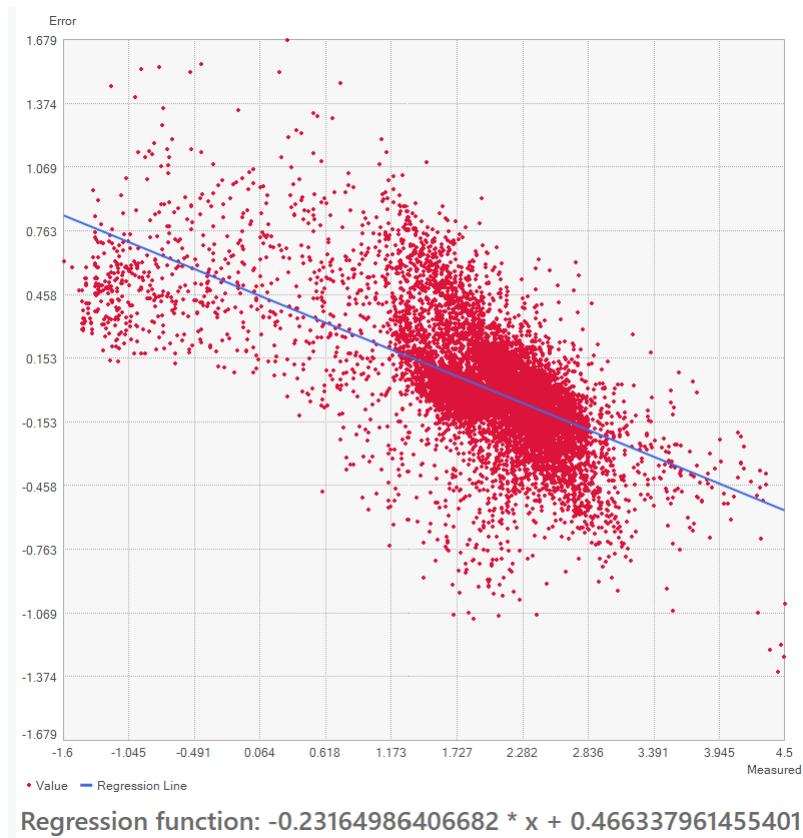
Regression function:  $-0.213897201037092 * x + 0.402801315169082$

### C1 – 2018 12m

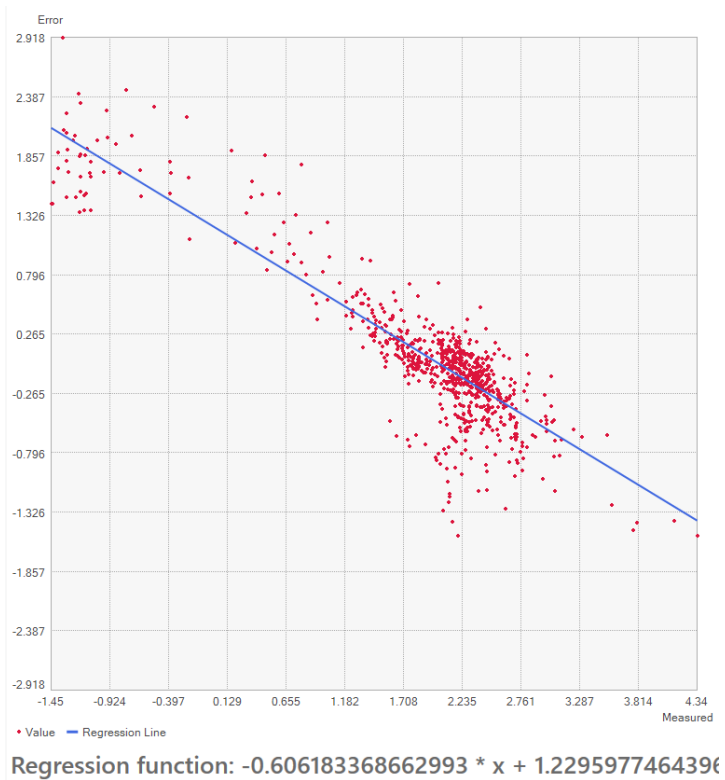


Regression function:  $-0.198052561256992 * x + 0.283437163504026$

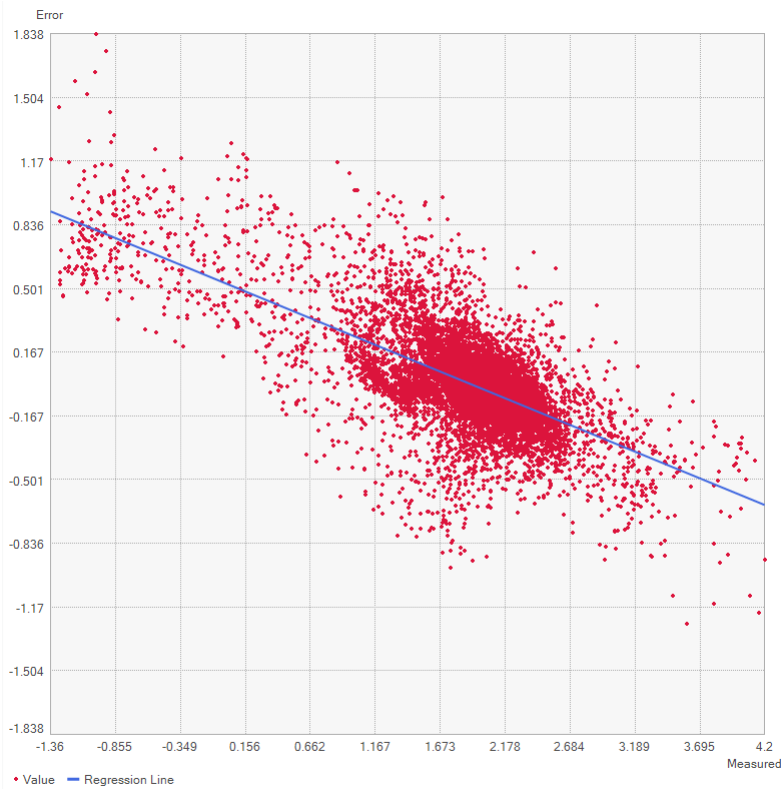
### C1 – 2019 3m



### C1 – 2019 12m

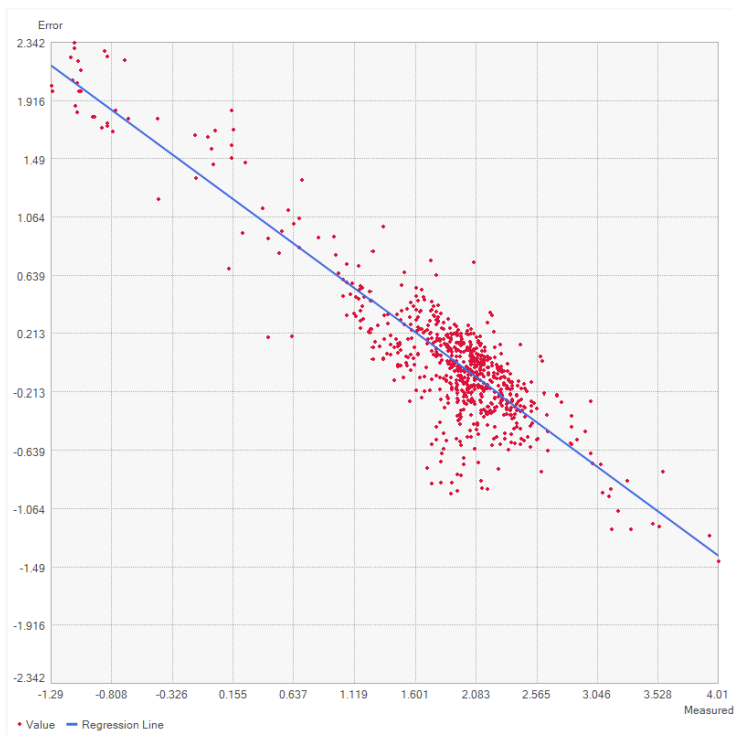


### C1 2021 – 3m



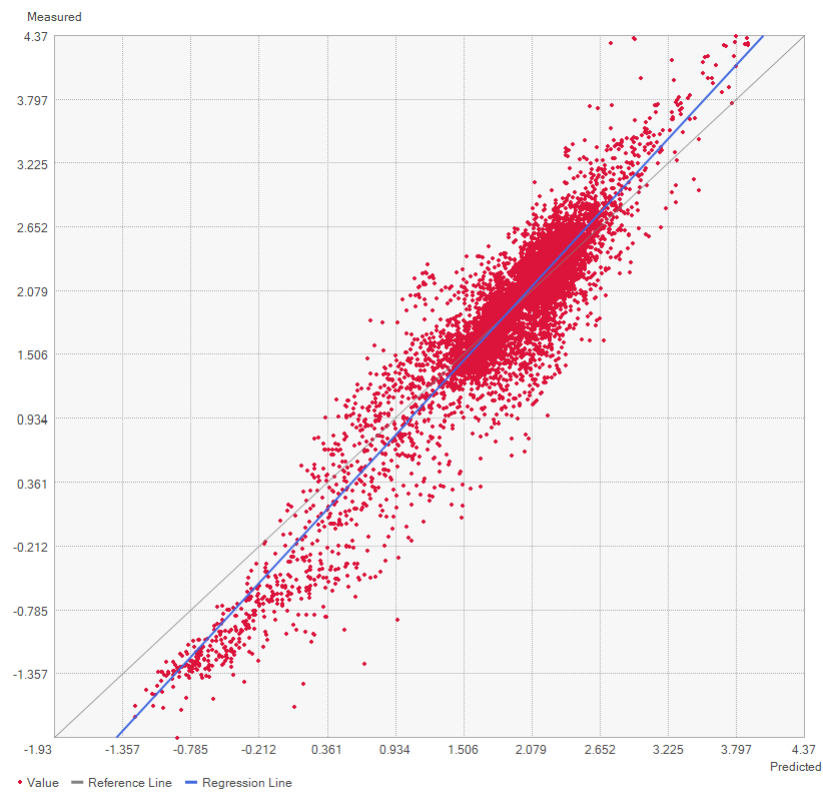
Regression function:  $-0.276941690766127 * x + 0.52925051586039$

### C1 – 2021 12m



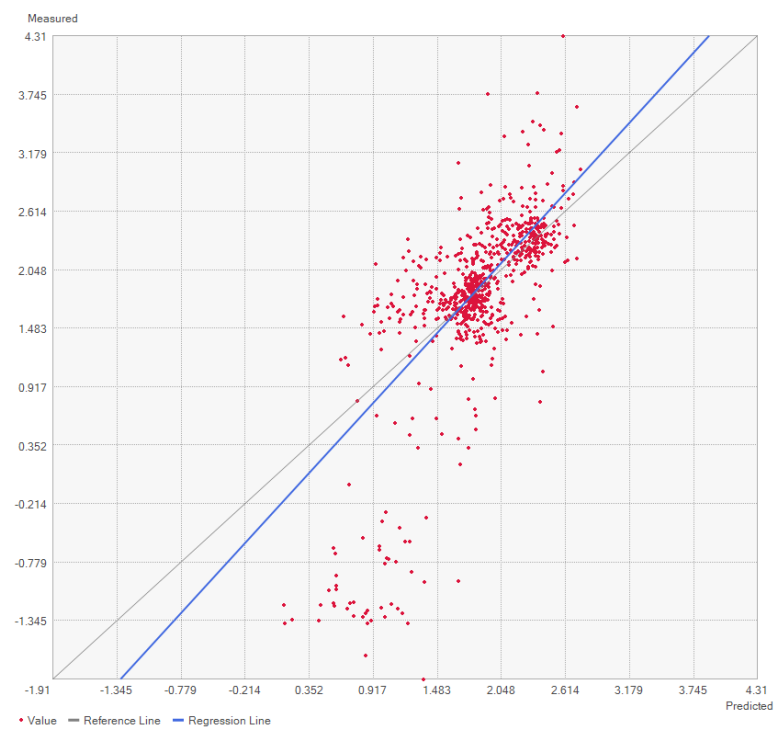
Regression function:  $-0.675158871685401 * x + 1.30117796072591$

## C1 – 2018 3m



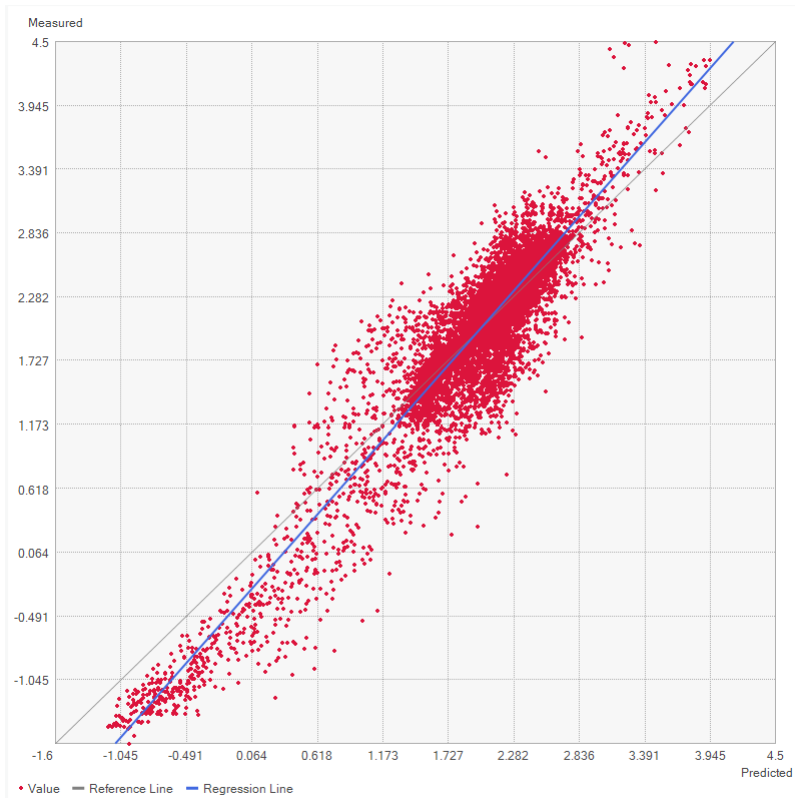
Regression function:  $1.15939438225609 * x + -0.295158101239735$

## C1 – 2018 12m



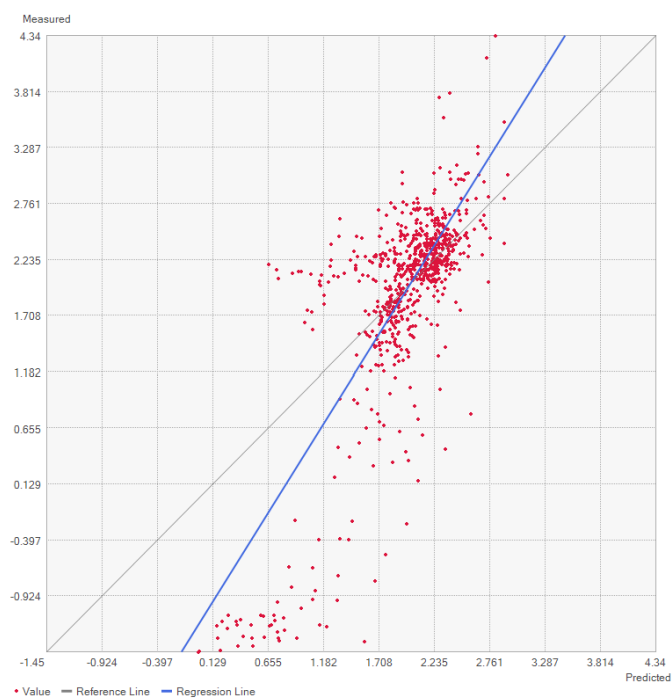
Regression function:  $1.19707389507126 * x + -0.339000783921252$

## C1 – 2019 3m



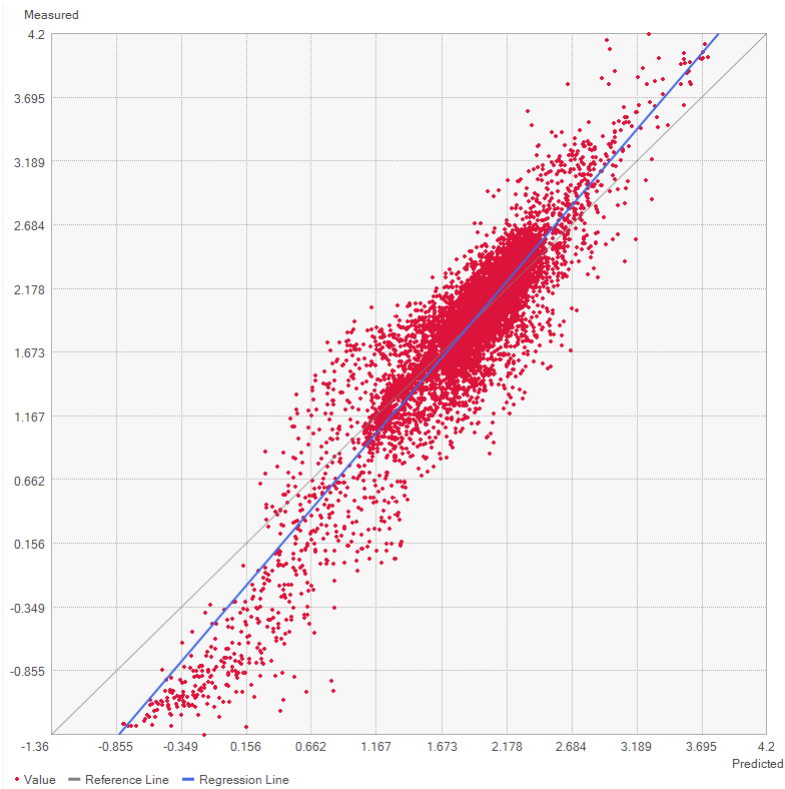
Regression function:  $1.16457605869878 * x + -0.326158559500077$

## C1 – 2019 12m



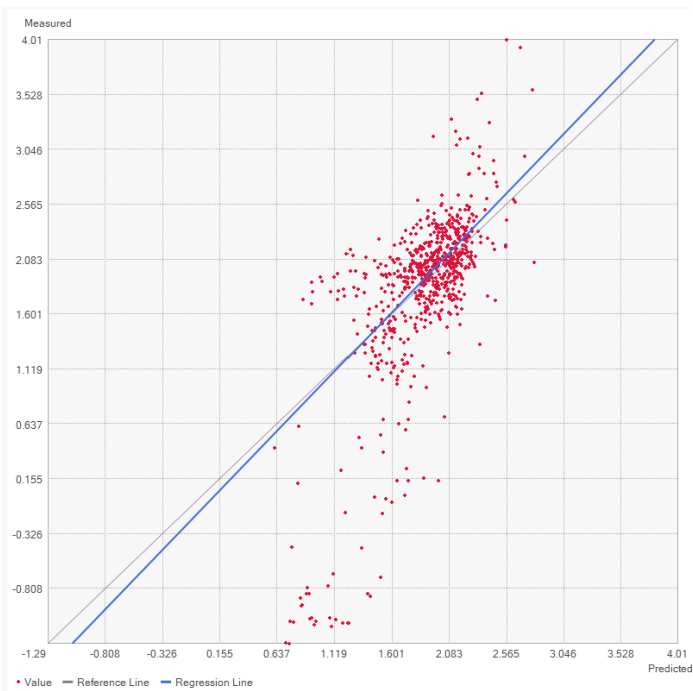
Regression function:  $1.58811543527571 * x + -1.1805411821523$

### C1 – 2021 3m



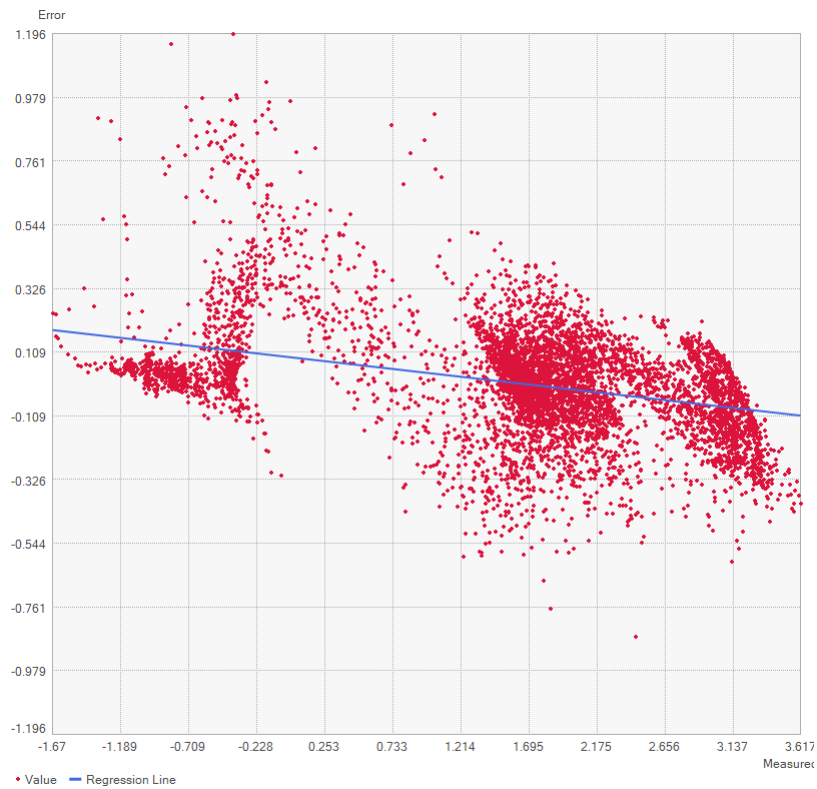
Regression function:  $1.19267553861401 * x + -0.363827881502567$

### C1 – 2021 12m



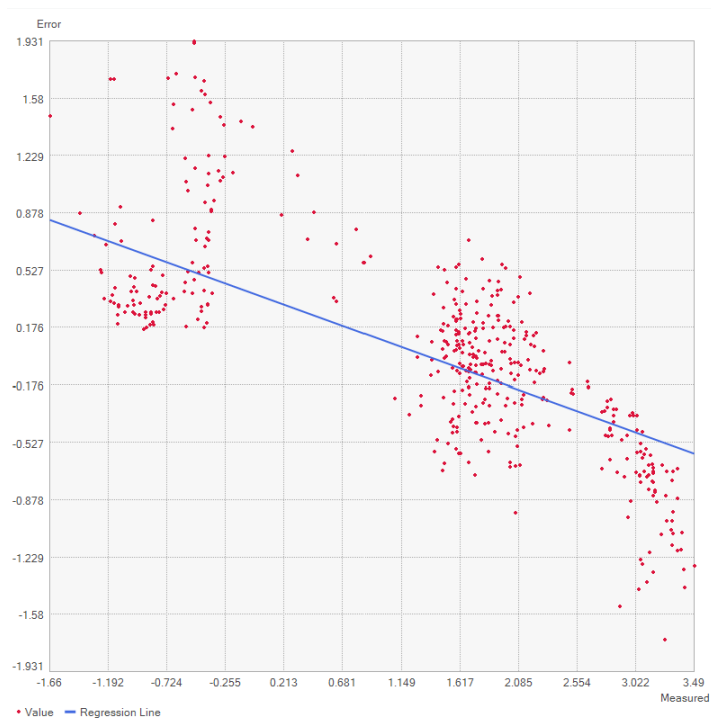
Regression function:  $1.08154630245314 * x + -0.115783633667279$

## C2 – 2016 3m



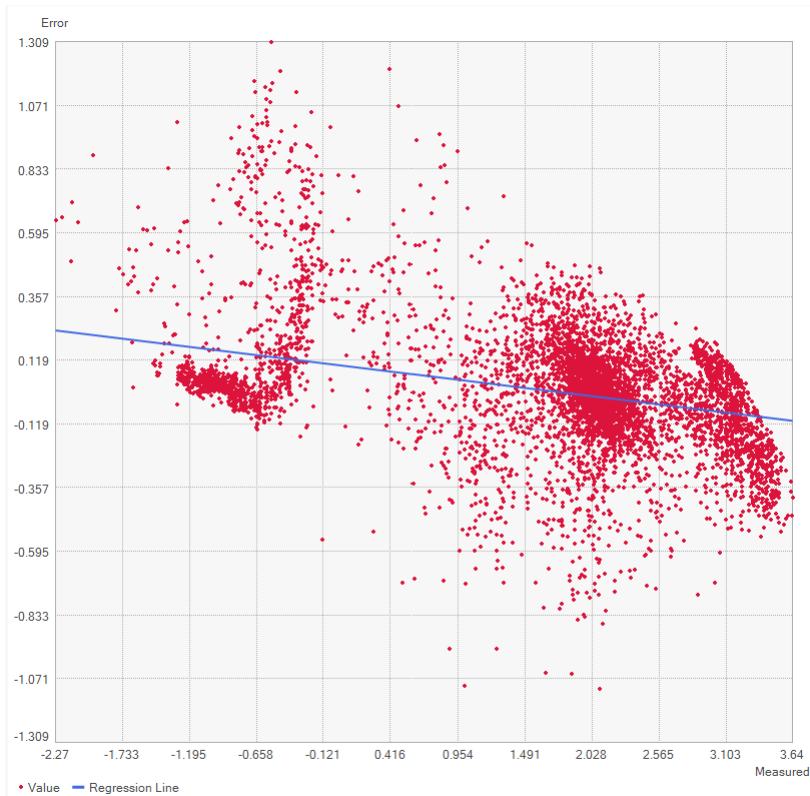
Regression function:  $-0.055238713169829 * x + 0.0921896599101189$

## C2 – 2016 12m



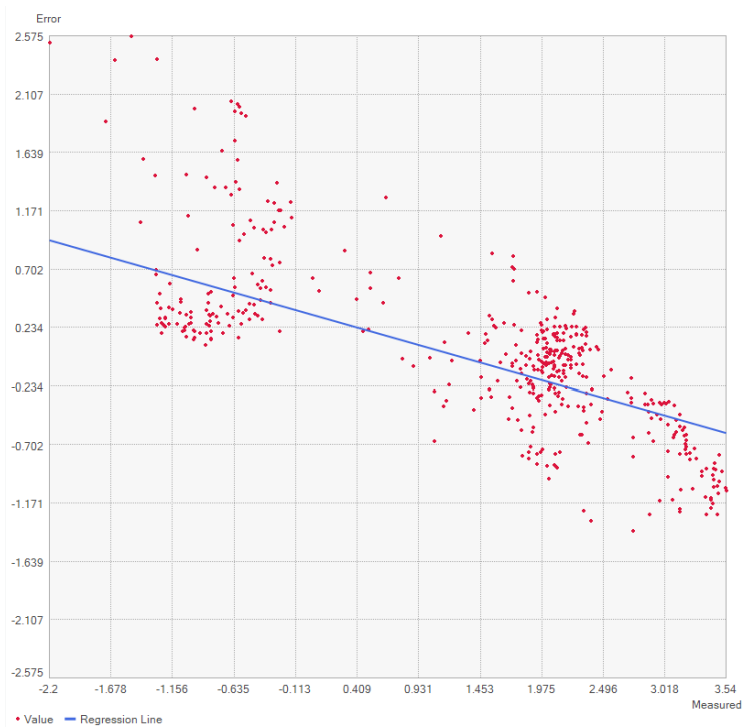
Regression function:  $-0.277321443363753 * x + 0.37350048009940$

## C2 – 2018 3m



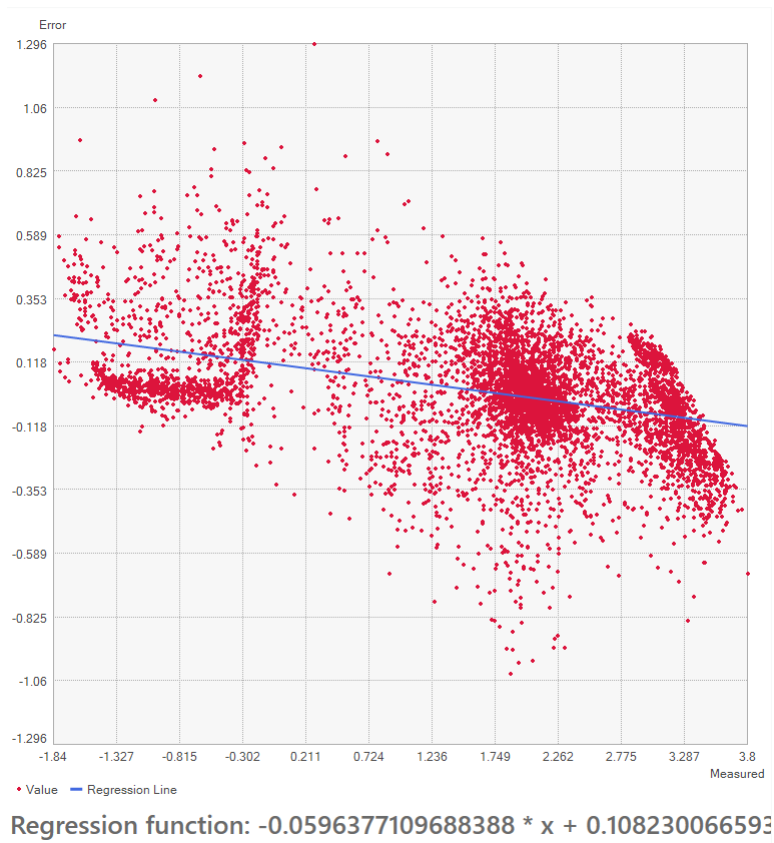
Regression function:  $-0.0570642532108219 * x + 0.100627379991073$

## C2 – 2018 12m

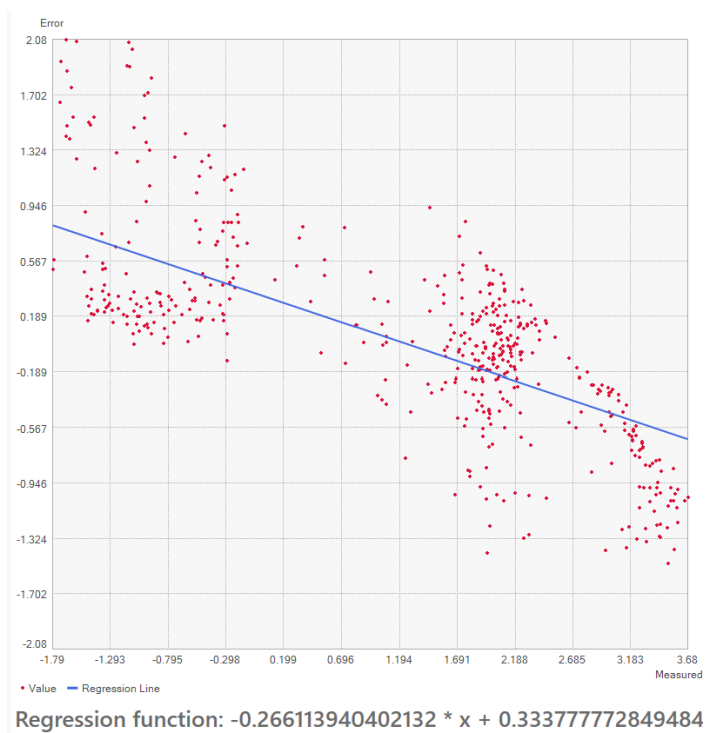


Regression function:  $-0.268415591586691 * x + 0.34282166298562$

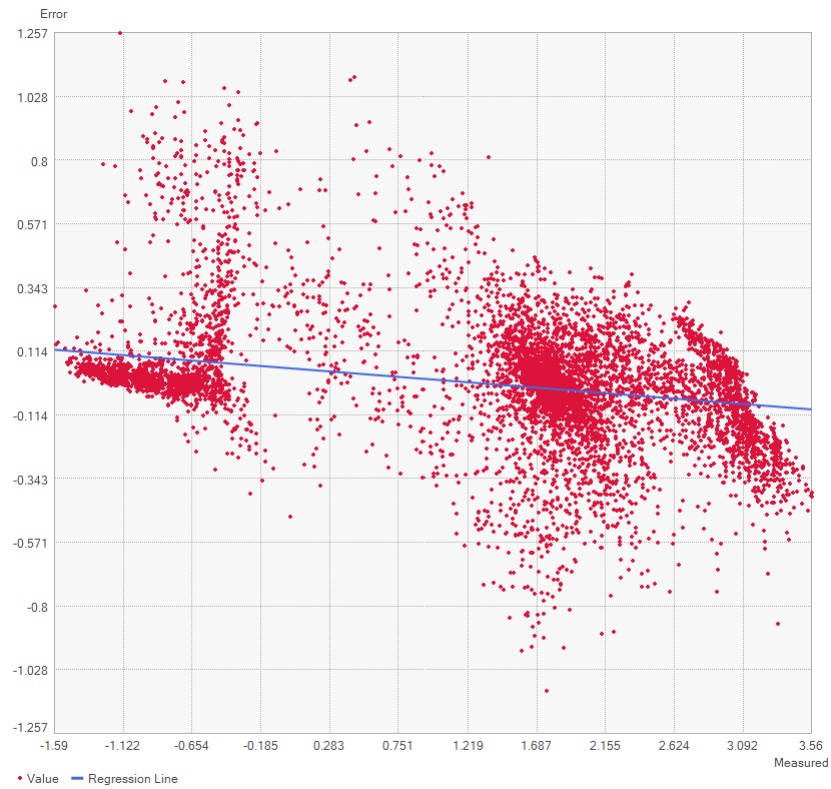
## C2 – 2019 3m



## C2 – 2019 12m

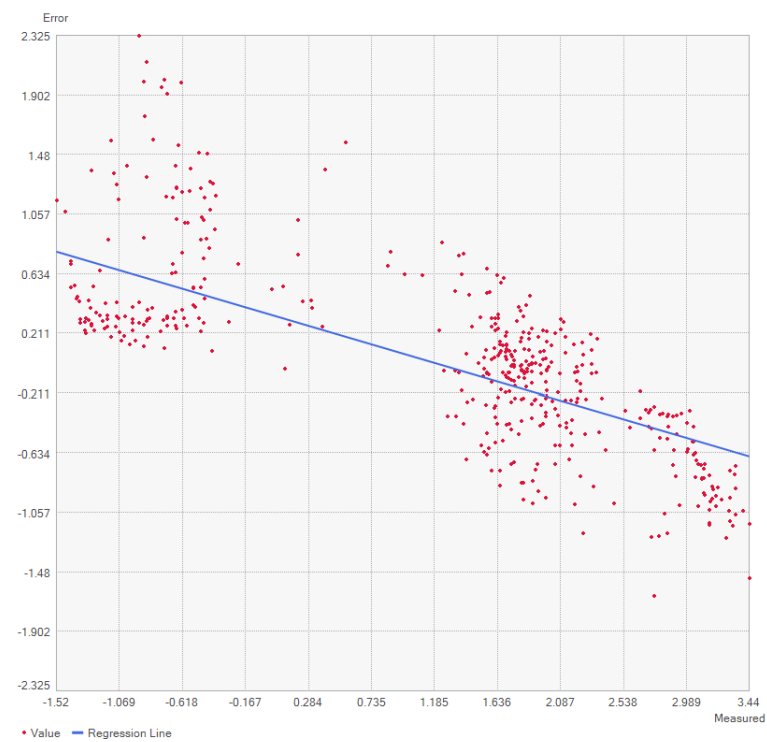


## C2 – 2021 3m



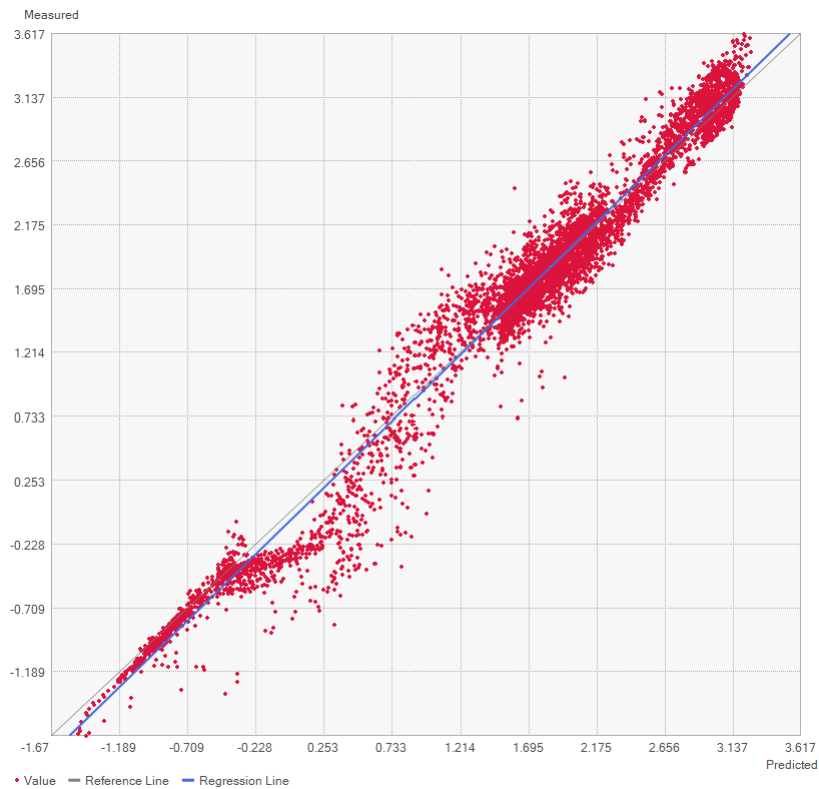
Regression function:  $-0.0415795687281917 * x + 0.053660318985414$

## C2 – 2021 12m



Regression function:  $-0.291867355871919 * x + 0.345272110261756$

## C2 – 2016 3m



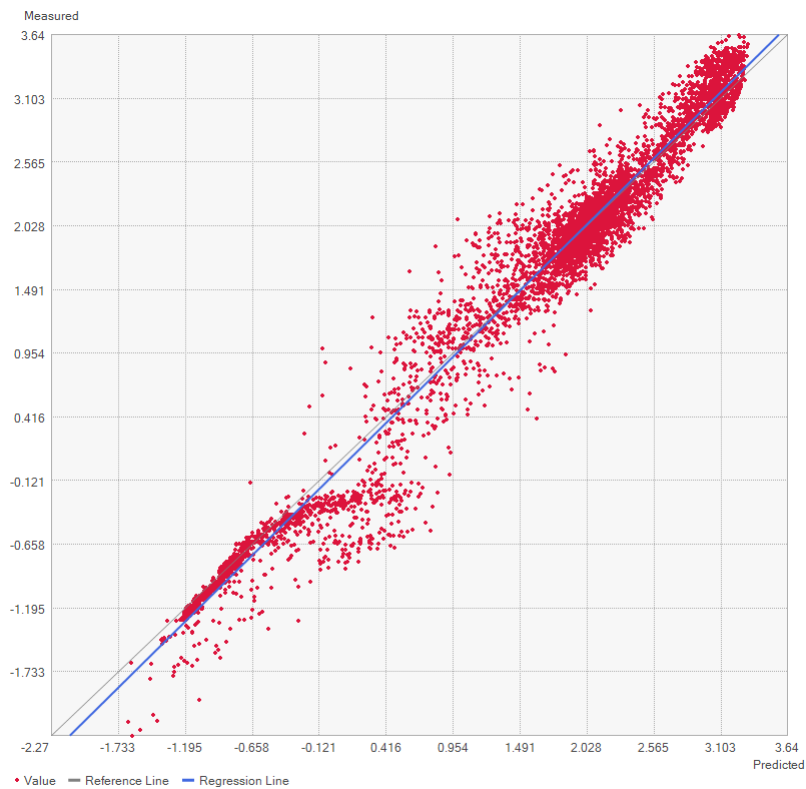
Regression function:  $1.03995677591284 * x + -0.0657425041383326$

## C2 – 2016 12m



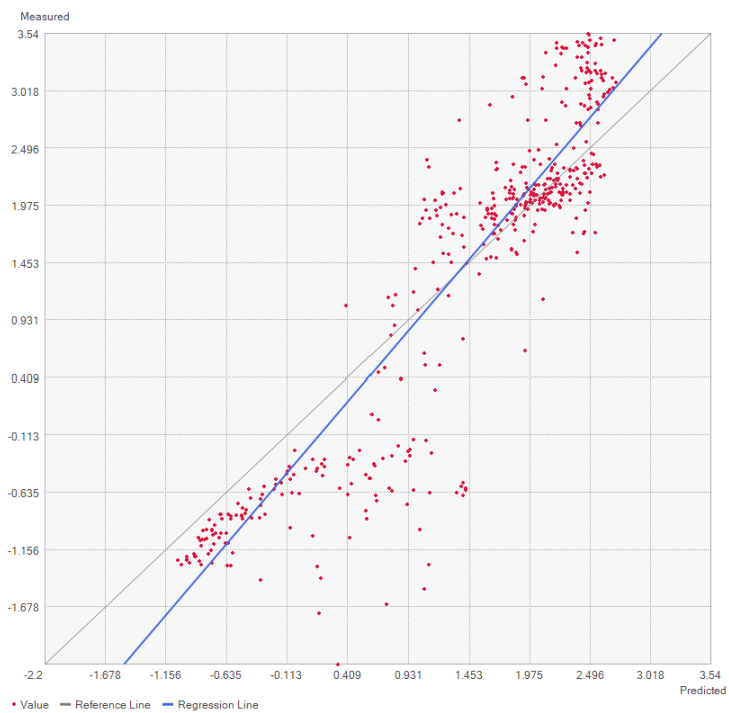
Regression function:  $1.25038880811477 * x + -0.346869877531237$

## C2 – 2018 3m



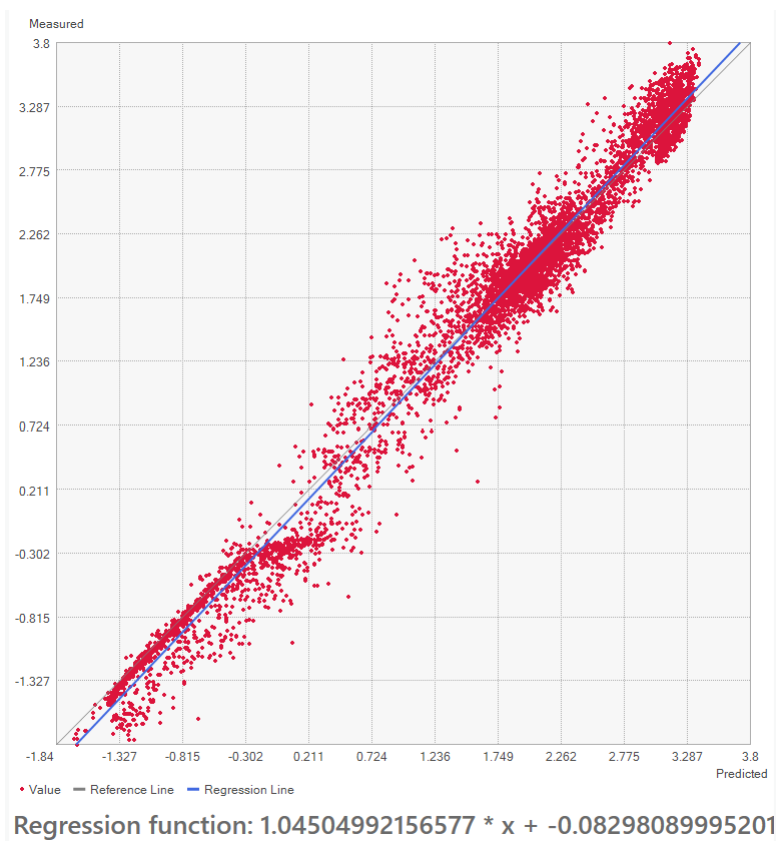
Regression function:  $1.03799084046245 * x + -0.0662164619073062$

## C2 -2018 12m

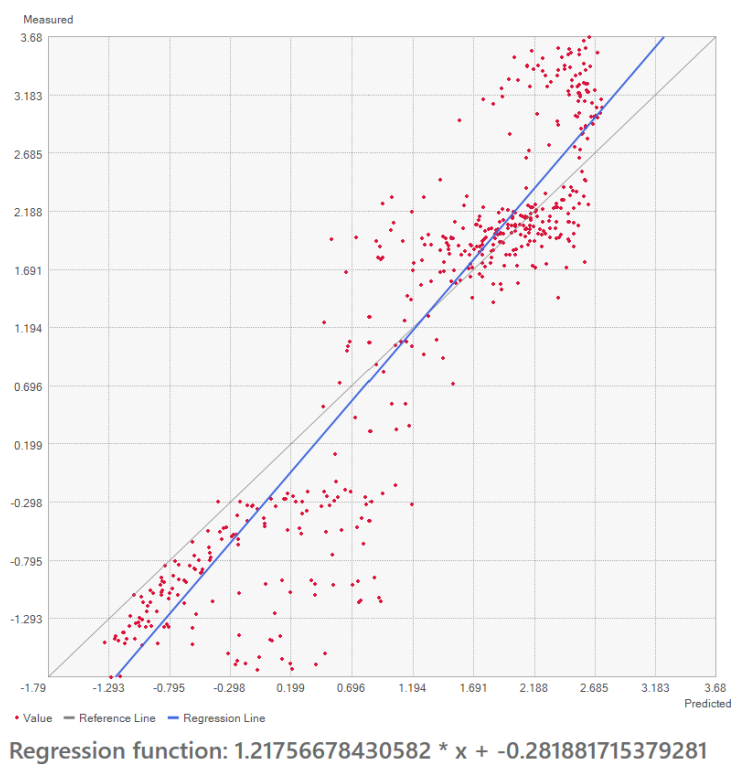


Regression function:  $1.23891440128785 * x + -0.319242660251376$

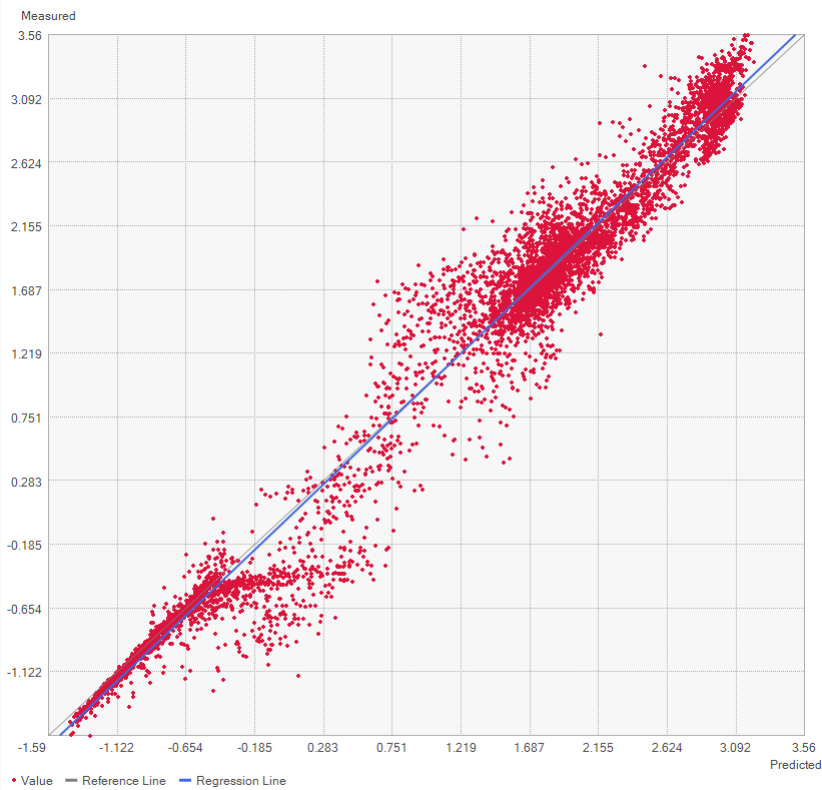
## C2 – 2019 3m



## C2 – 2019 12m

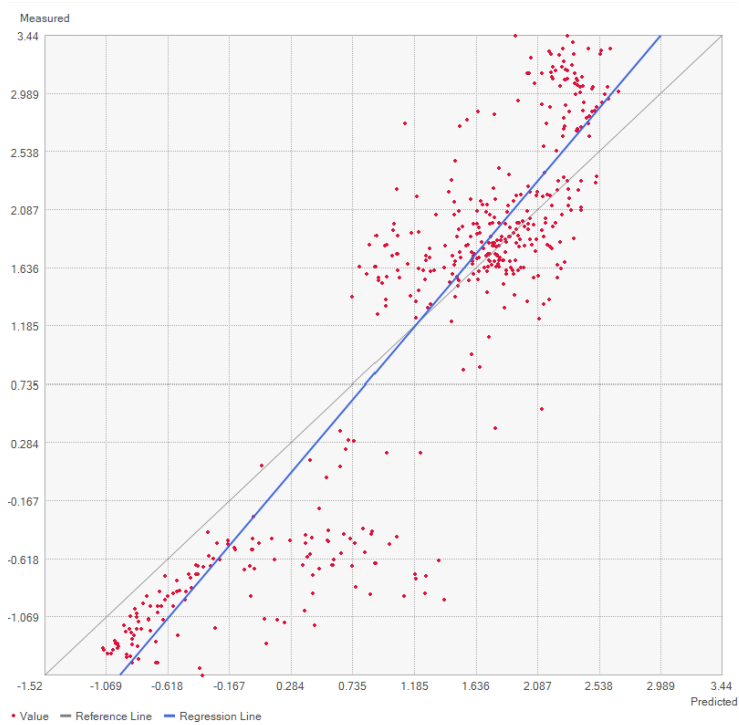


## C2 – 2021 3m



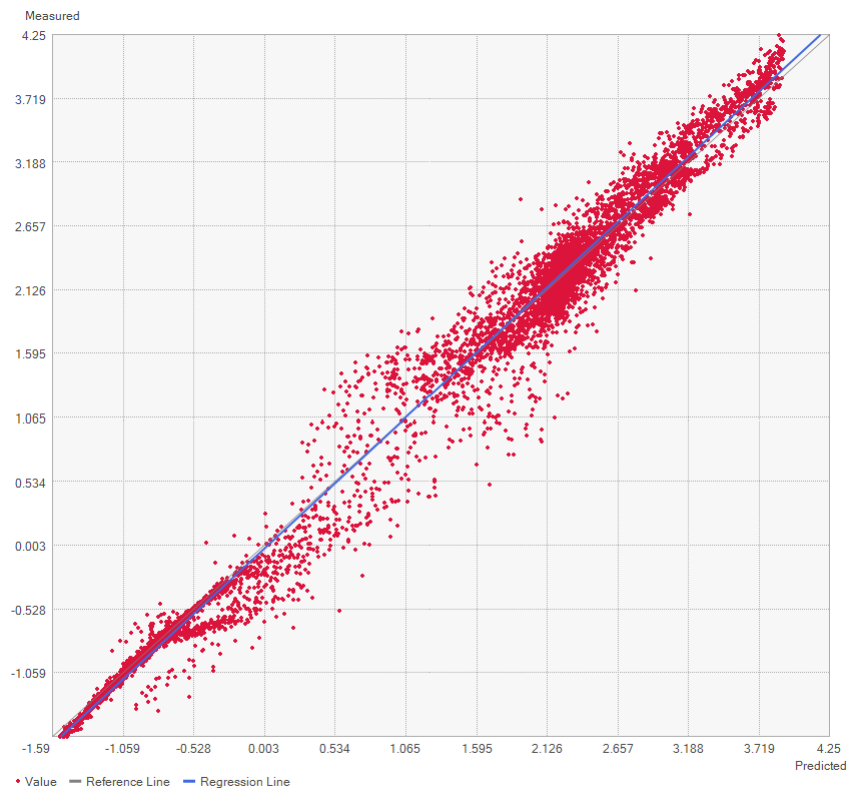
Regression function:  $1.02755927330238 * x + -0.0344640771856546$

## C2 – 2021 12m



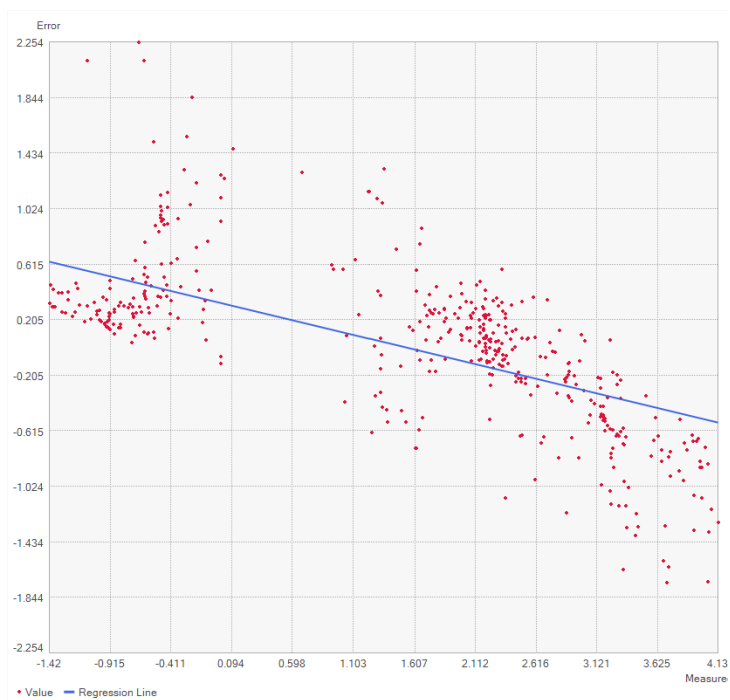
Regression function:  $1.25246152609434 * x + -0.304628342835384$

## C5 – 2016 3m



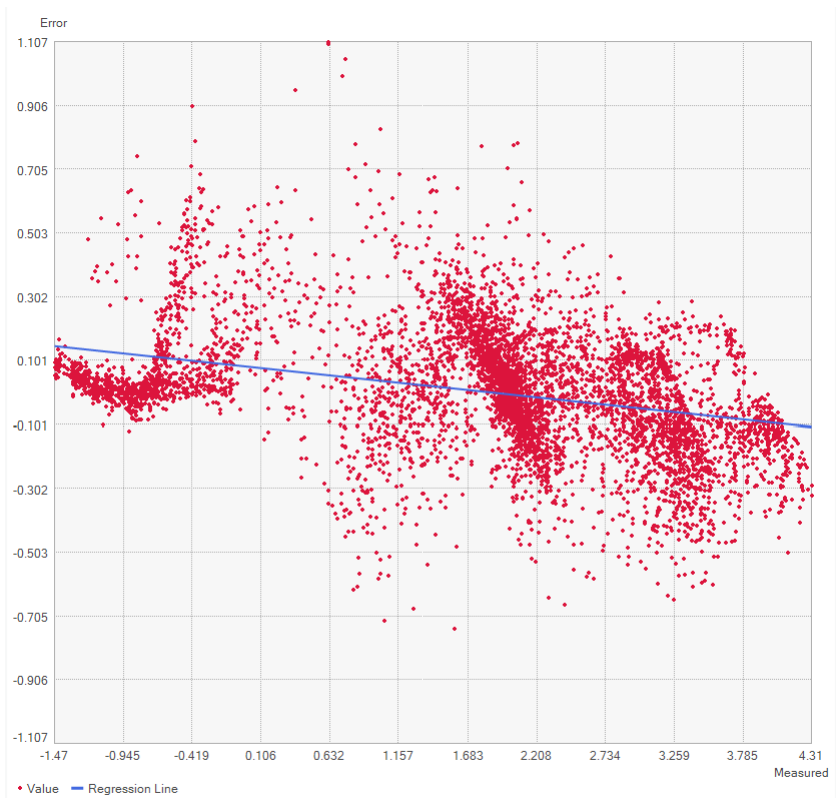
Regression function:  $1.02283443572437 * x + -0.0279723780002912$

## C5 – 2016 12m



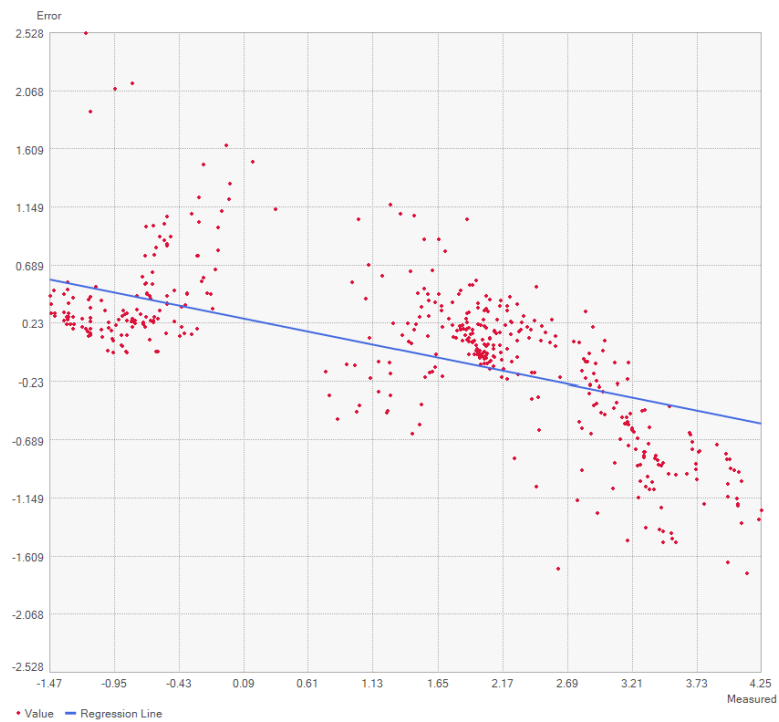
Regression function:  $-0.213735923157934 * x + 0.329040476340617$

### C5 – 2018 3m



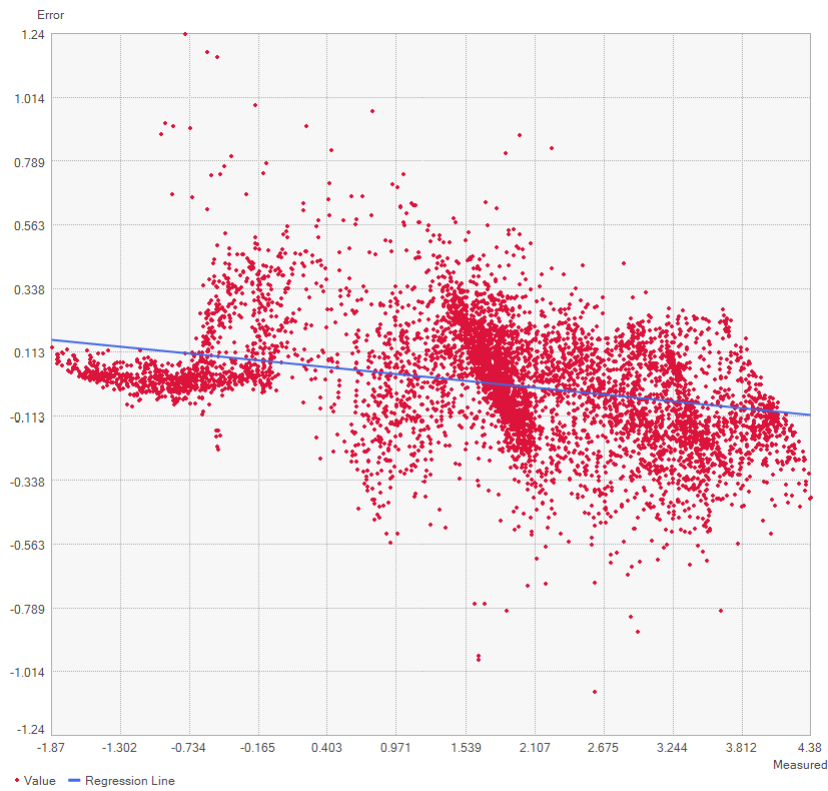
Regression function:  $-0.0439718507387328 * x + 0.0805687643357758$

### C5 – 2018 12m



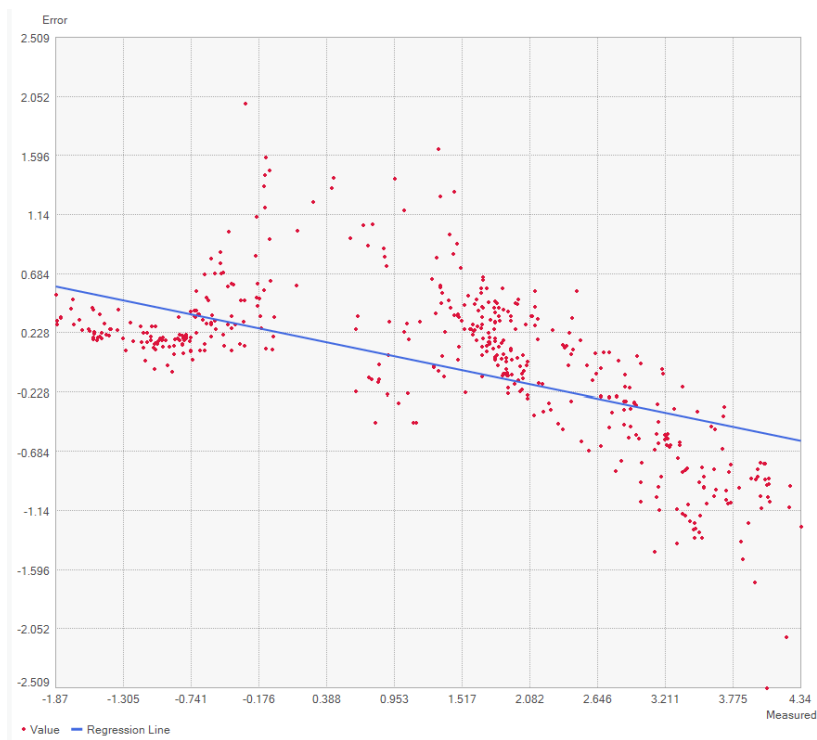
Regression function:  $-0.198052561256992 * x + 0.283437163504026$

### C5 – 2019 3m



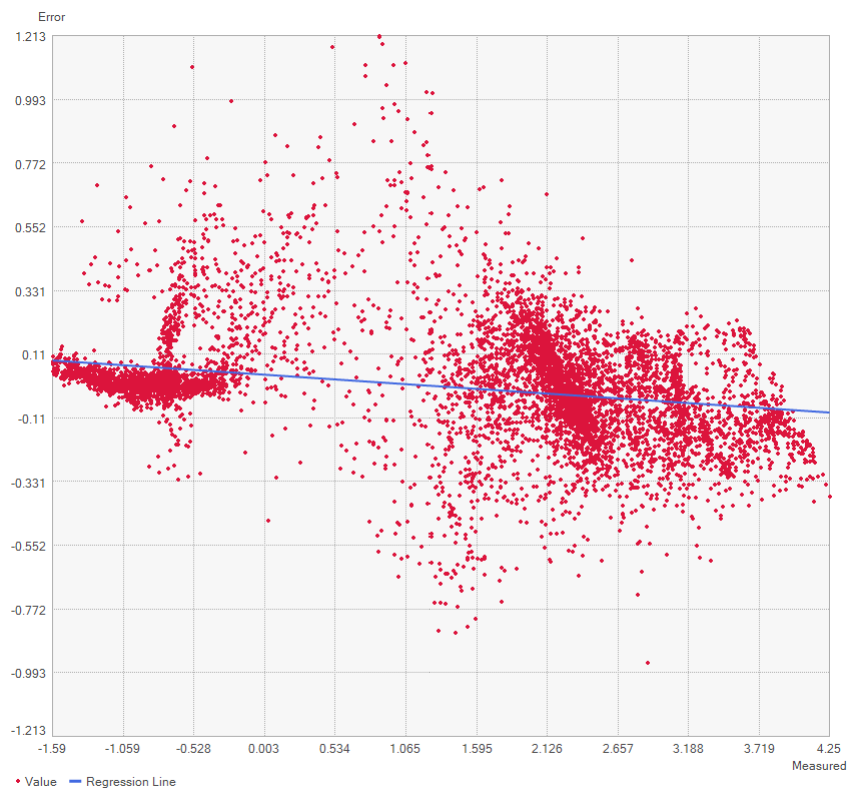
Regression function:  $-0.0424706510235537 * x + 0.0768688628244821$

### C5 – 2019 12m



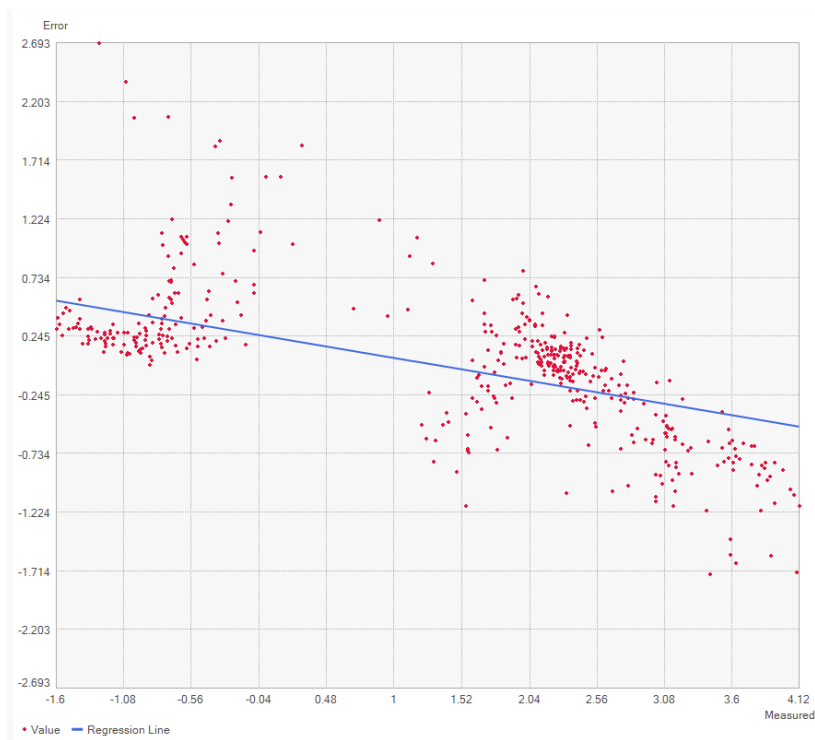
Regression function:  $-0.190862407846958 * x + 0.227895896800611$

### C5 – 2021 3m



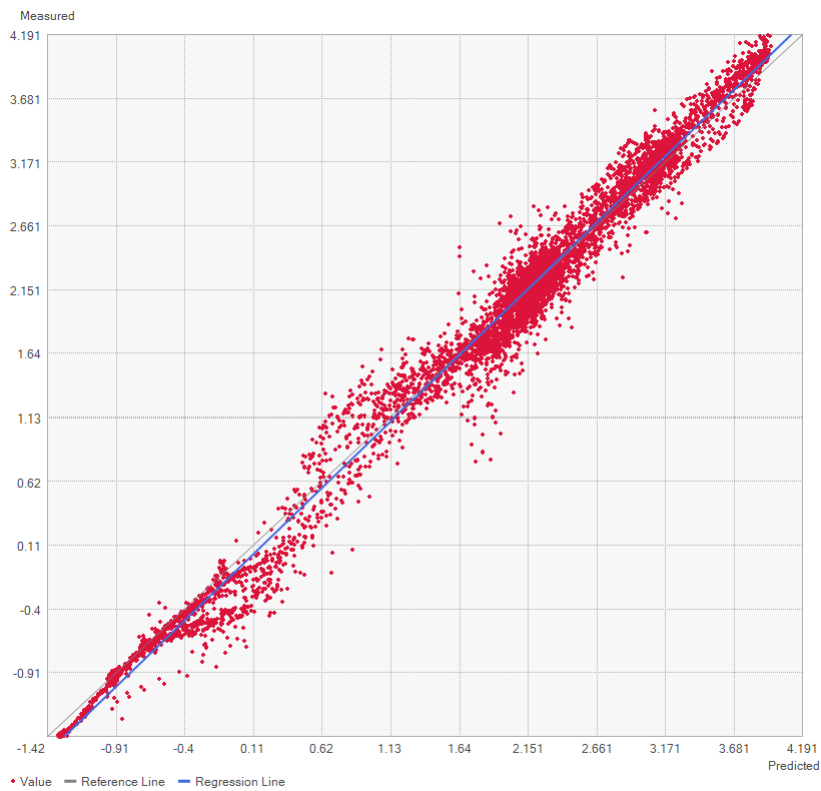
Regression function:  $-0.0308543331426281 * x + 0.0395776564689841$

### C5 – 2021 12m



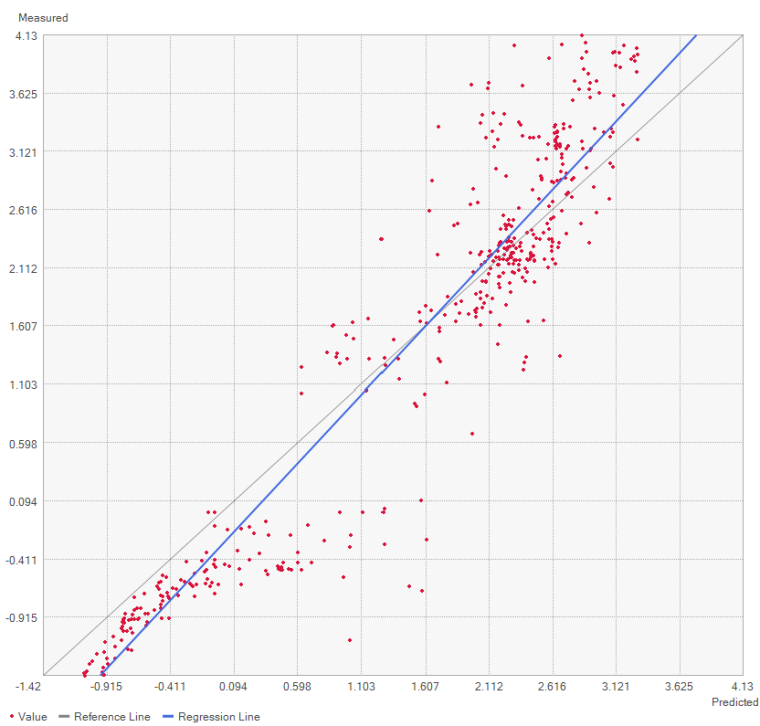
Regression function:  $-0.183751351101181 * x + 0.24698154245843$

## C5 – 2016 3m



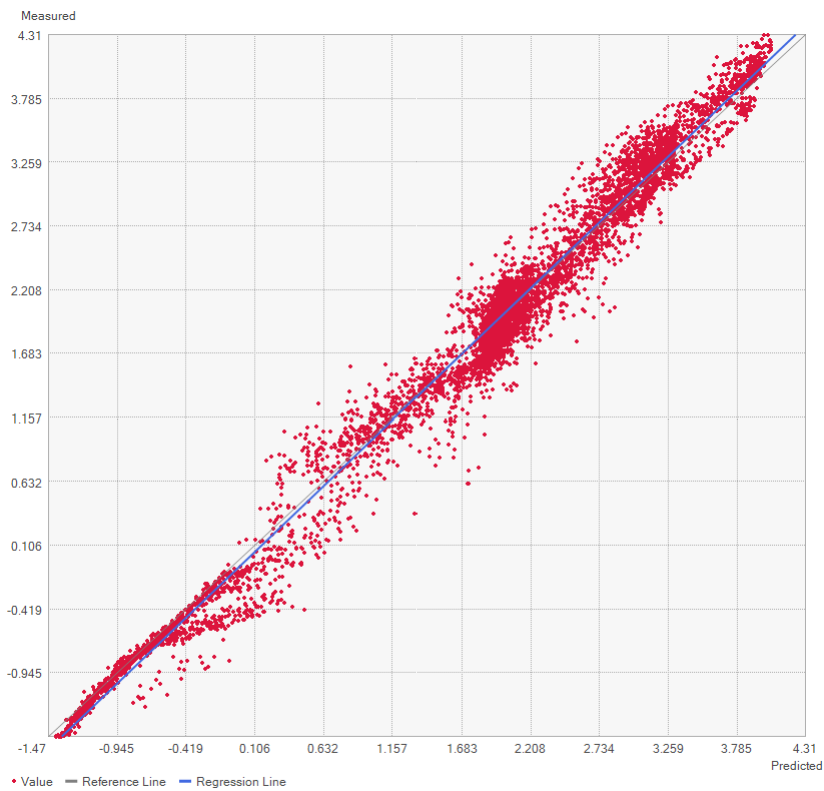
Regression function:  $1.03885574206335 * x + -0.0752667523077255$

## C5 – 2016 12m



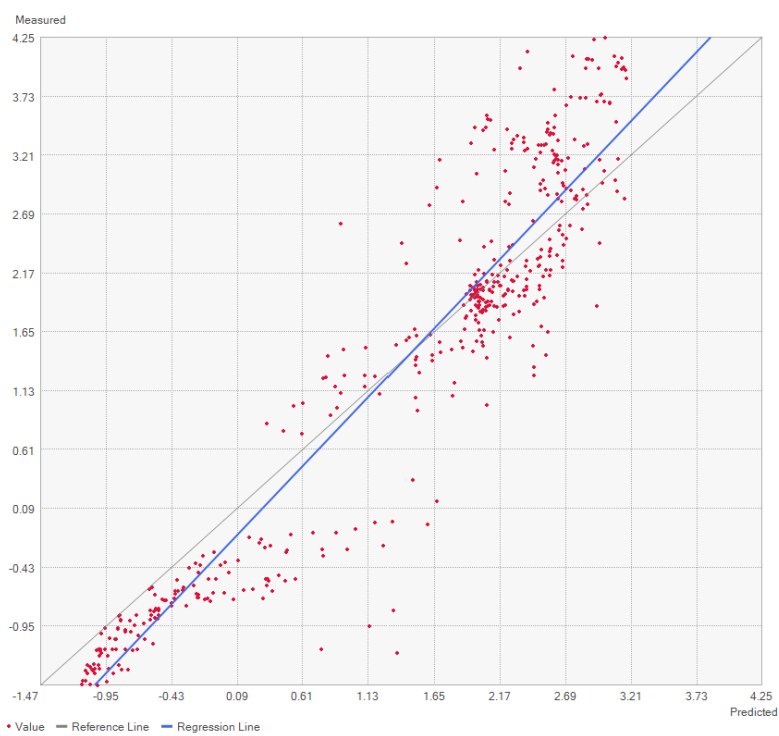
Regression function:  $1.17390023610788 * x + -0.28303204679464$

### C5 – 2018 3m



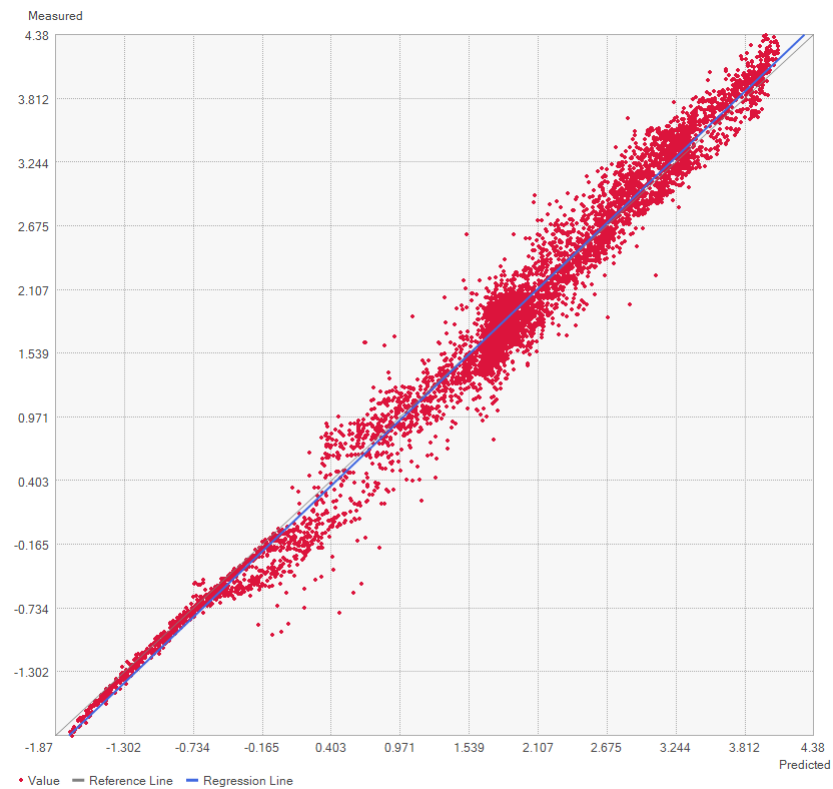
Regression function:  $1.03150335195232 * x + -0.0576044518304368$

### C5 – 2018 12m



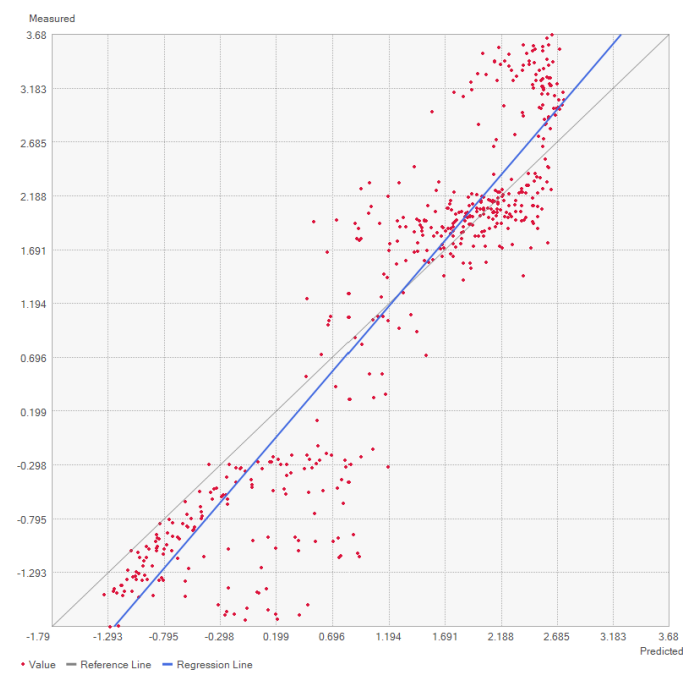
Regression function:  $1.17129676284324 * x + -0.250890165019673$

## C5 – 2019 3m



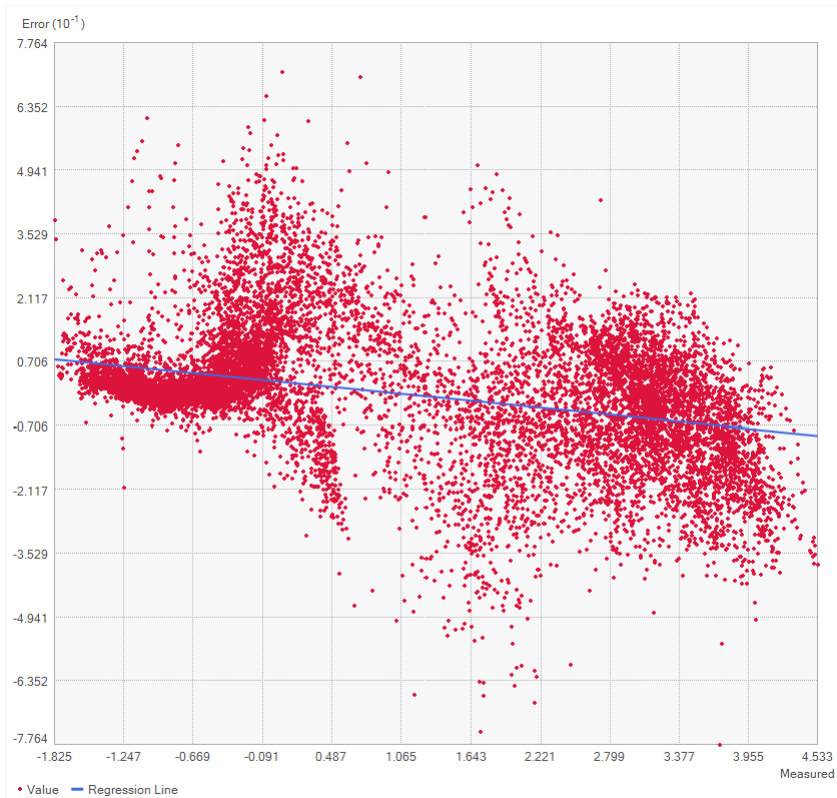
Regression function:  $1.03062460333917 * x + -0.0566768018096619$

## C5 – 2021 12m



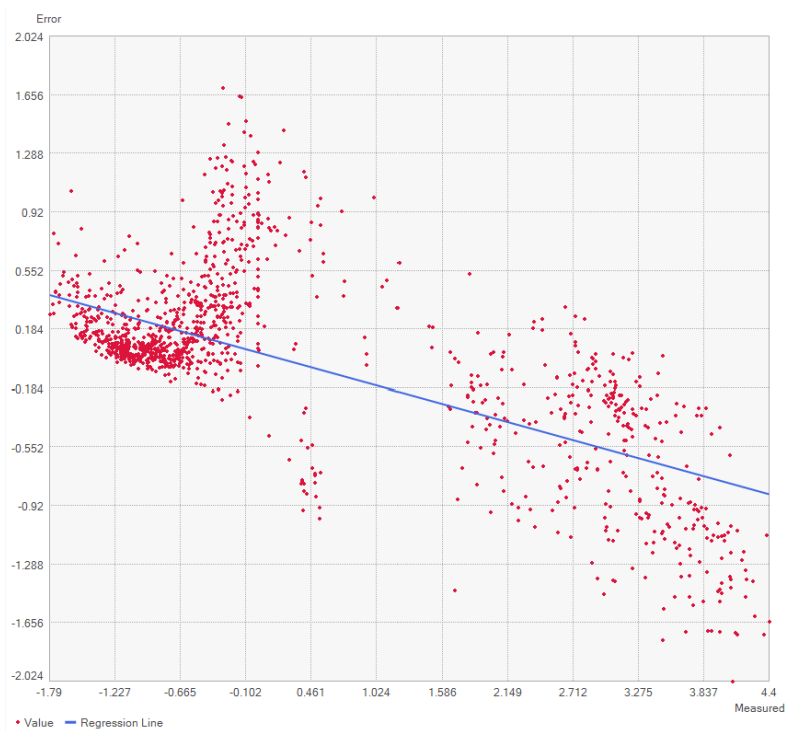
Regression function:  $1.21756678430582 * x + -0.281881715379281$

## C8 – 2016 3m



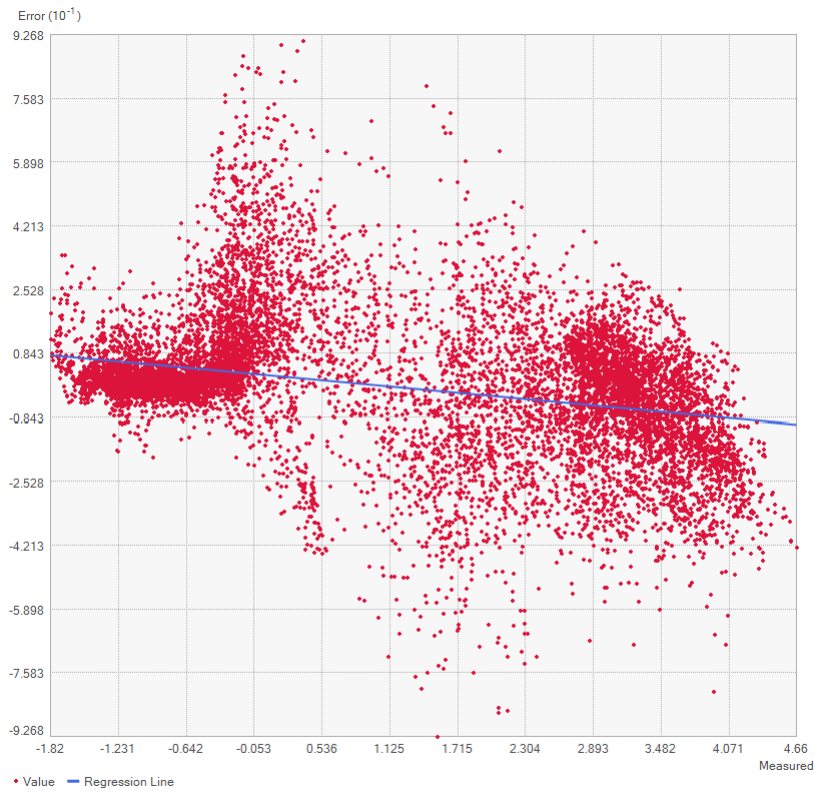
Regression function:  $-0.0264276936291335 * x + 0.0267089003387152$

## C8 – 2016 12m



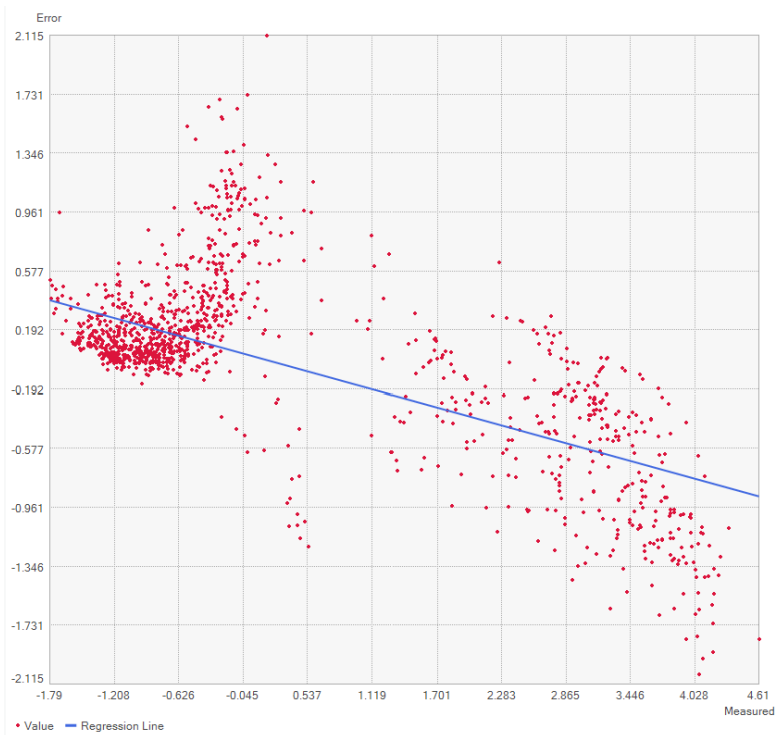
Regression function:  $-0.20119385005098 * x + 0.0365044125262197$

### C8 – 2018 3m



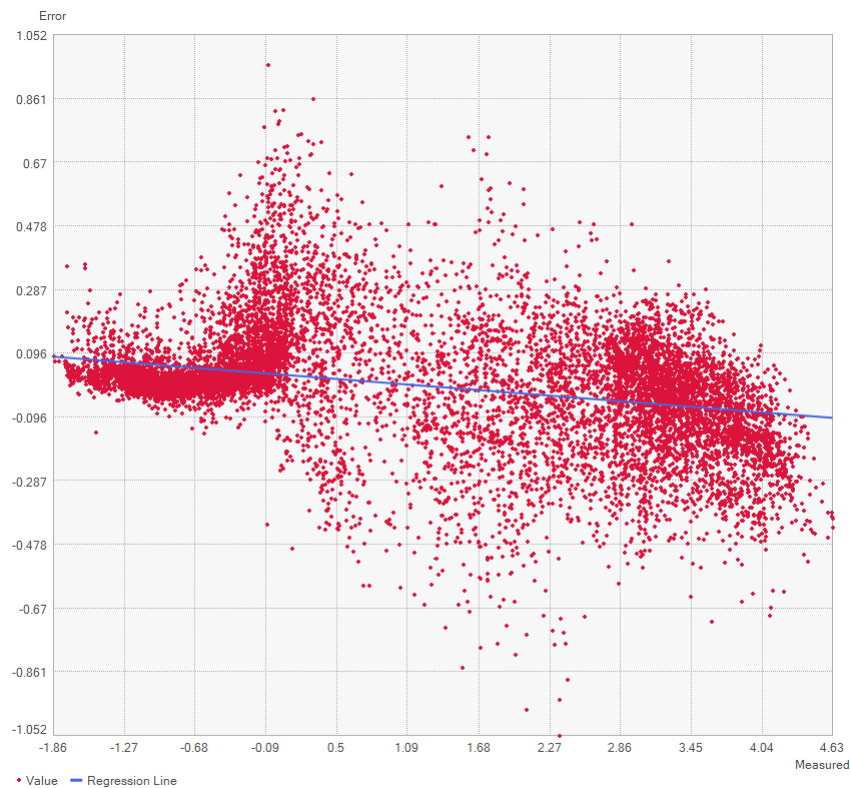
Regression function:  $-0.0280639683491792 * x + 0.027878215371262!$

### C8 – 2018 12m



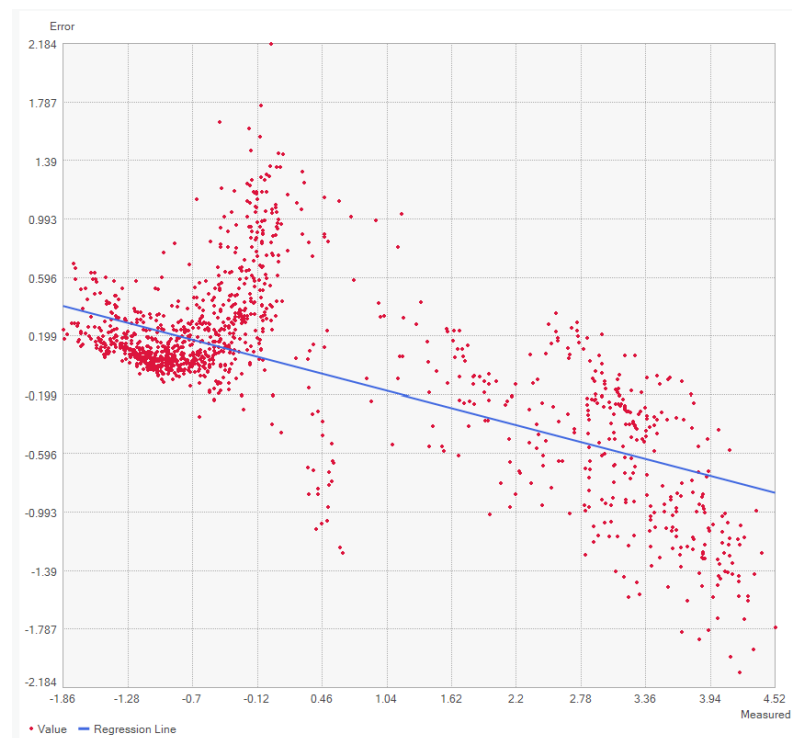
Regression function:  $-0.19908050261859 * x + 0.0287351142509814$

## C8 – 2019 3m



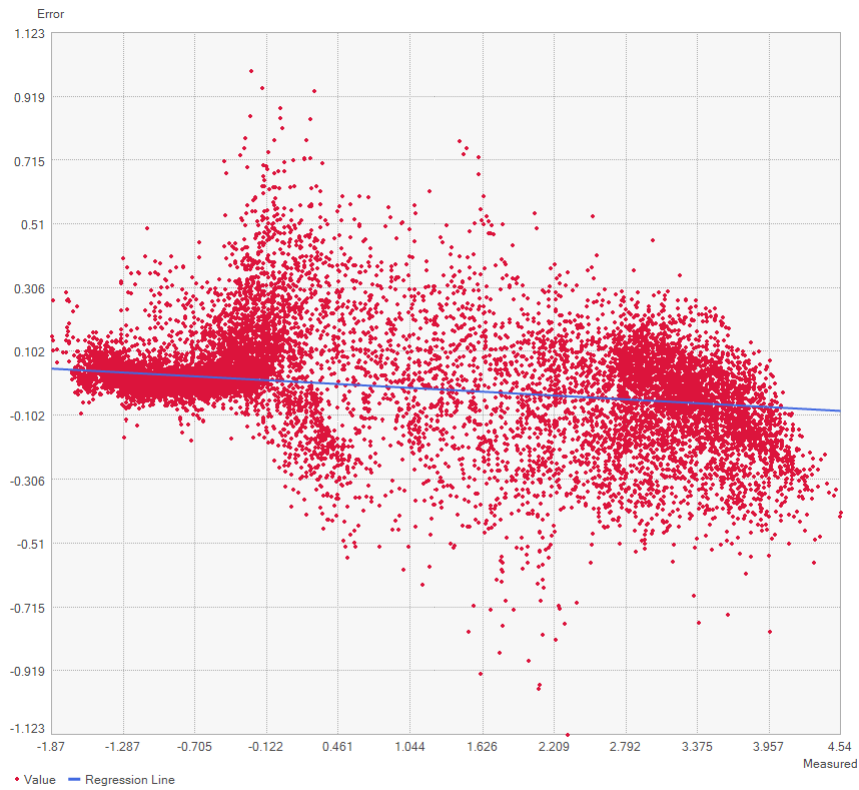
Regression function:  $-0.0282953091850352 * x + 0.032648873726647$

## C8 – 2019 12m



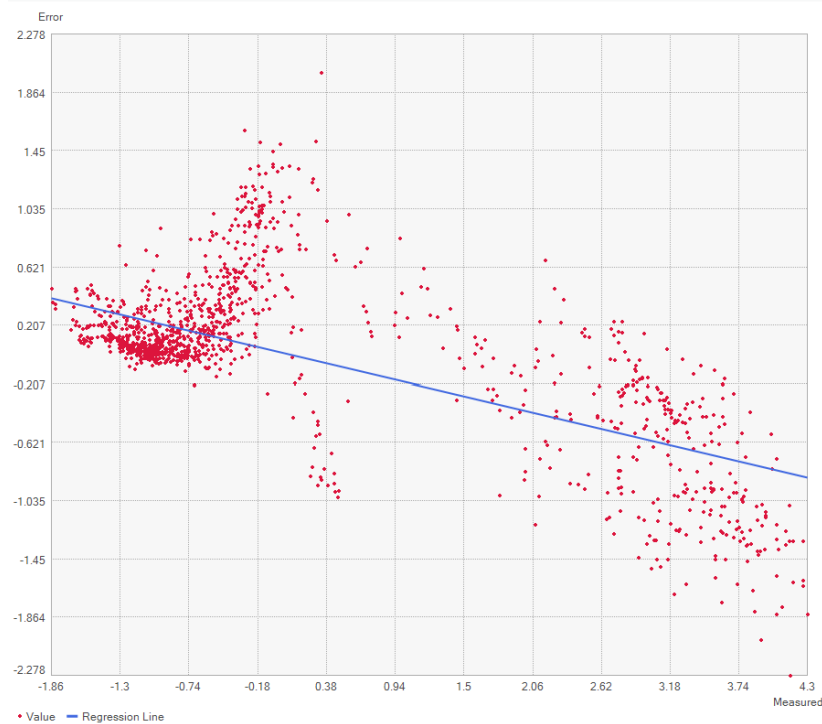
Regression function:  $-0.197846726415427 * x + 0.0339944342932461$

## C8 – 2021 3m



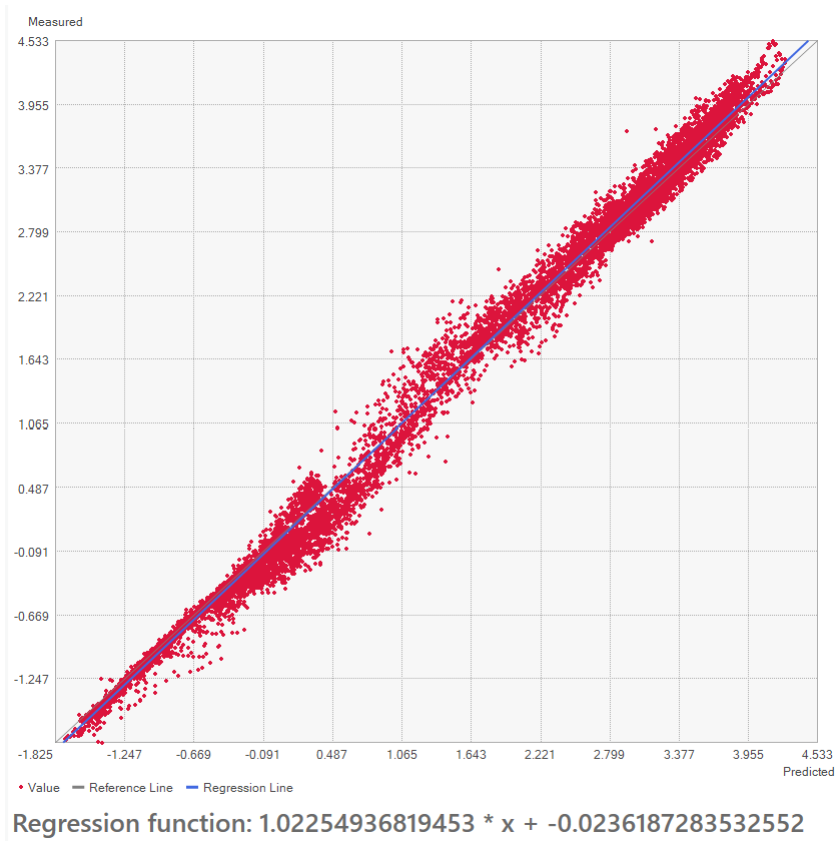
Regression function:  $-0.0211083562984289 * x + 0.00667390338622579$

## C8 – 2021 12m

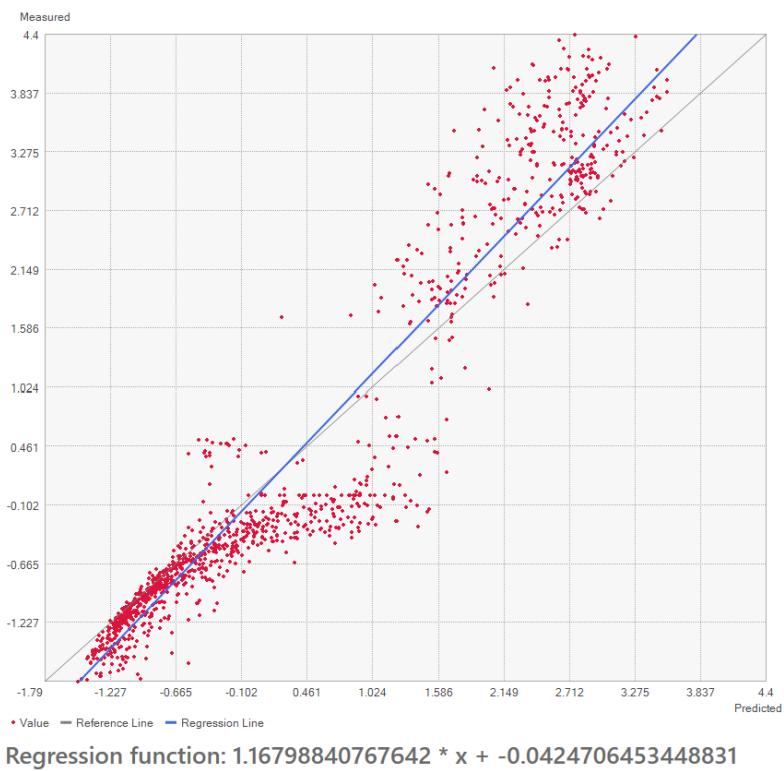


Regression function:  $-0.206080394698403 * x + 0.0154565289578773$

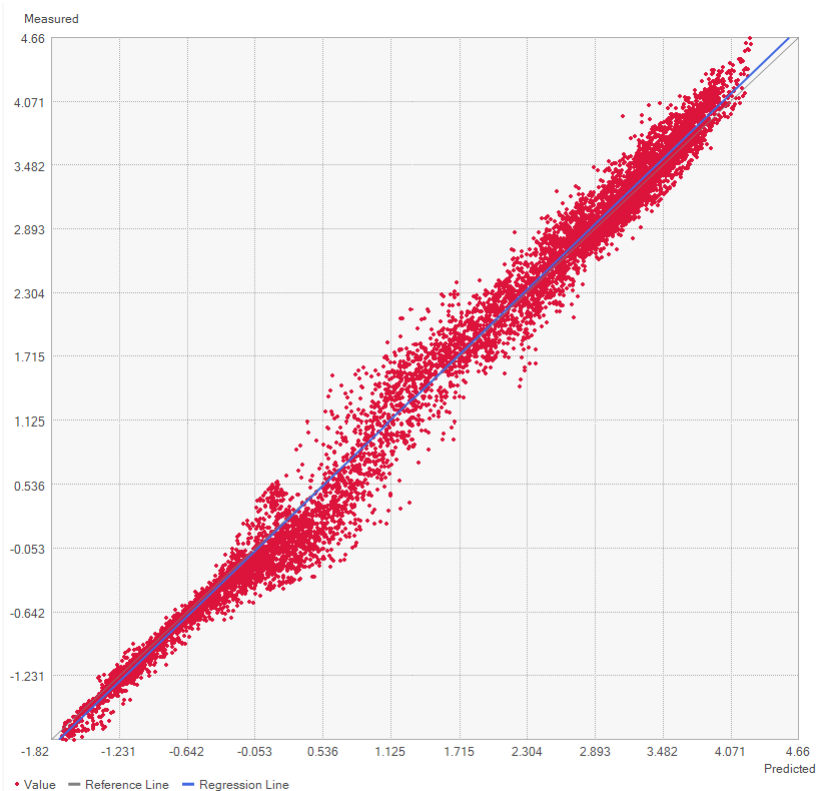
### C8 2016 – 3m



### C8 – 2016 12m

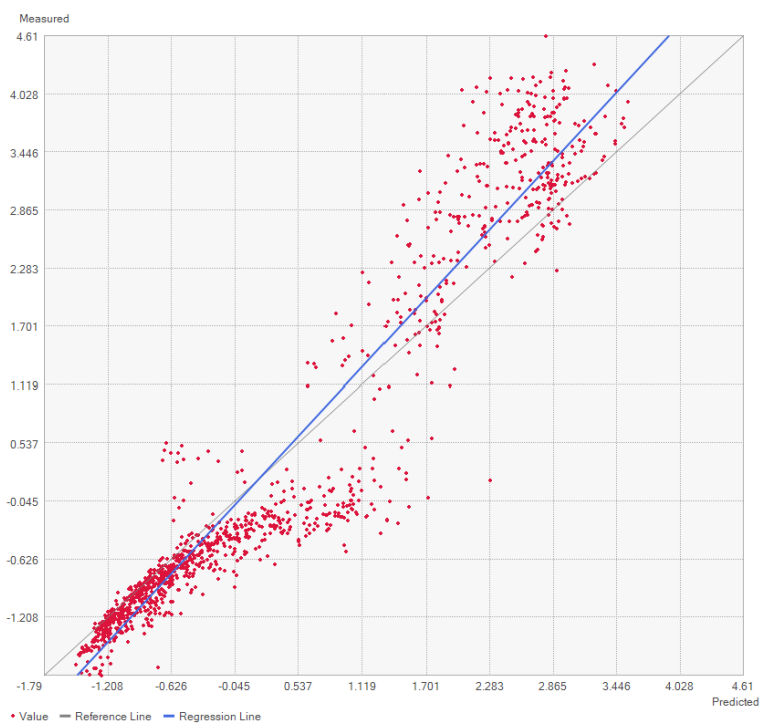


### C8 – 2018 3m



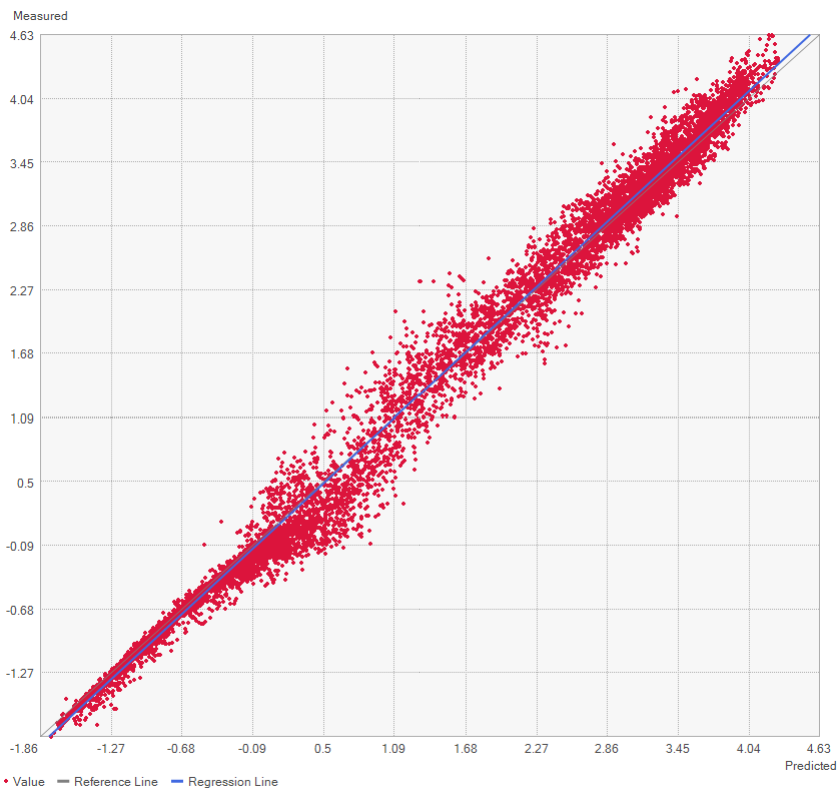
Regression function:  $1.0230131806128 * x + -0.0236302514021485$

### C8 – 2018 12m



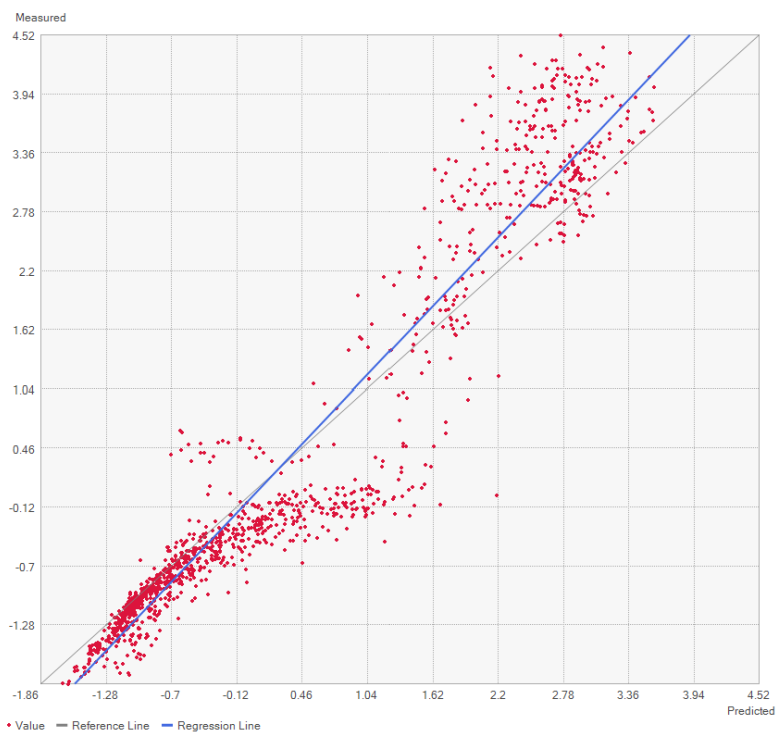
Regression function:  $1.18146565825334 * x + -0.0301913310115337$

### C8 – 2019 3m



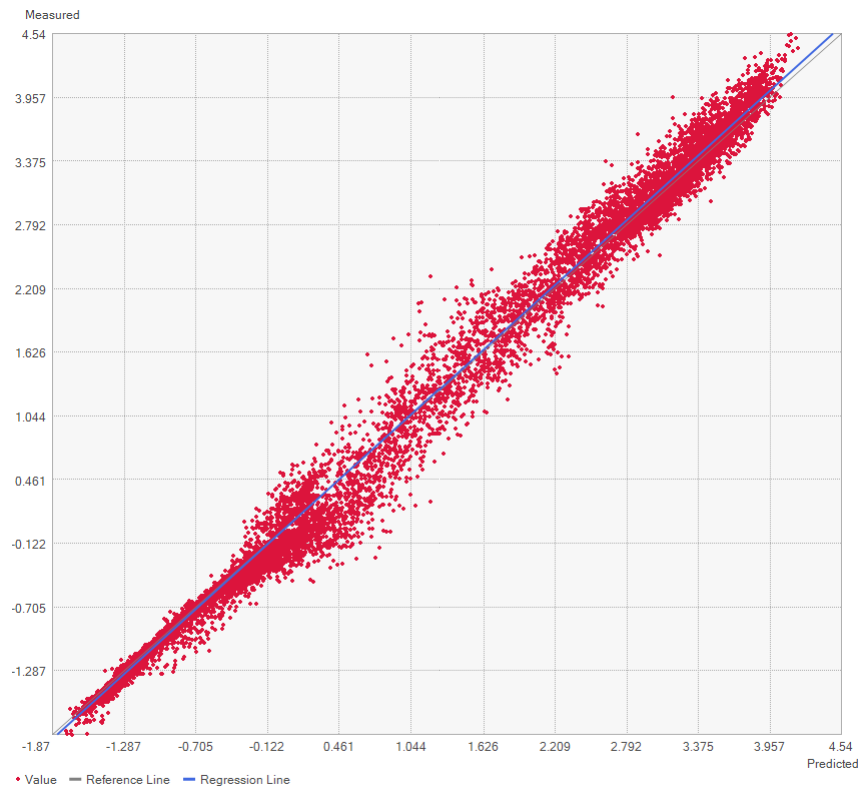
Regression function:  $1.02344509459029 * x + -0.0281974468923158$

### C8 – 2019 12m



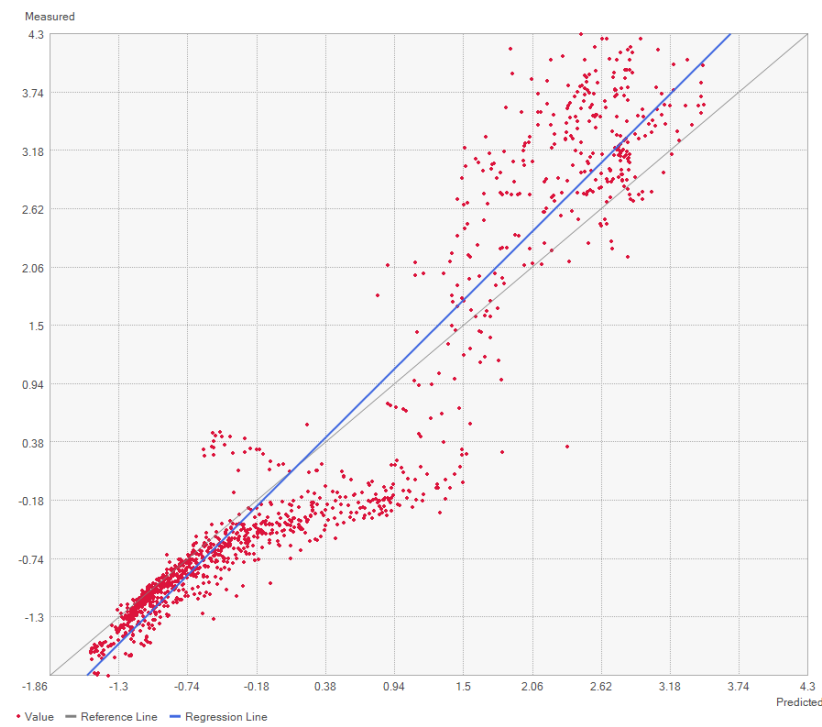
Regression function:  $1.1677176028367 * x + -0.0391758890911842$

### C8 – 2021 3m



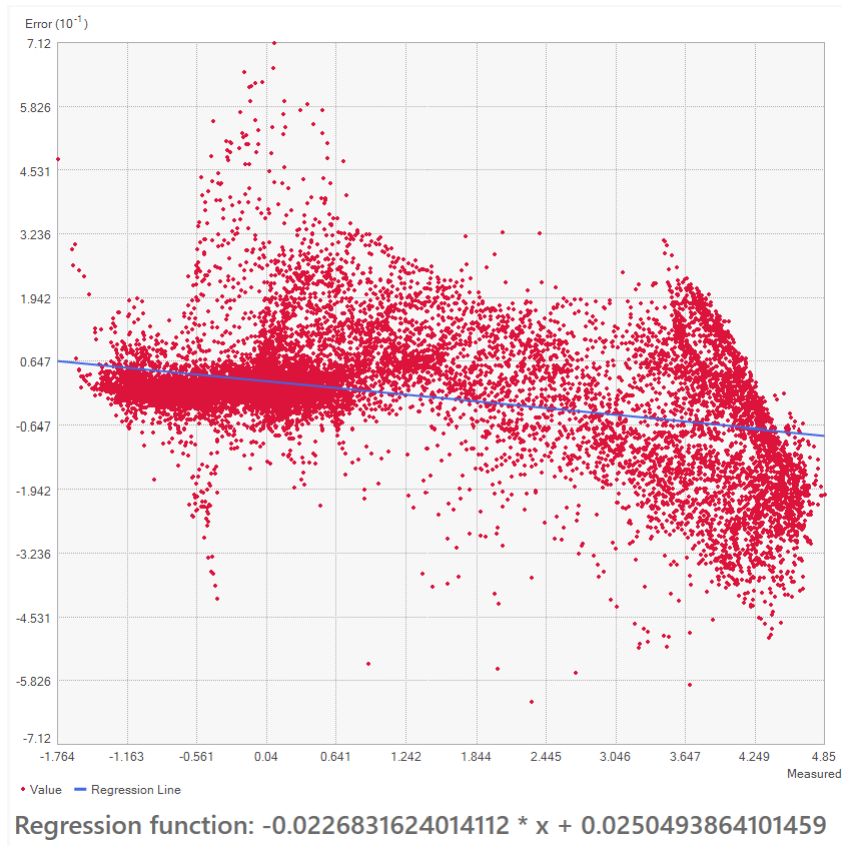
Regression function:  $1.01714330268221 * x + -0.00640735355217448$

### C8 – 2021 12m

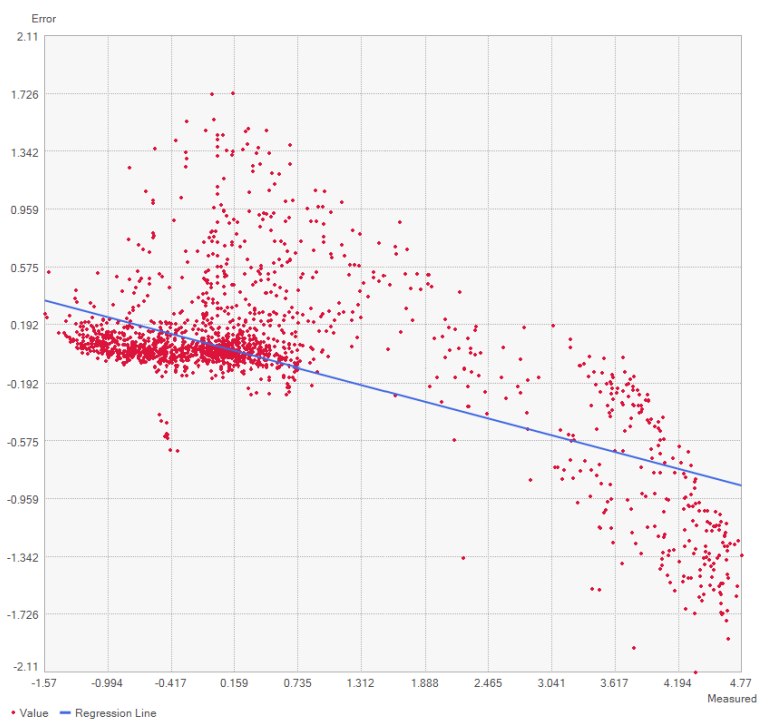


Regression function:  $1.17735298399032 * x + -0.0237751685989487$

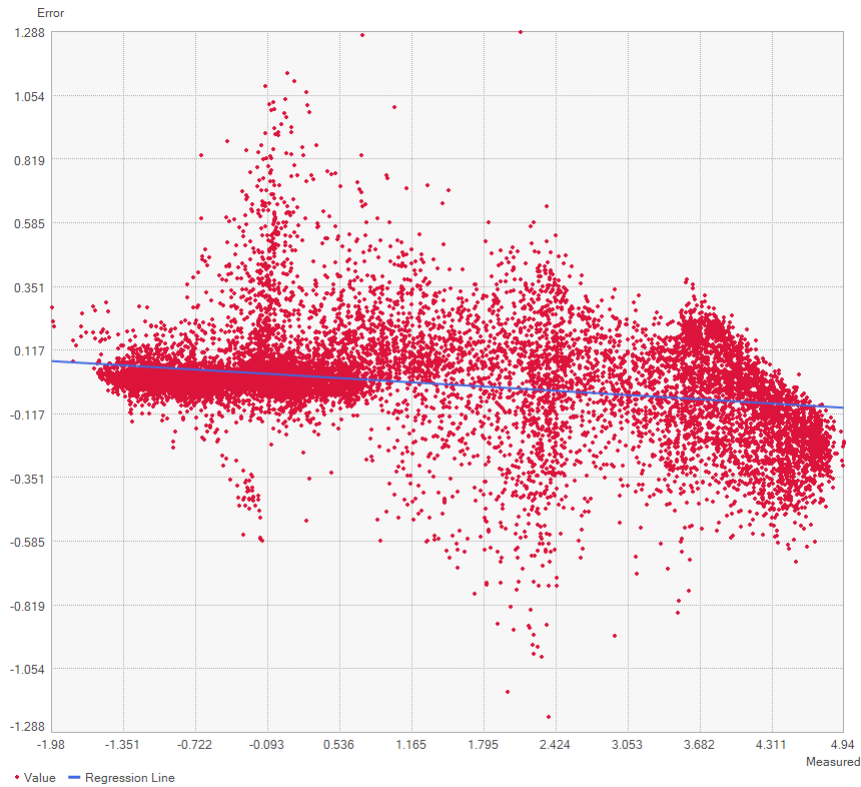
## C12 – 2016 3m



## C12 – 2016 12m

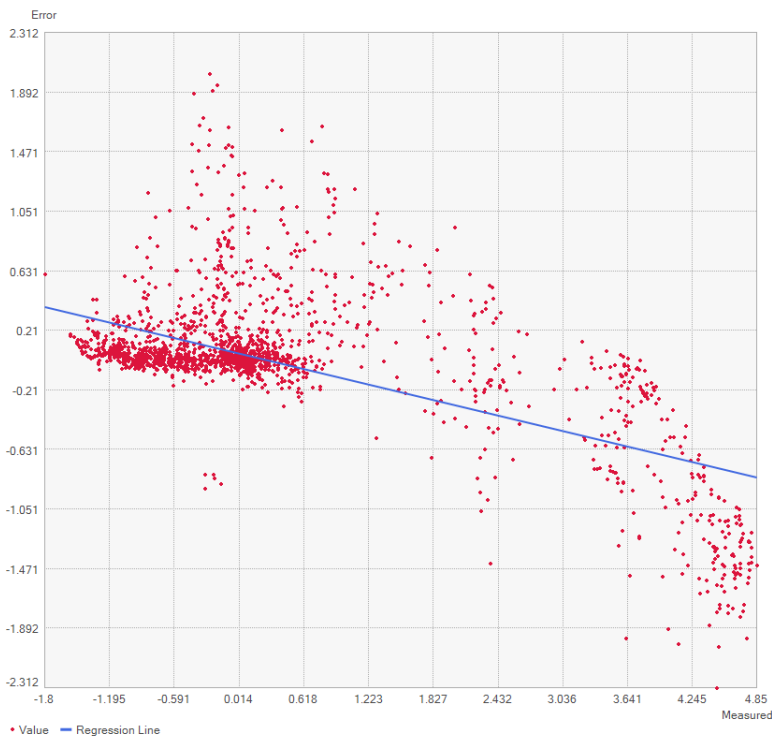


### C12 – 2018 3m



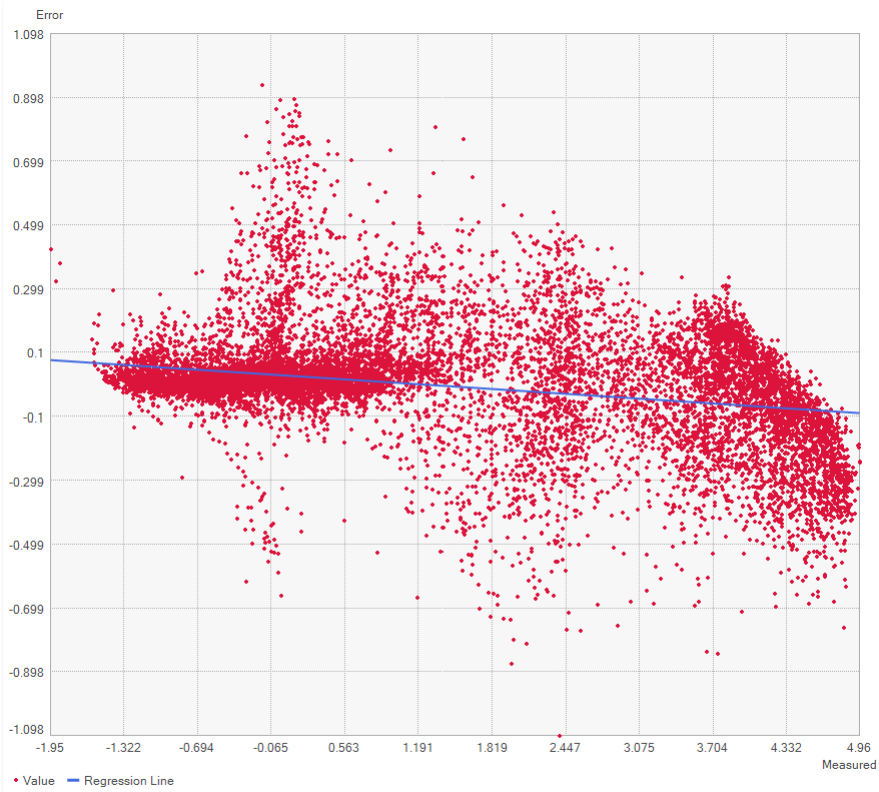
Regression function:  $-0.0247648221010827 * x + 0.02812899427917$

### C12 – 2018 12m



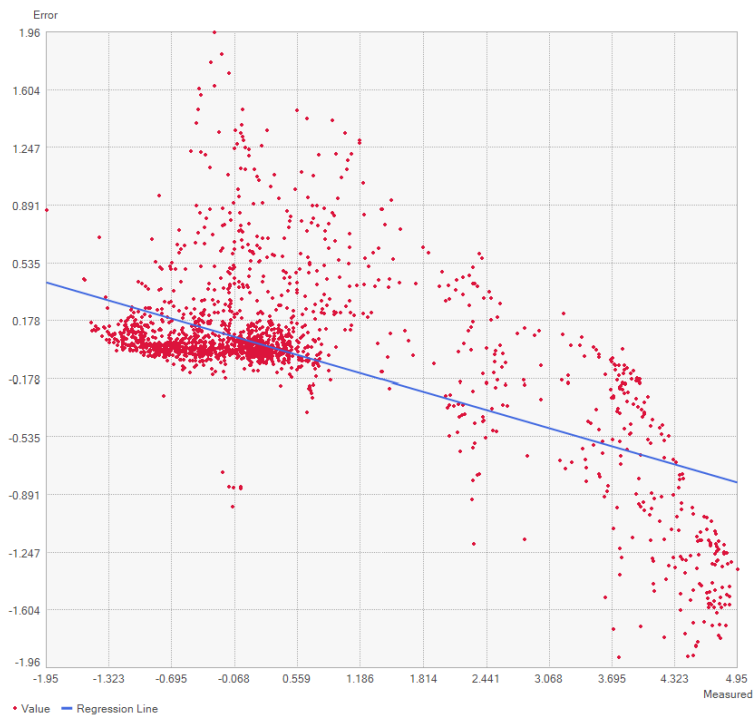
Regression function:  $-0.180791089094942 * x + 0.0488301481558548$

## C12 – 2019 3m



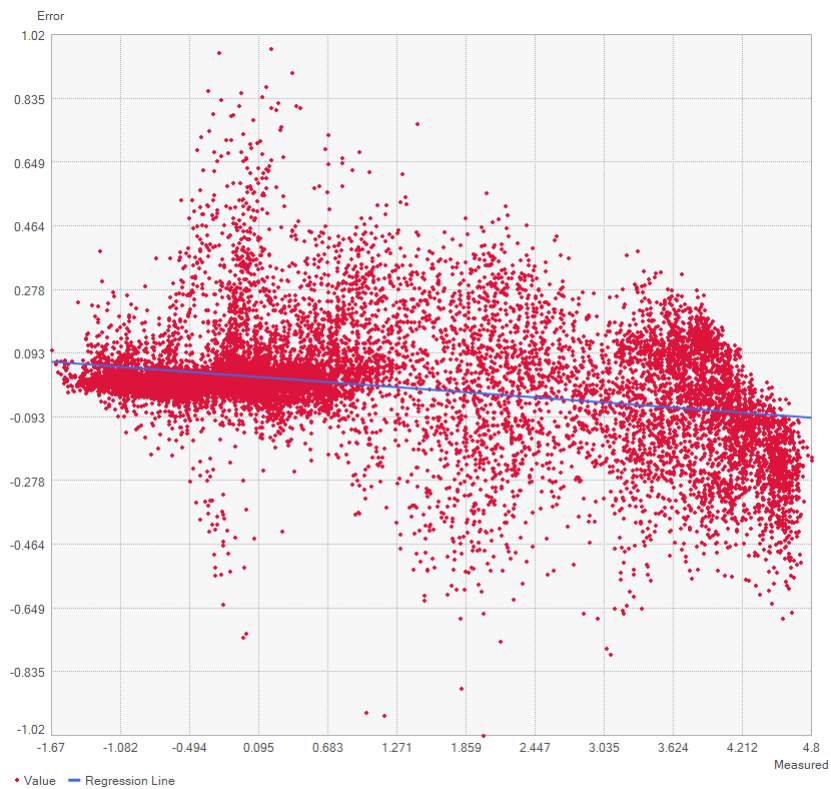
Regression function:  $-0.0240173653548318 * x + 0.0283415596154547$

## C12 – 2019 12m



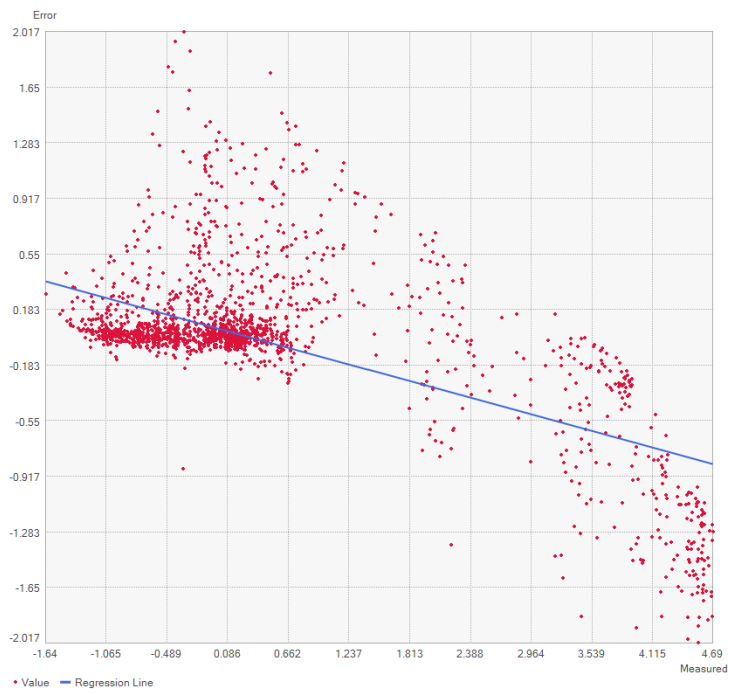
Regression function:  $-0.178213893705472 * x + 0.0661000354630423$

### C12 – 2021 3m



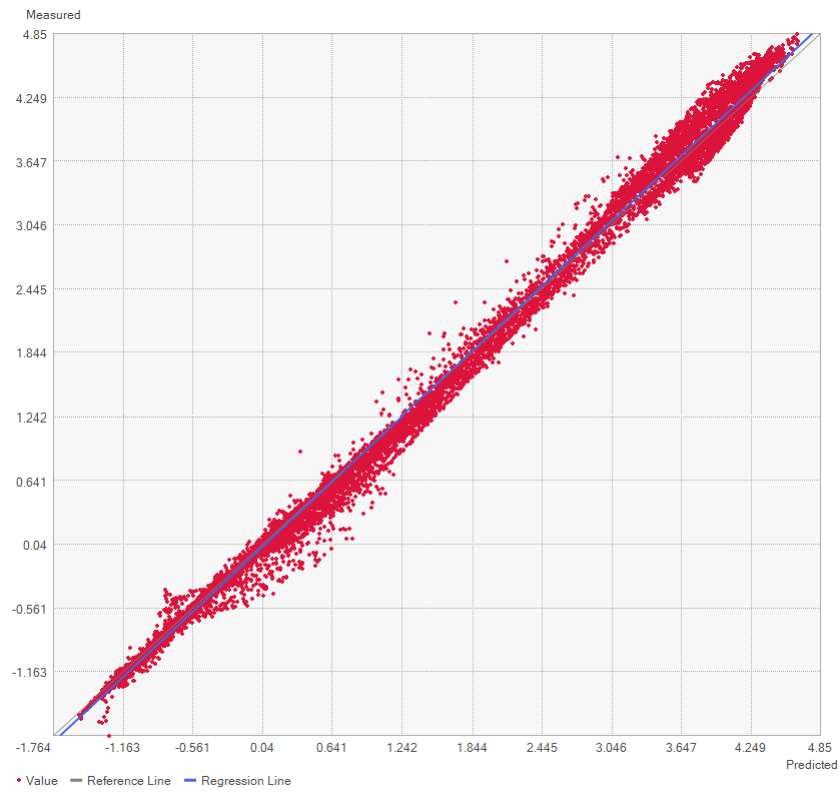
Regression function:  $-0.0251896050036496 * x + 0.0259068601790686$

### C12 – 2021 12m



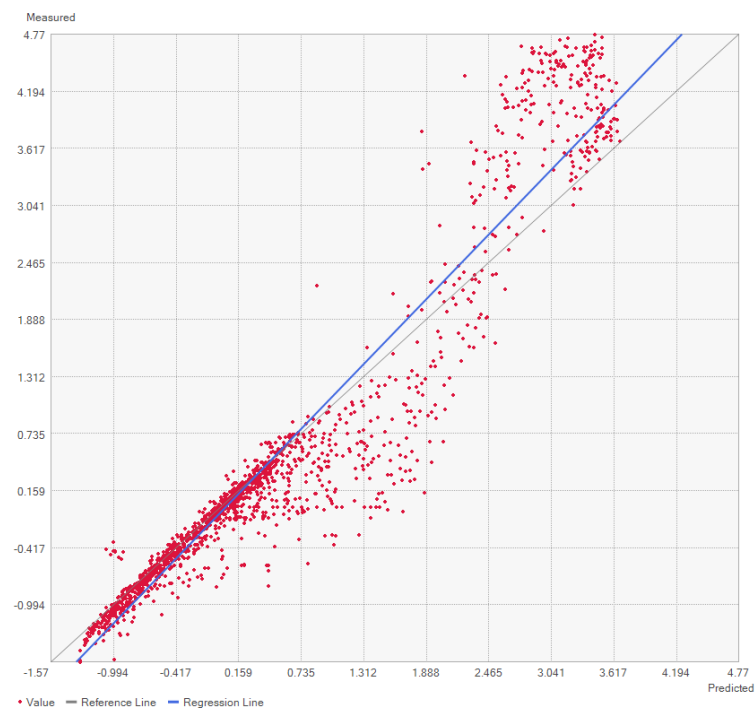
Regression function:  $-0.190335480391484 * x + 0.057015009750628$

## C12 – 2016 3m



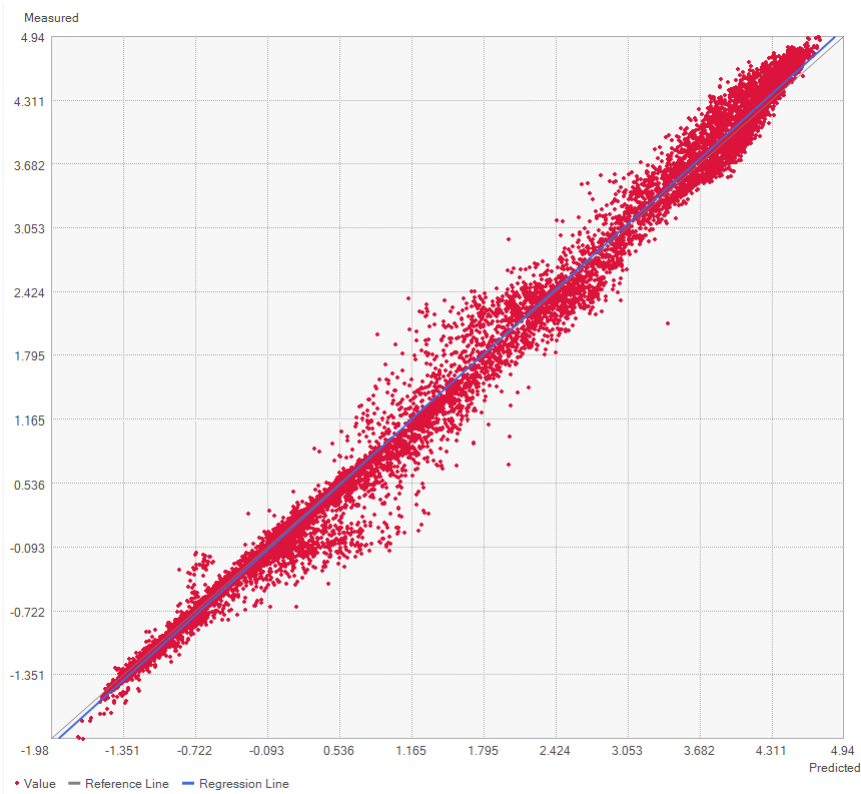
Regression function:  $1.01978712337921 * x + -0.0230109491496469$

## C12 – 2016 12m



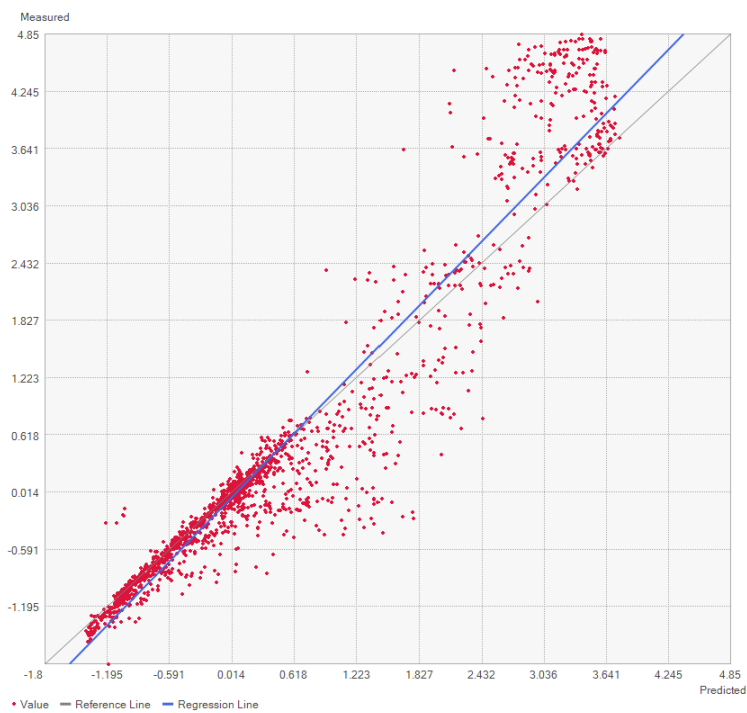
Regression function:  $1.13556079642204 * x + -0.0515405733825308$

## C12 – 2018 3m



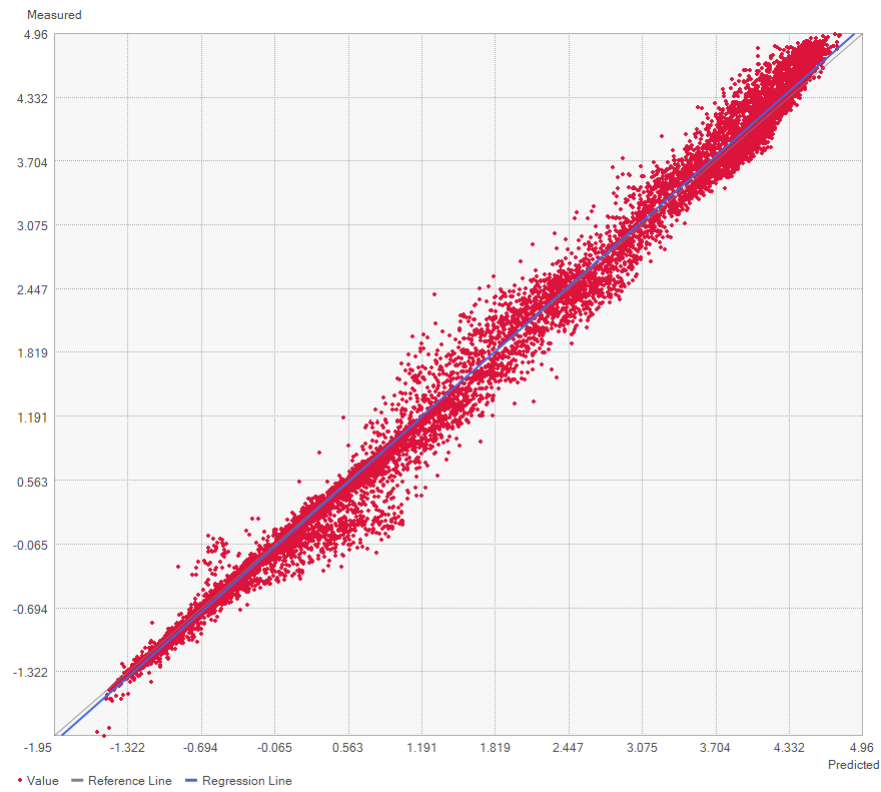
Regression function:  $1.01983292334147 * x + -0.0238823995432891$

## C12 – 2018 12m



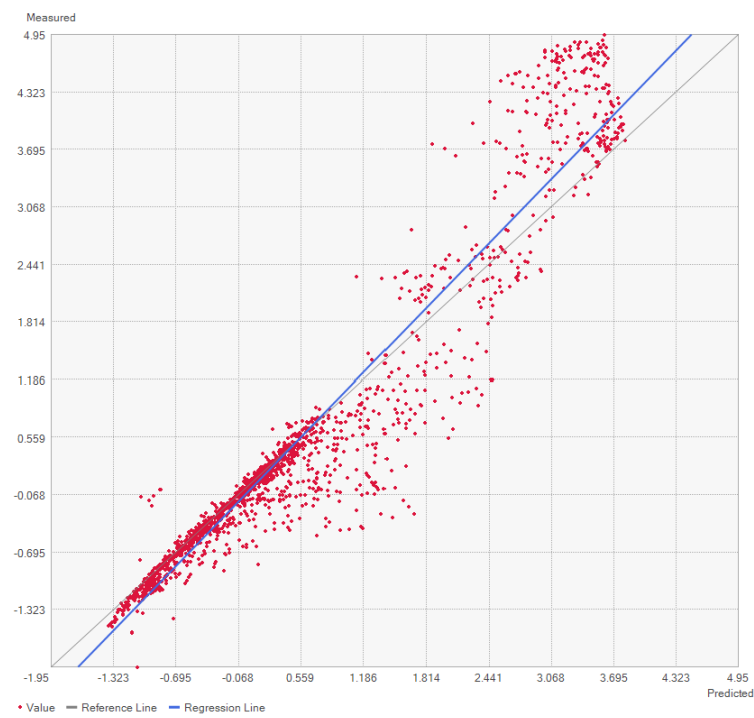
Regression function:  $1.11695557612633 * x + -0.0561153413256619$

## C12 – 2019 3m



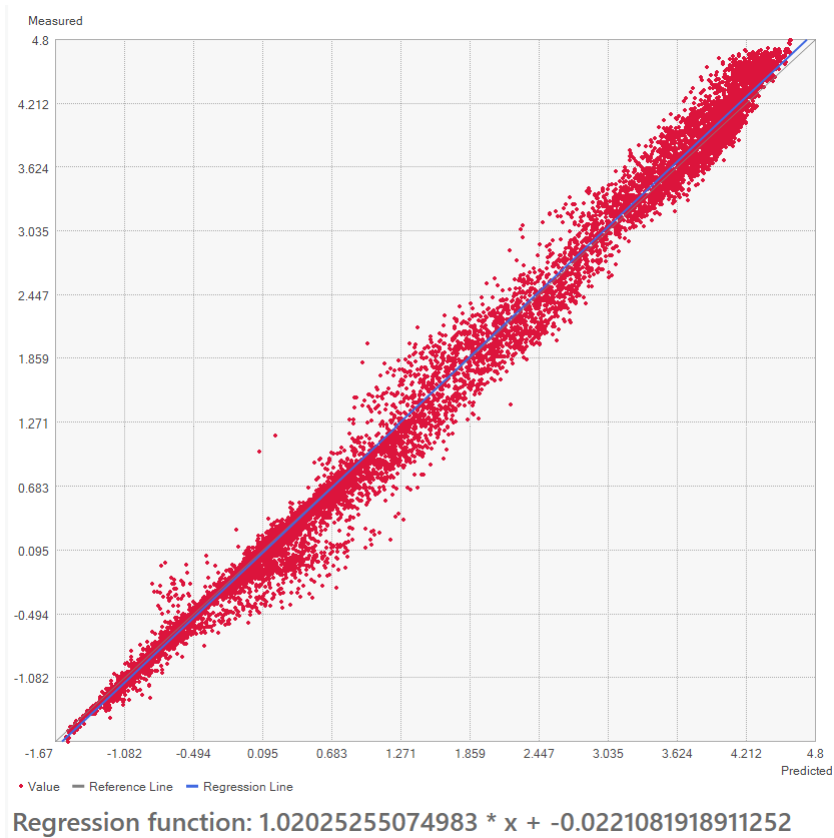
Regression function:  $1.01905926277142 * x + -0.024307552906699$

## C12 – 2019 12m

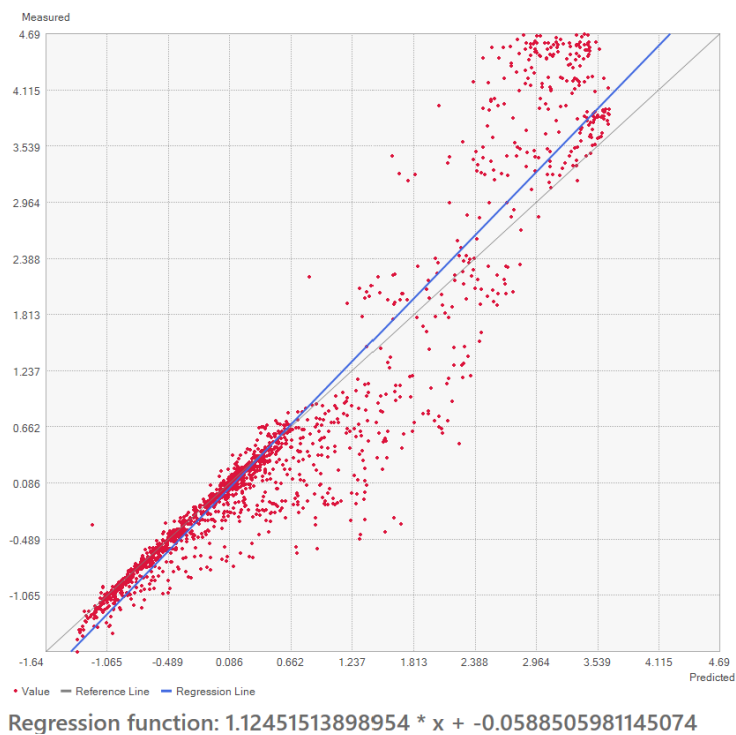


Regression function:  $1.1202121244912 * x + -0.0678089225600811$

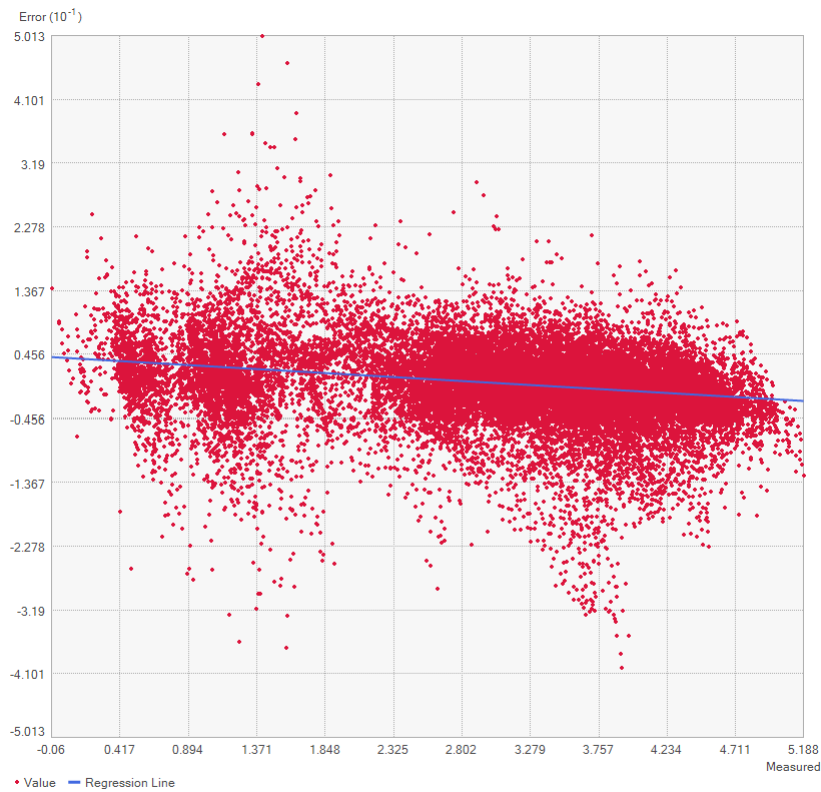
## C12 – 2021 3m



## C12 – 2021 12m

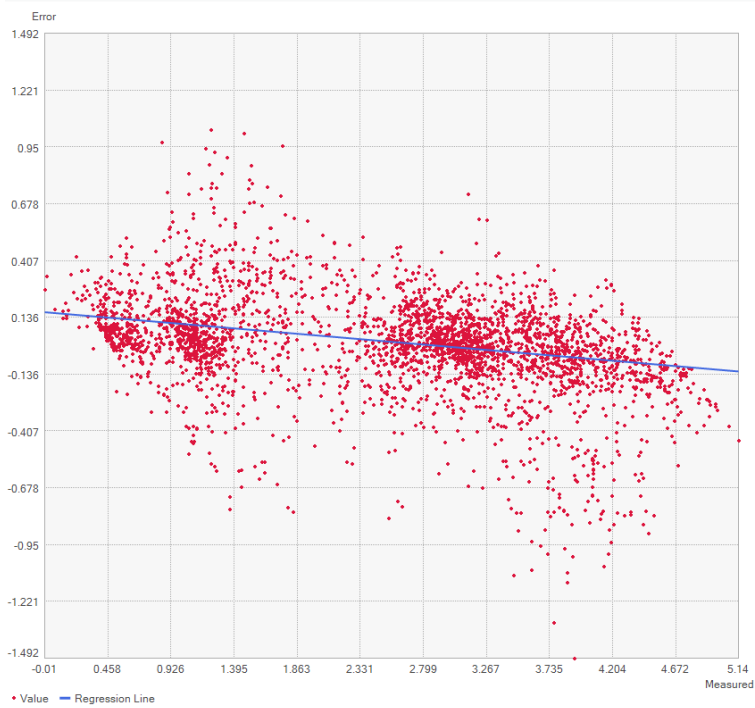


## C16 – 2016 3m



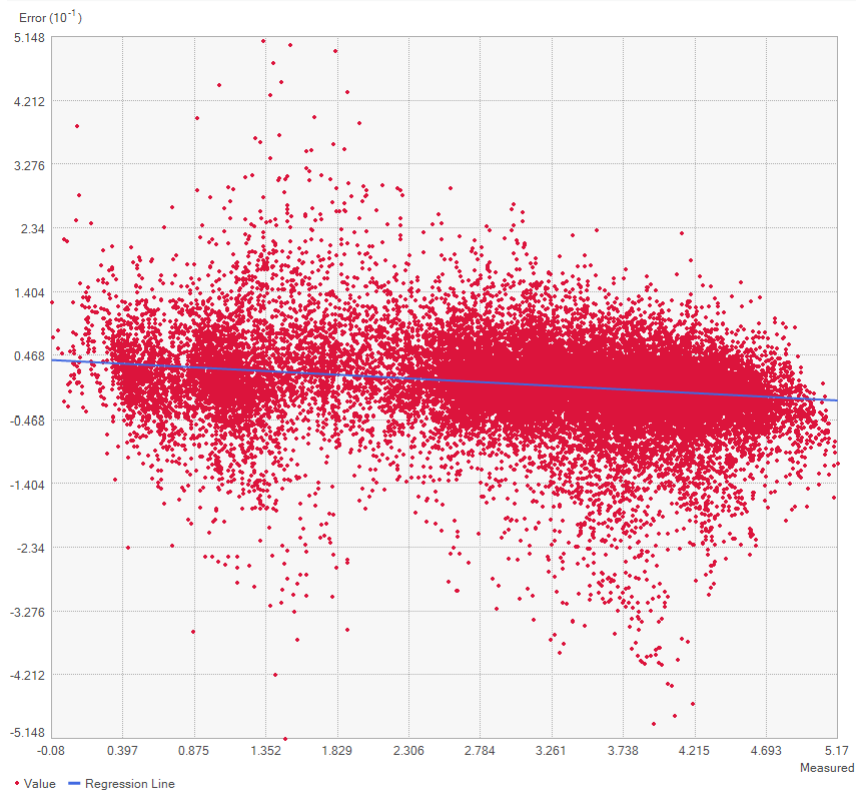
Regression function:  $-0.0119562103669287 * x + 0.0407393810739995$

## C16 – 2016 12m



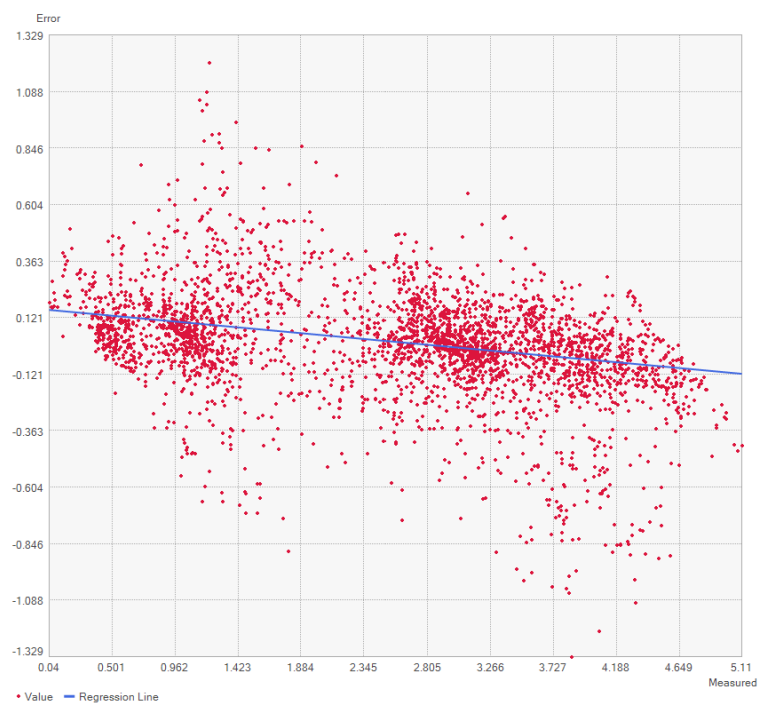
Regression function:  $-0.0549559682109234 * x + 0.159754408852535$

## C16 – 2018 3m



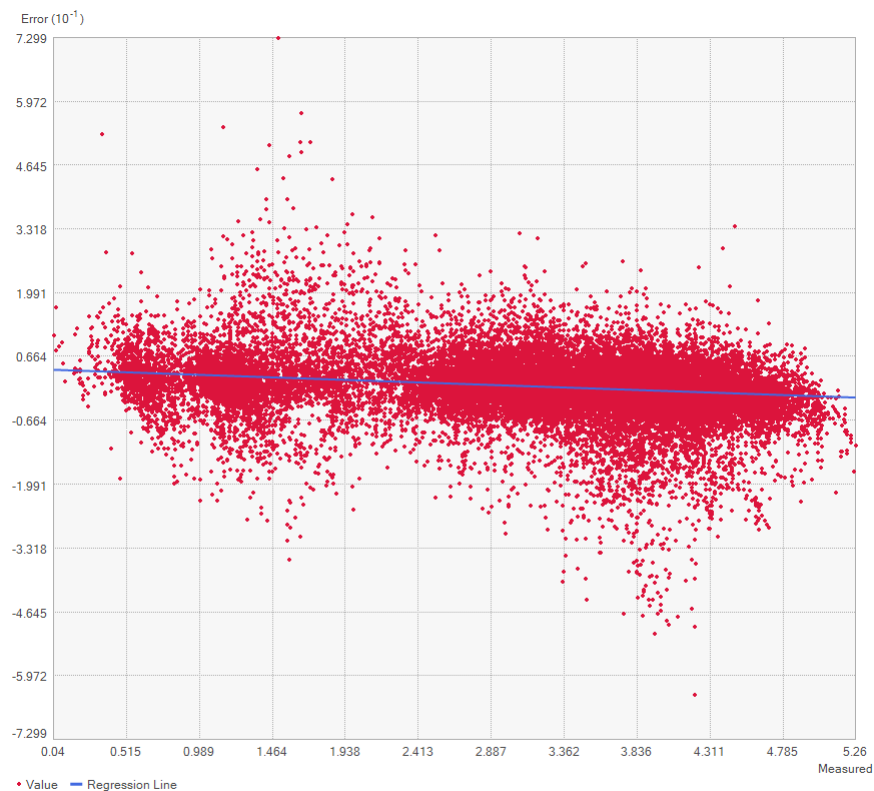
Regression function:  $-0.0113162938458941 * x + 0.0388857188816781$

## C16 – 2018 12m



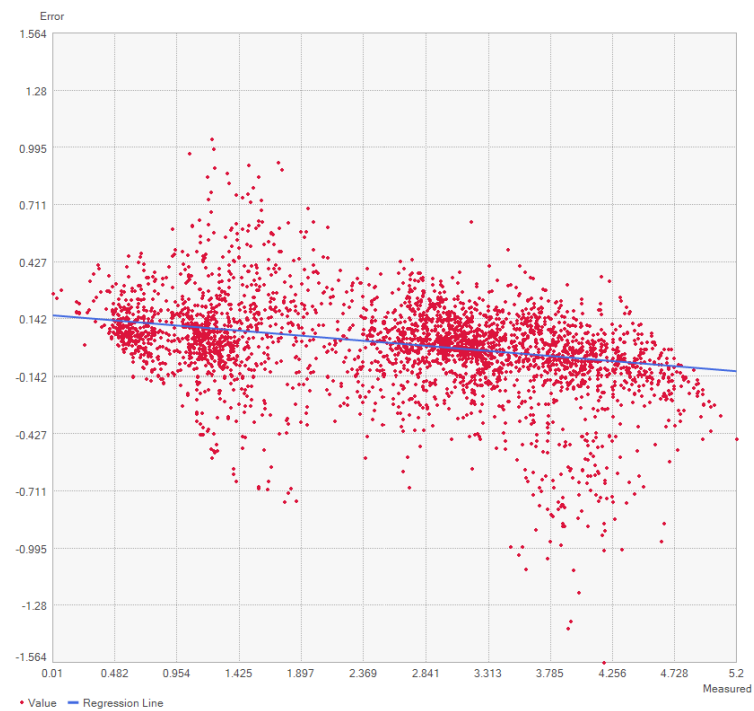
Regression function:  $-0.0538499771595229 * x + 0.155740081617646$

## C16 – 2019 3m



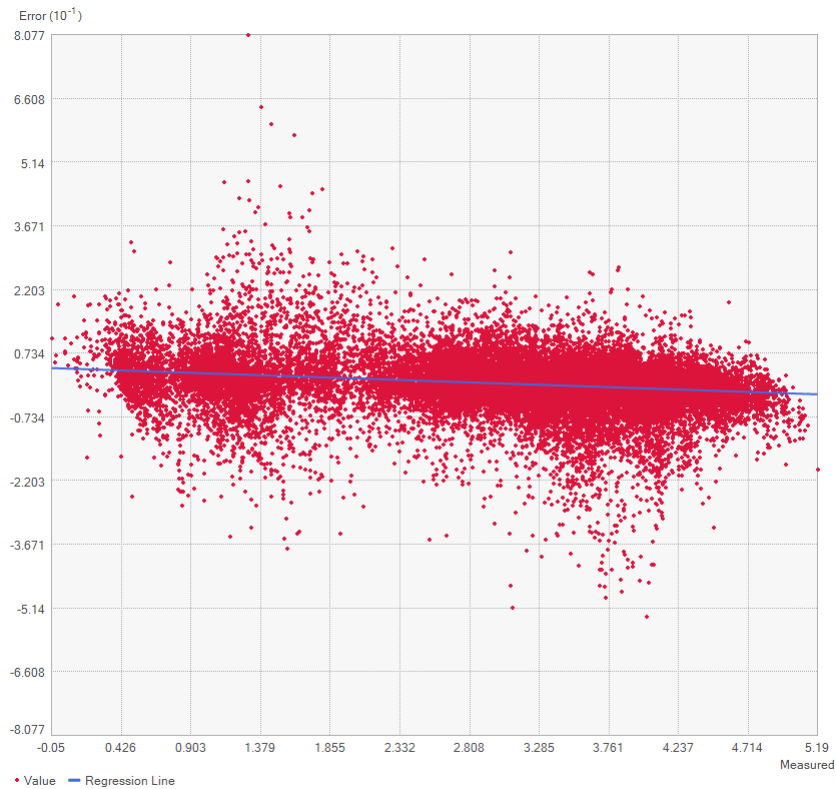
Regression function:  $-0.0110668890424779 * x + 0.0385038887007616$

## C16 – 2019 12m



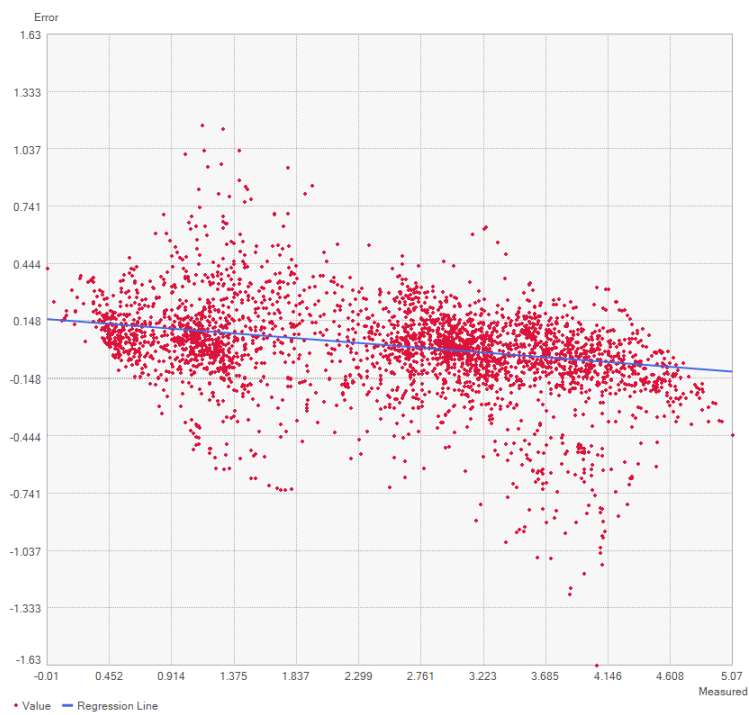
Regression function:  $-0.0535267568681008 * x + 0.159490350502865$

## C16 – 2021 3m



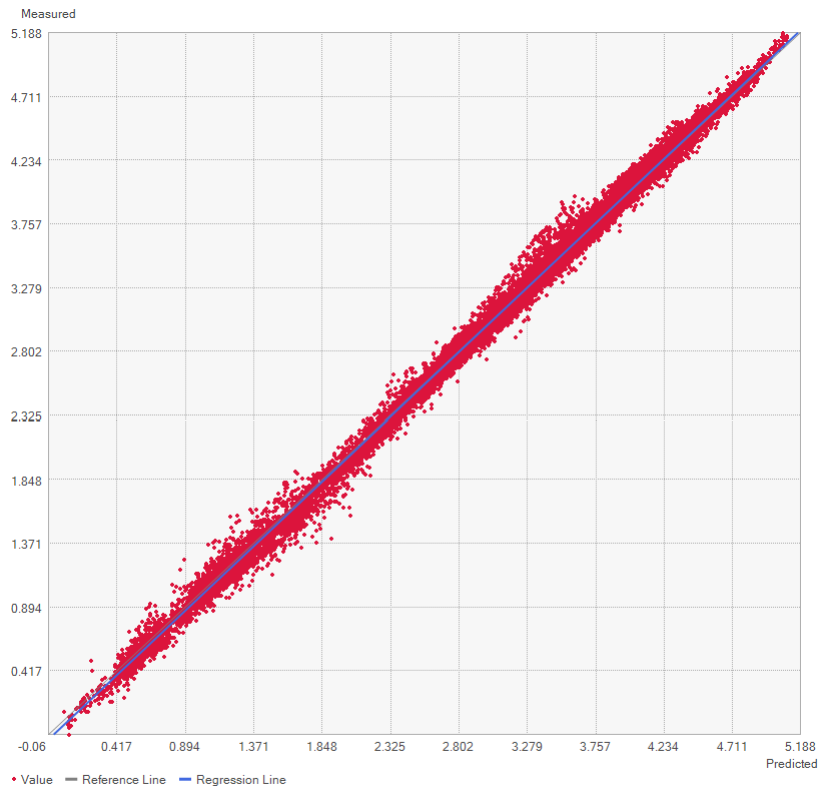
Regression function:  $-0.0115362533310563 * x + 0.0386543180001962$

## C16 – 2021 12m



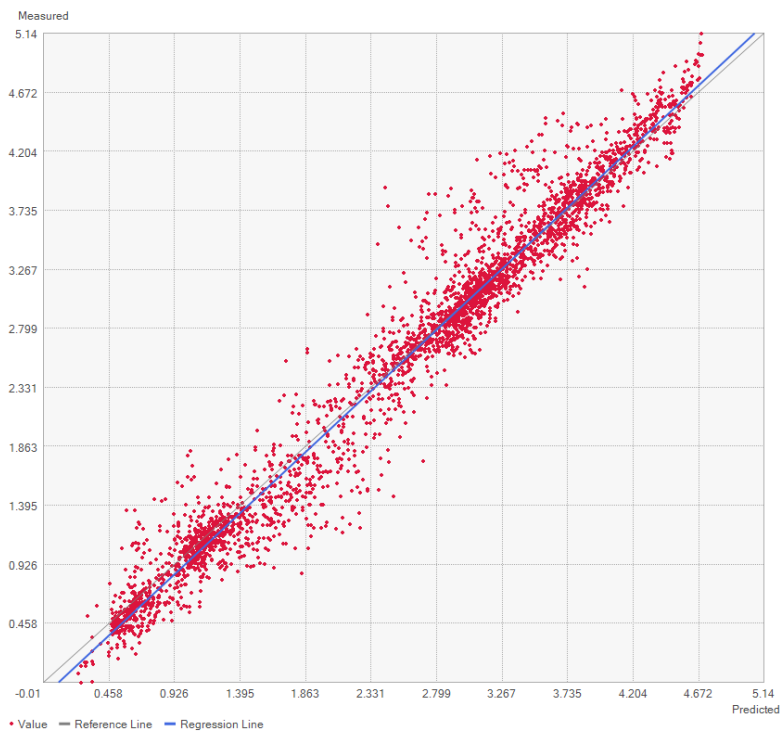
Regression function:  $-0.0534041137461043 * x + 0.1554352655496$

## C16 – 2016 3m



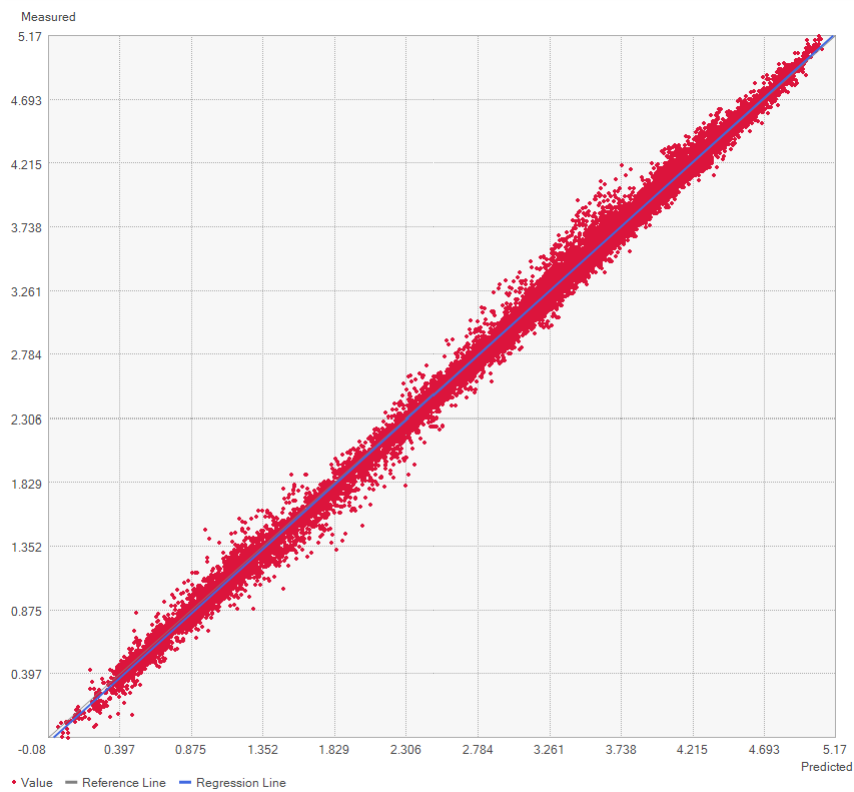
Regression function:  $1.01028722641101 * x + -0.0354335276384945$

## C16 – 2016 12m



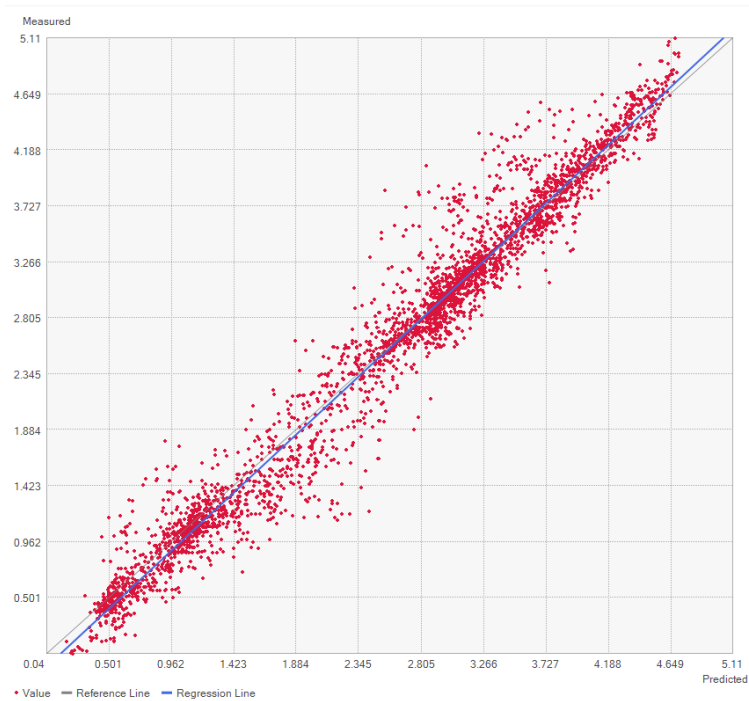
Regression function:  $1.03505124455345 * x + -0.110827751729168$

## C16 – 2018 3m



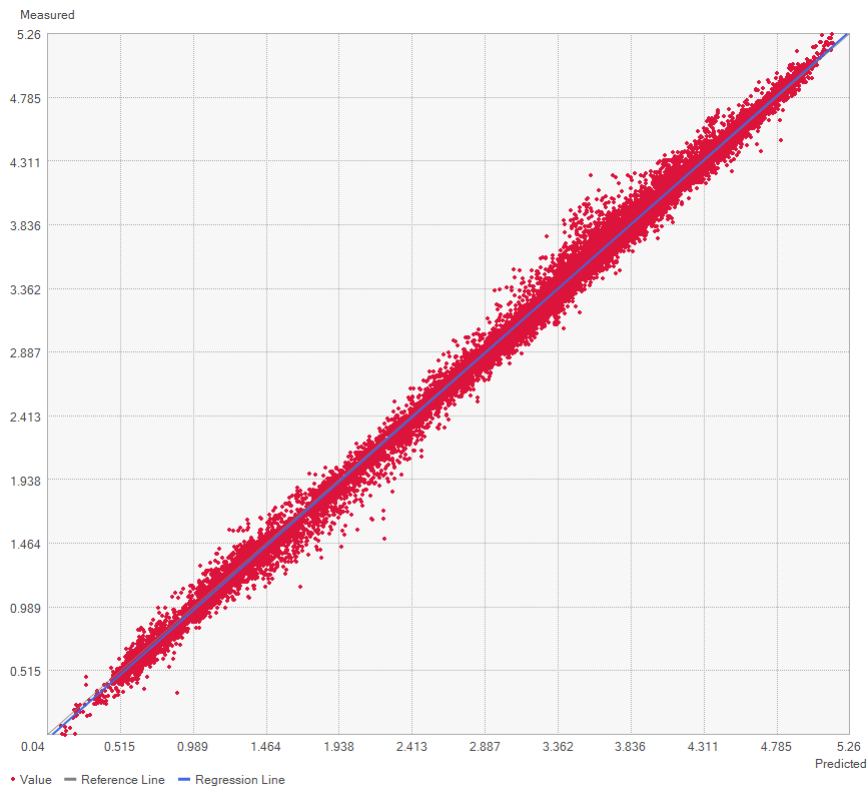
Regression function:  $1.00947687523289 * x + -0.0331331343387258$

## C16 – 2018 12m



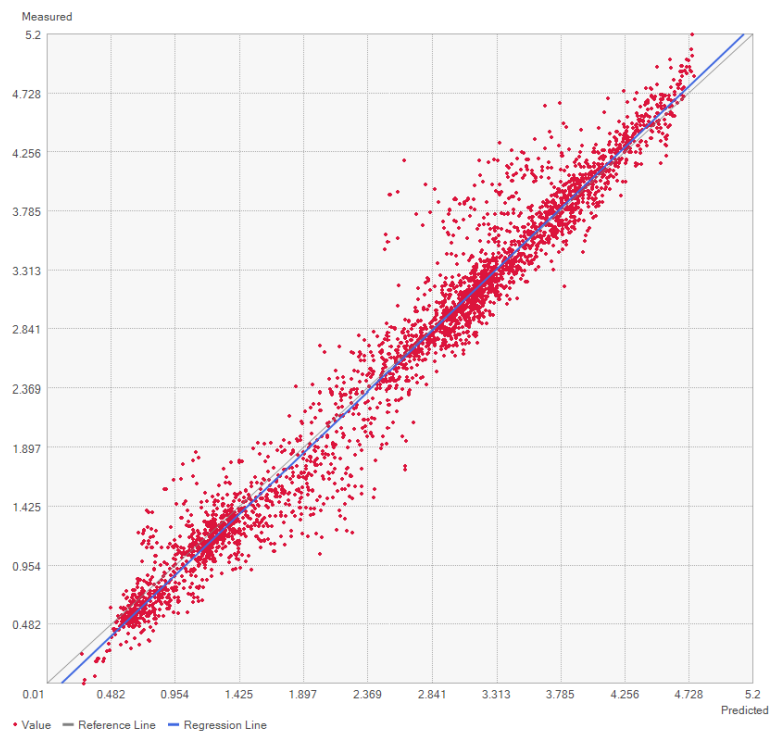
Regression function:  $1.03502739594927 * x + -0.108531390113894$

## C16 – 2019 3m



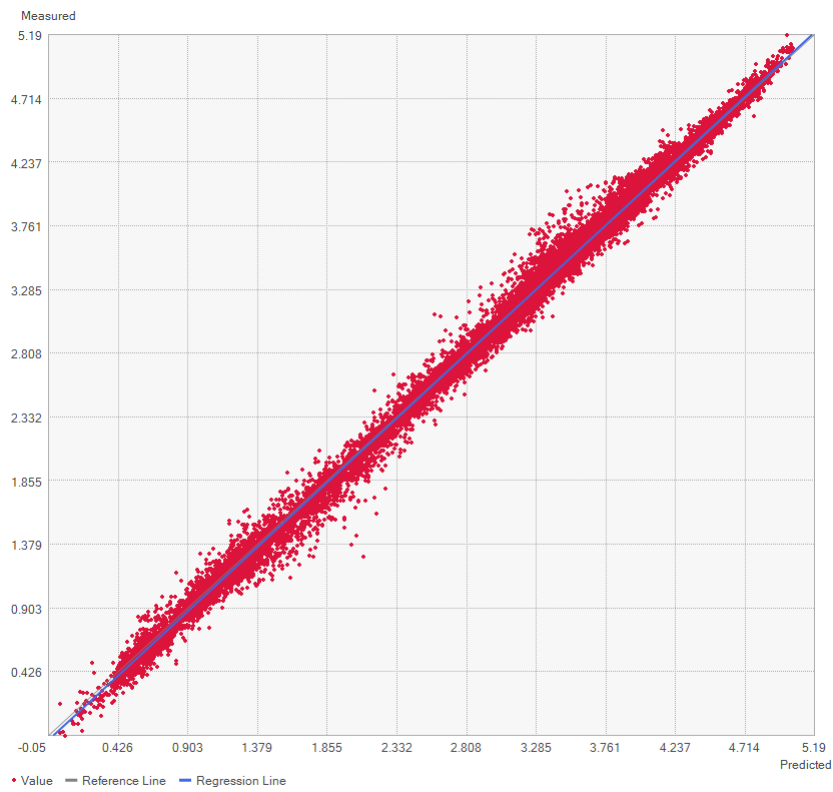
Regression function:  $1.00907682547551 * x + -0.0321266815645123$

## C16 – 2019 12m



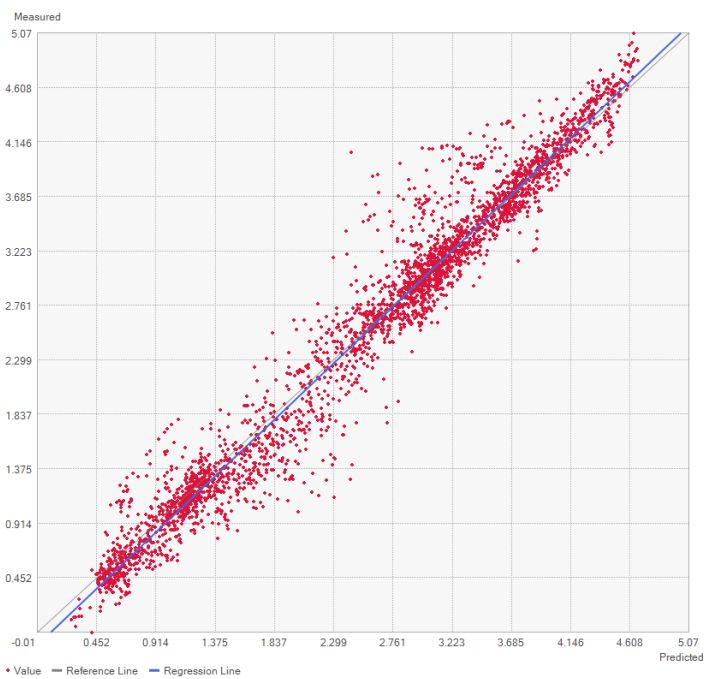
Regression function:  $1.03430967252404 * x + -0.110071561999542$

## C16 – 2021 3m



Regression function:  $1.00948691172712 * x + -0.0322465824286842$

## C16 – 2021 12m



Regression function:  $1.03385395484075 * x + -0.10742192327109$

Littoral Drift equations

$$Q_l = \frac{I_l}{(\rho_s - \rho)g(1 - e)}$$

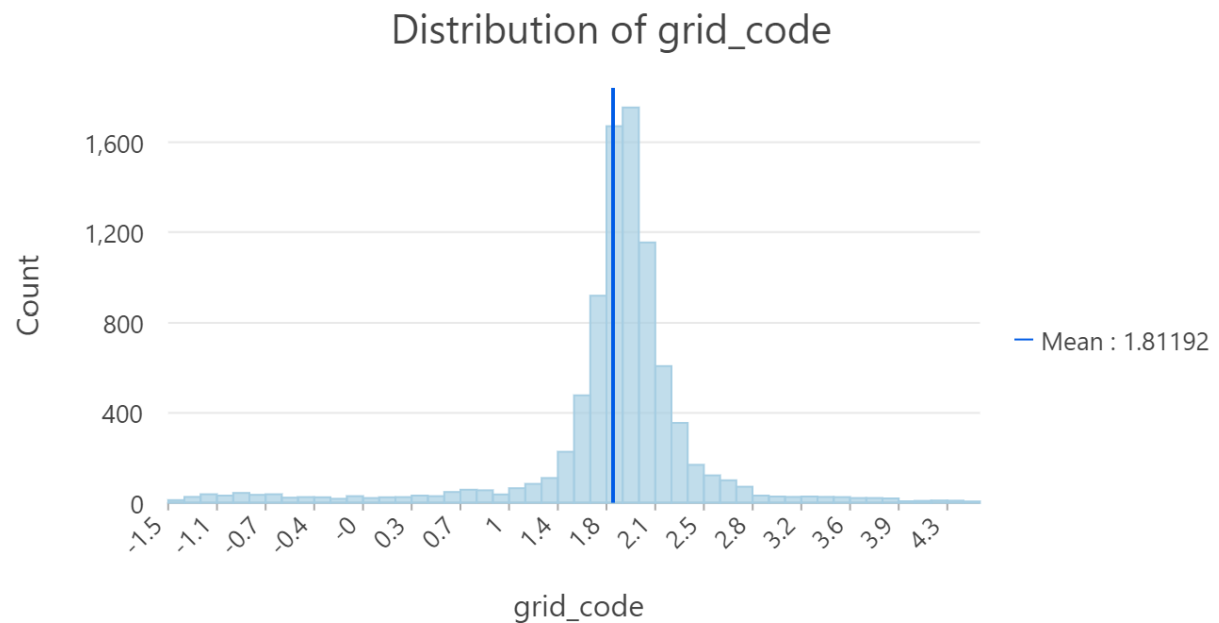
CERC formula taken from SOES3014 L25 Slide 17, delivered by Dr Hachem Kassem in 2023

$$Q_l = 7.3 H_{sb}^2 T_{op}^{1.5} m_b^{0.75} d_{50}^{-0.25} \sin^{0.6} (2\alpha_b)$$

Kamphuis 2002 formula taken from SOES3014 L25 Slide 20, delivered by Dr Hachem Kassem in 2023

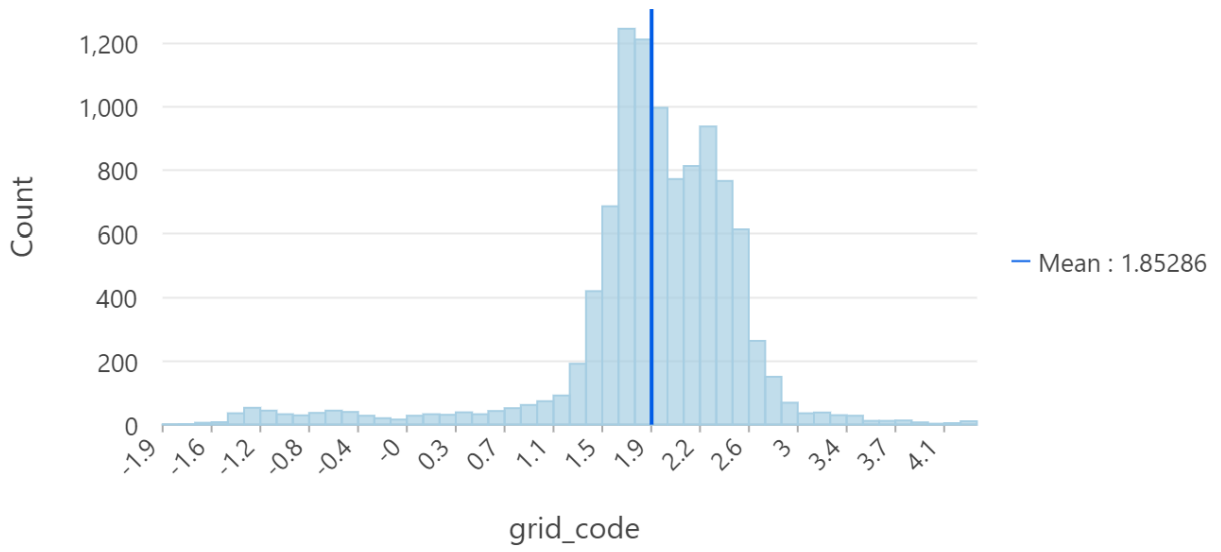
### Histograms

C1 2016 3m



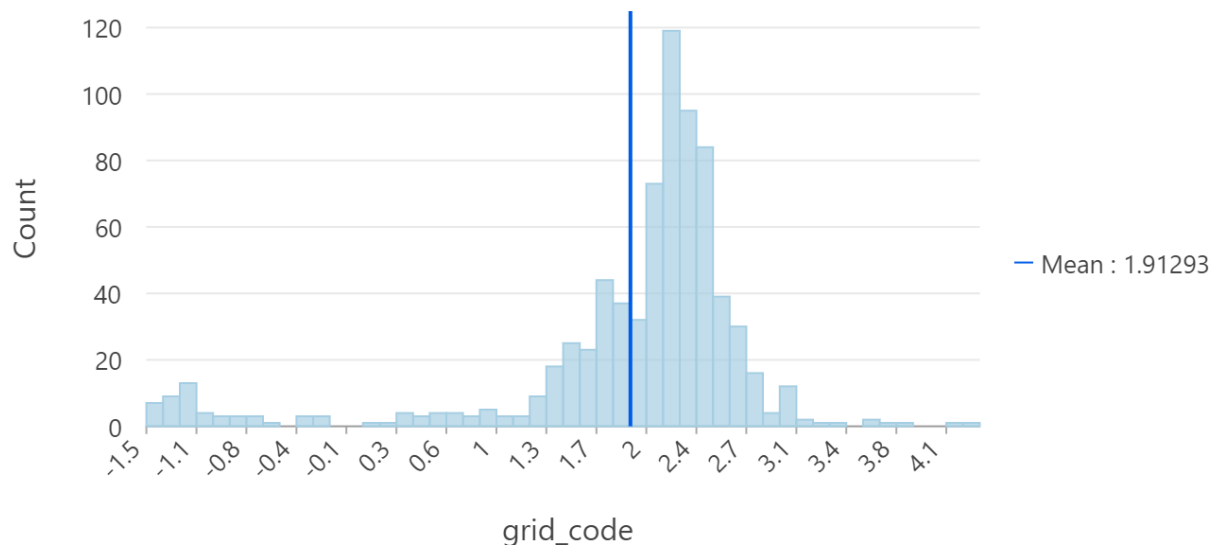
C1 2018 3m

Distribution of grid\_code

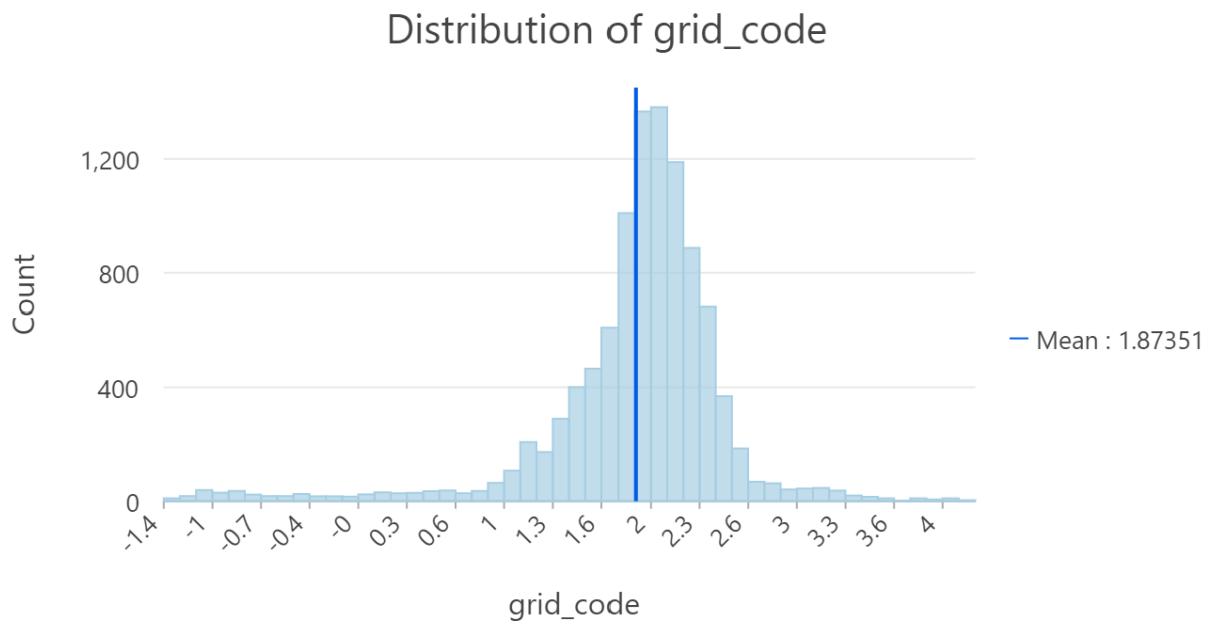


C1 2019 3m

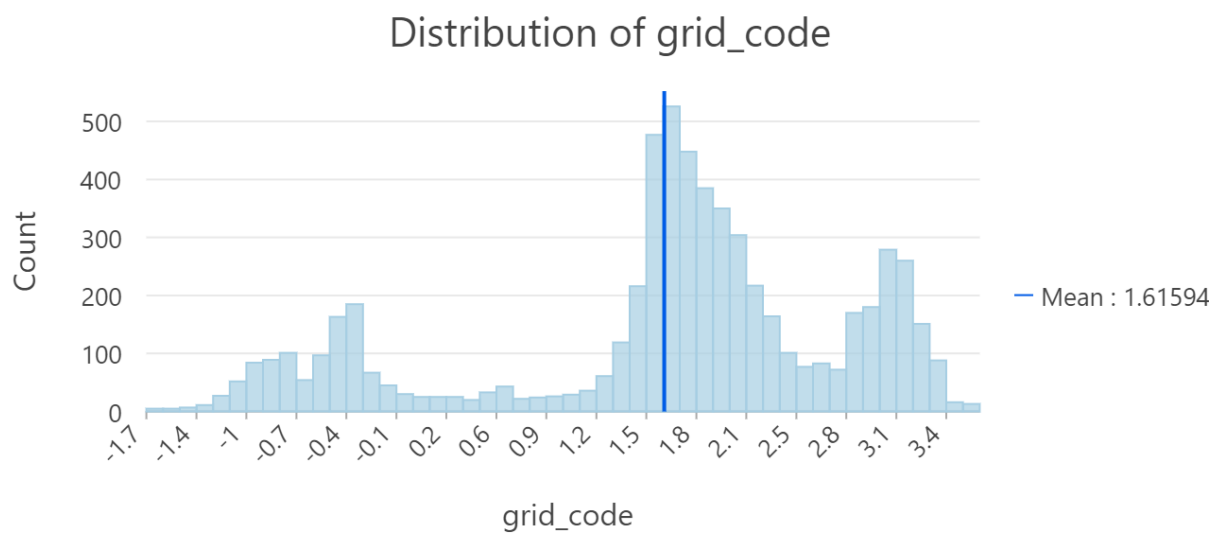
Distribution of grid\_code



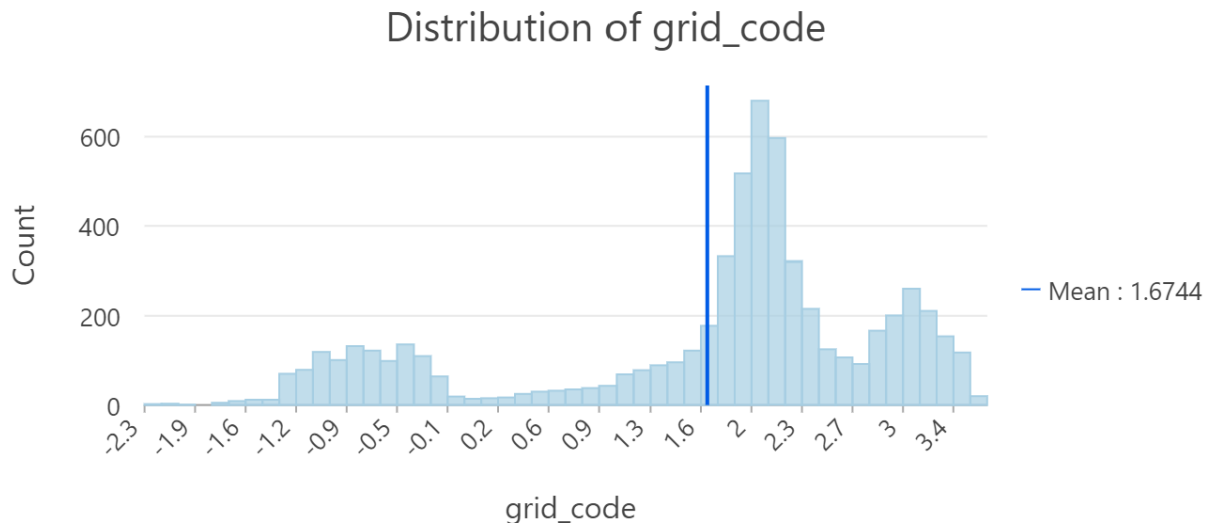
C1 2021 3m



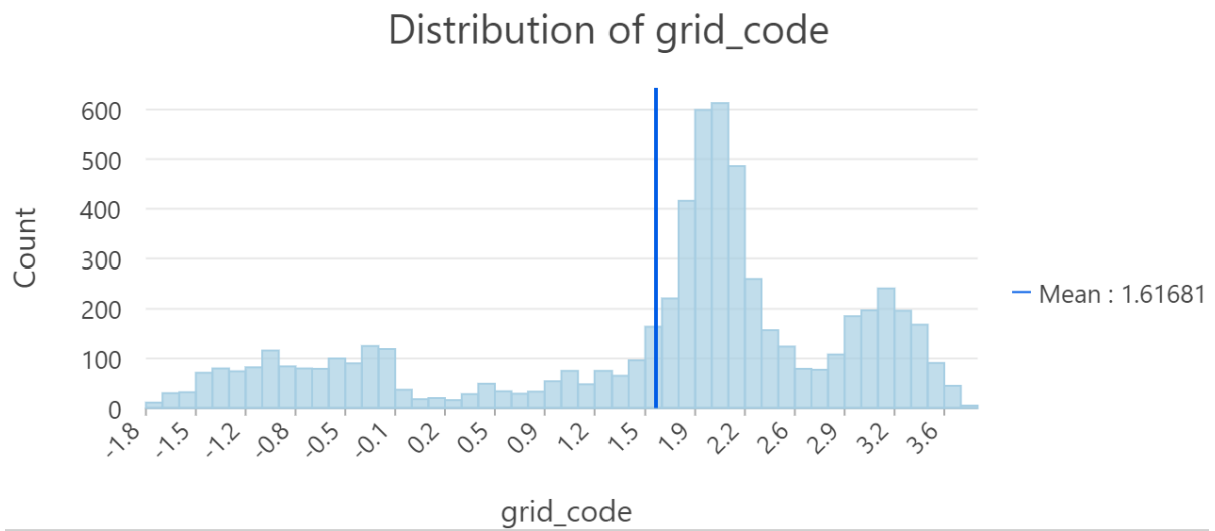
C2 2016 3m



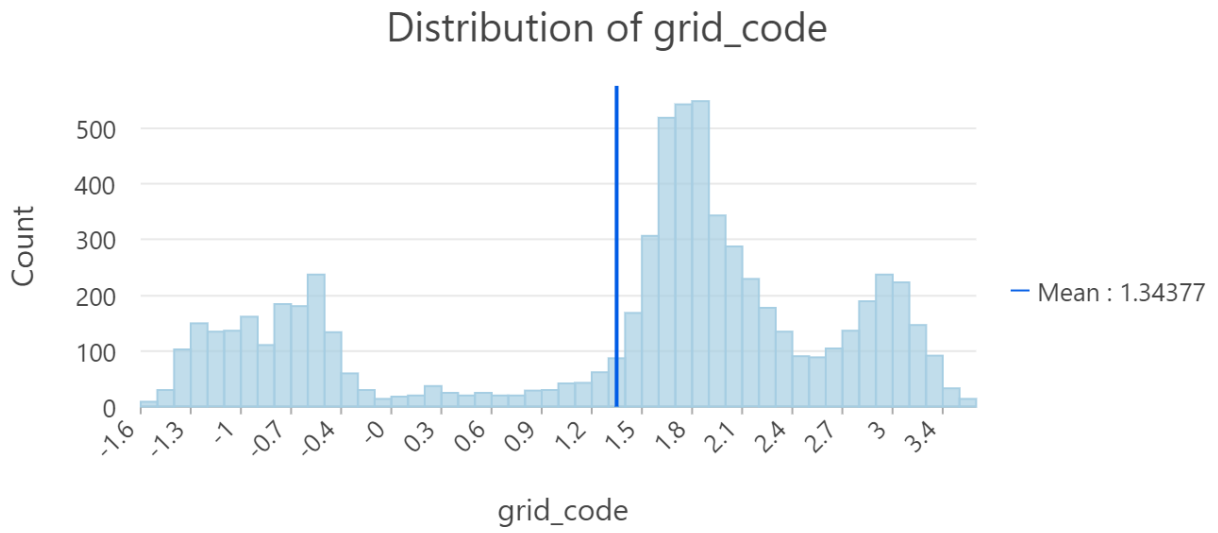
C2 2018 3m



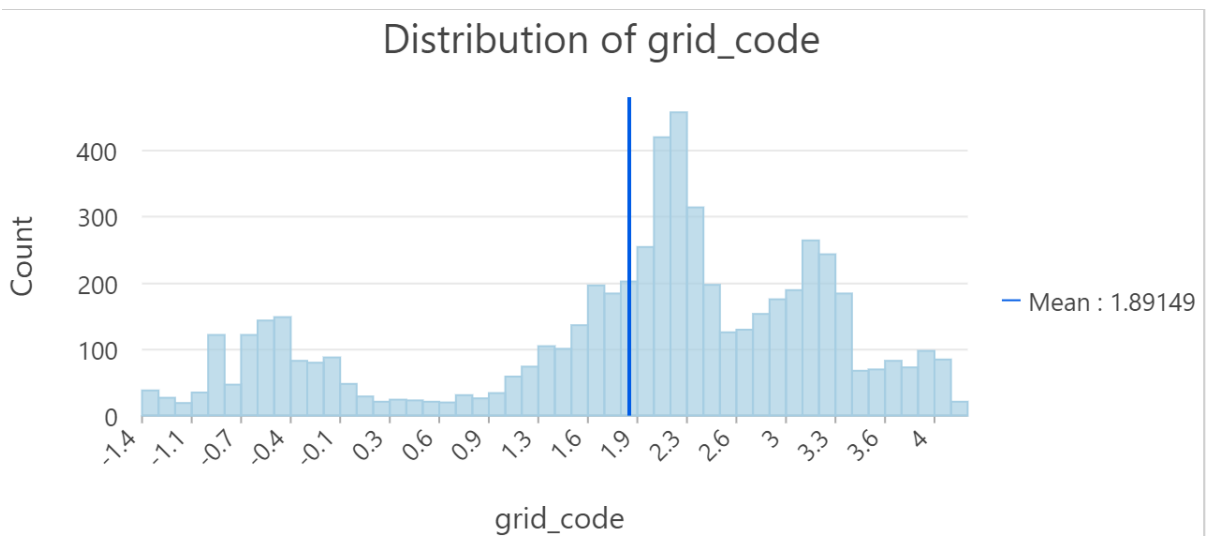
C2 2019 3m



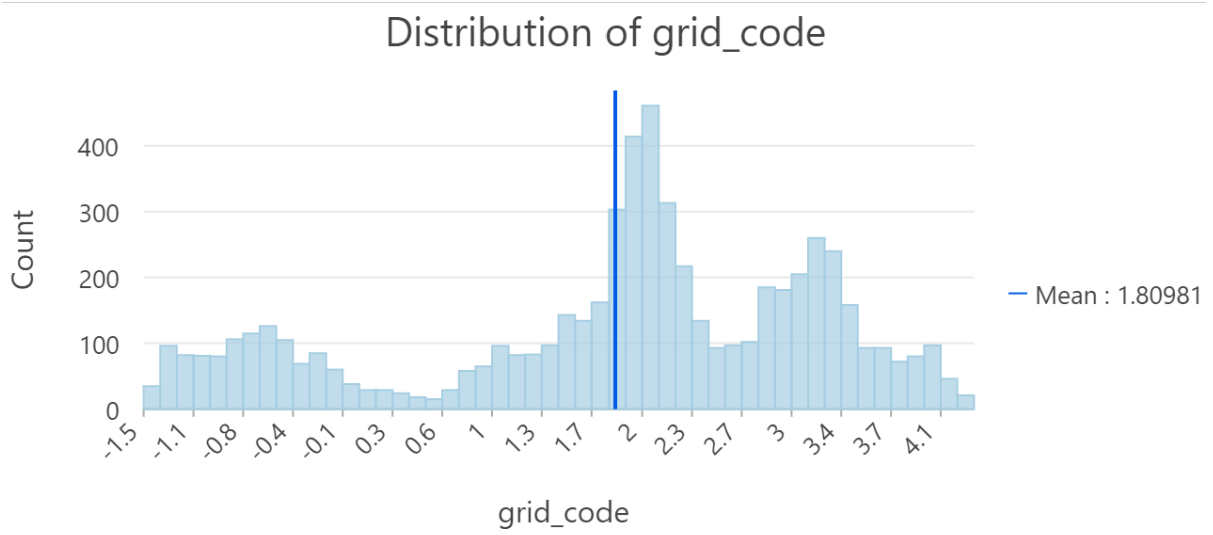
C2 2021 3m



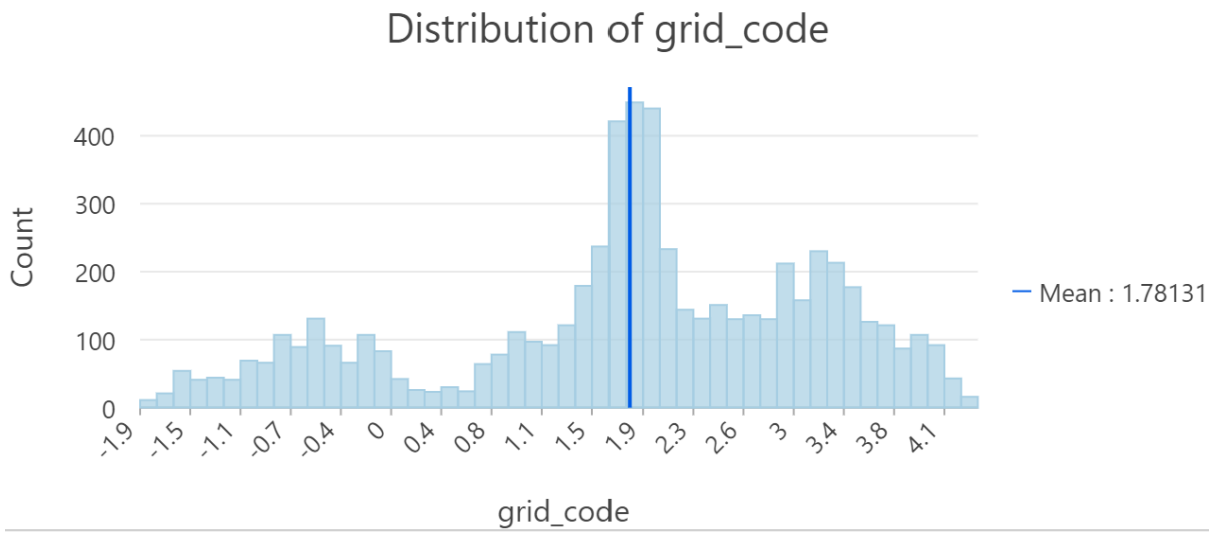
C5 2016 3m



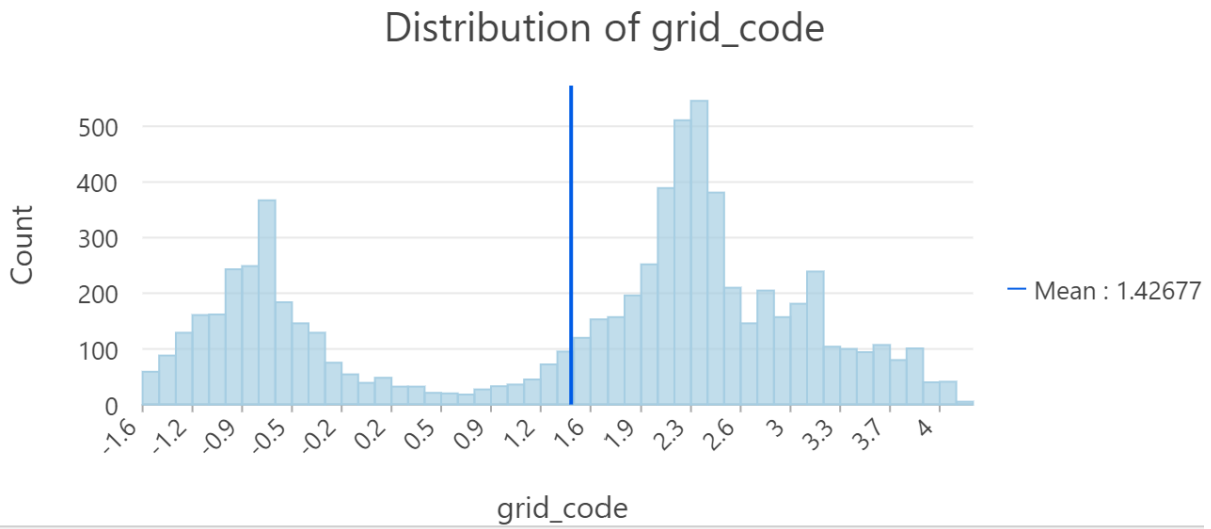
C5 2018 3m



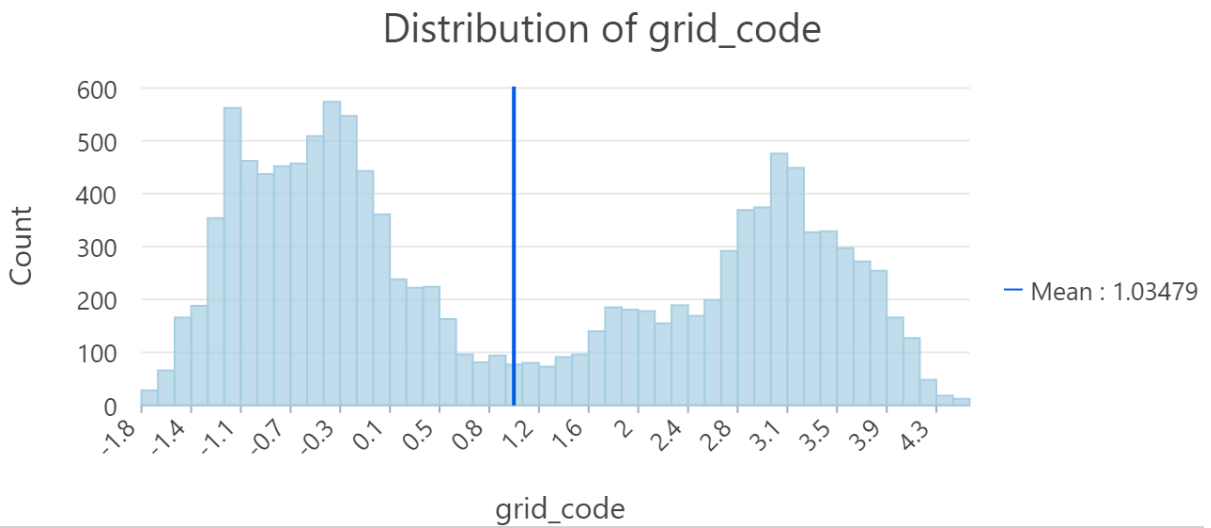
C5 2019 3m



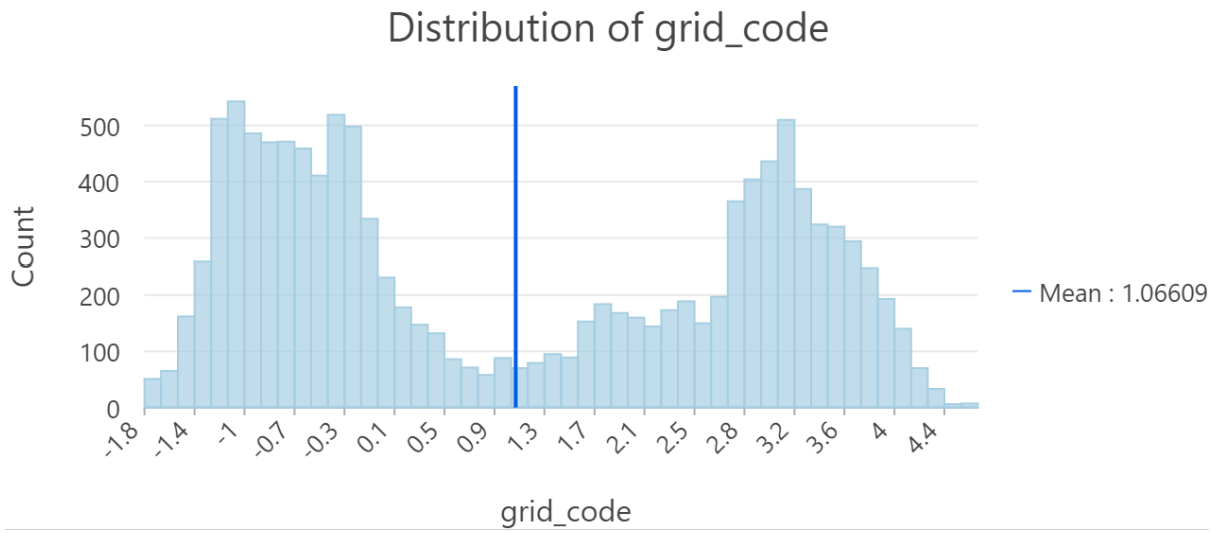
C5 2021 3m



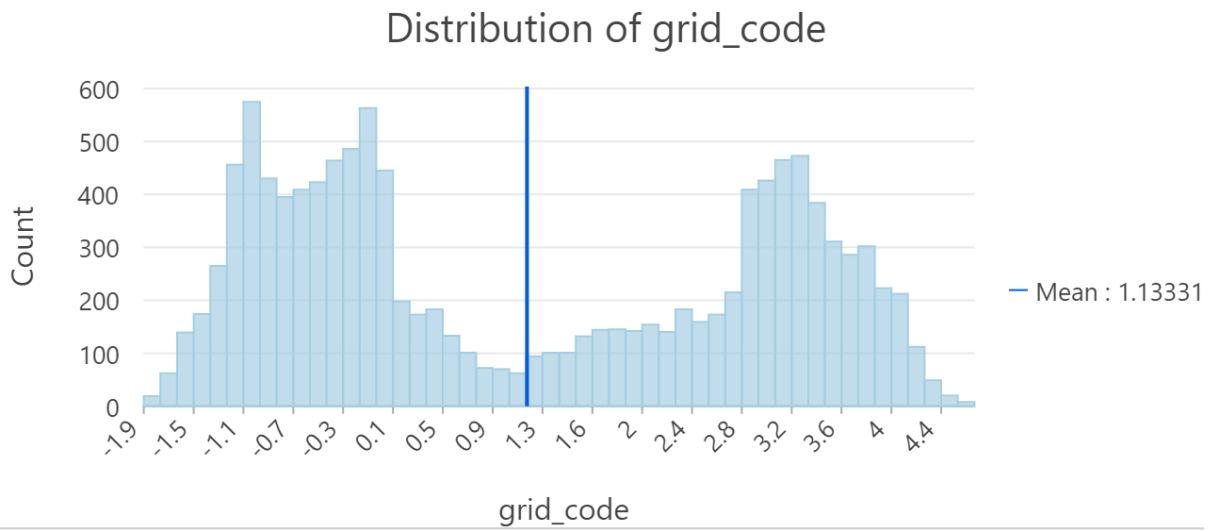
C8 2016 3m



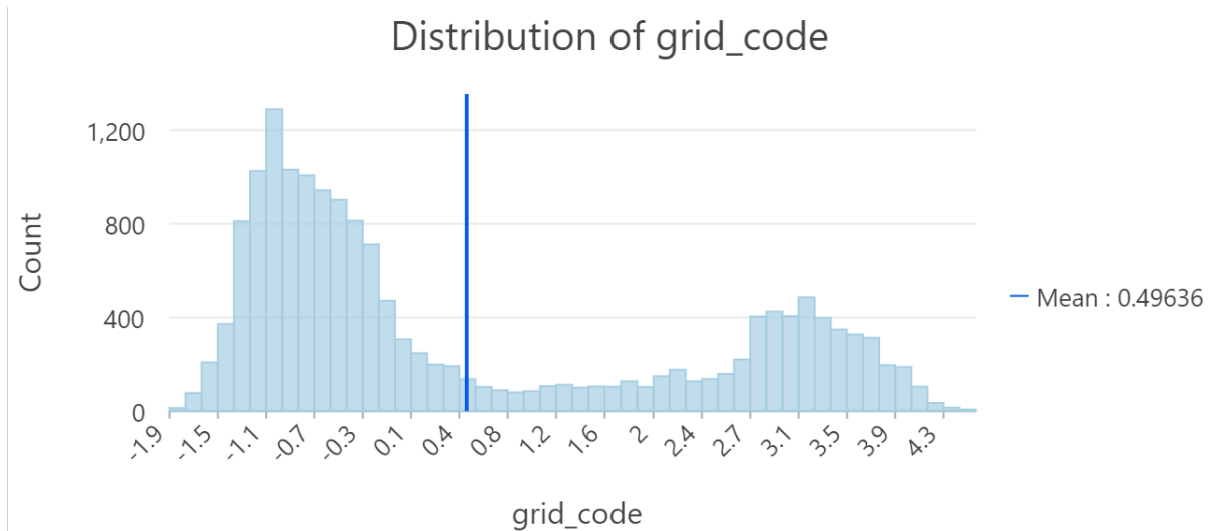
C8 2018 3m



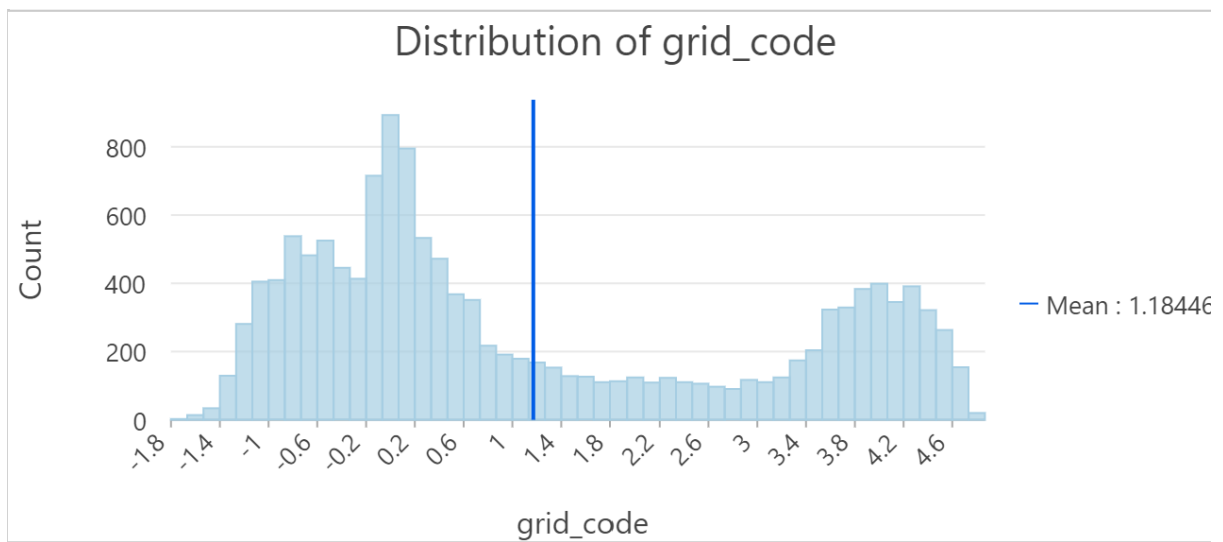
C8 2019 3m



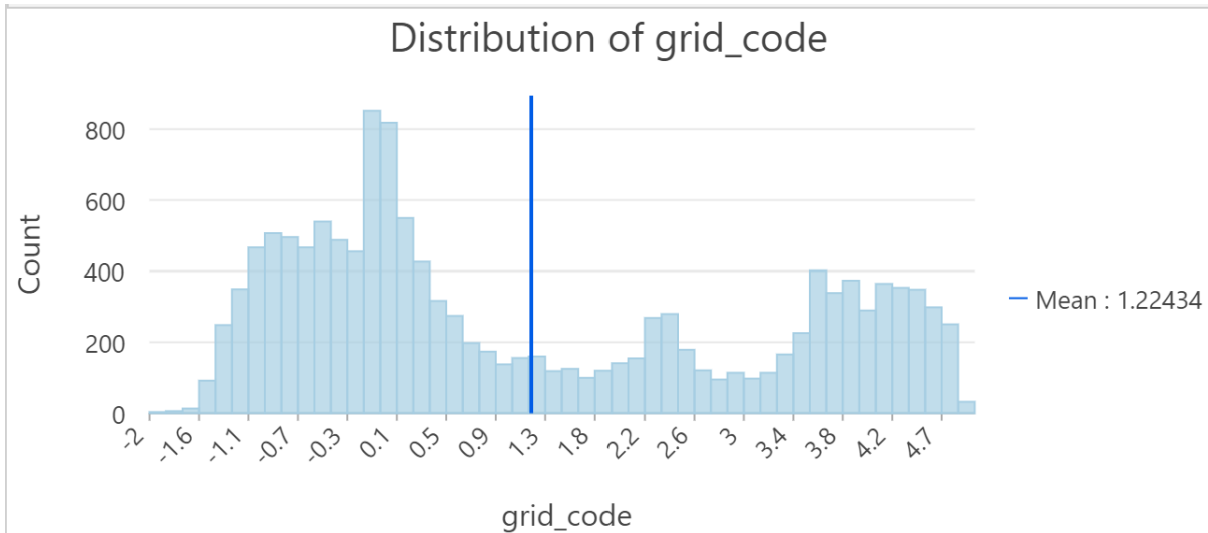
C8 2021 3m



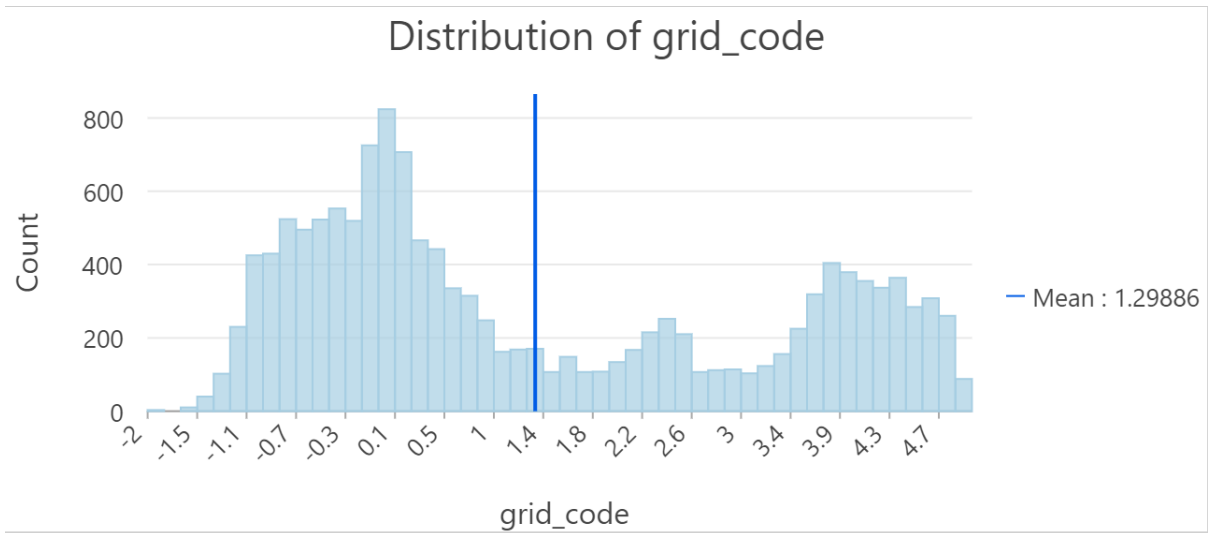
C12 2016 3m



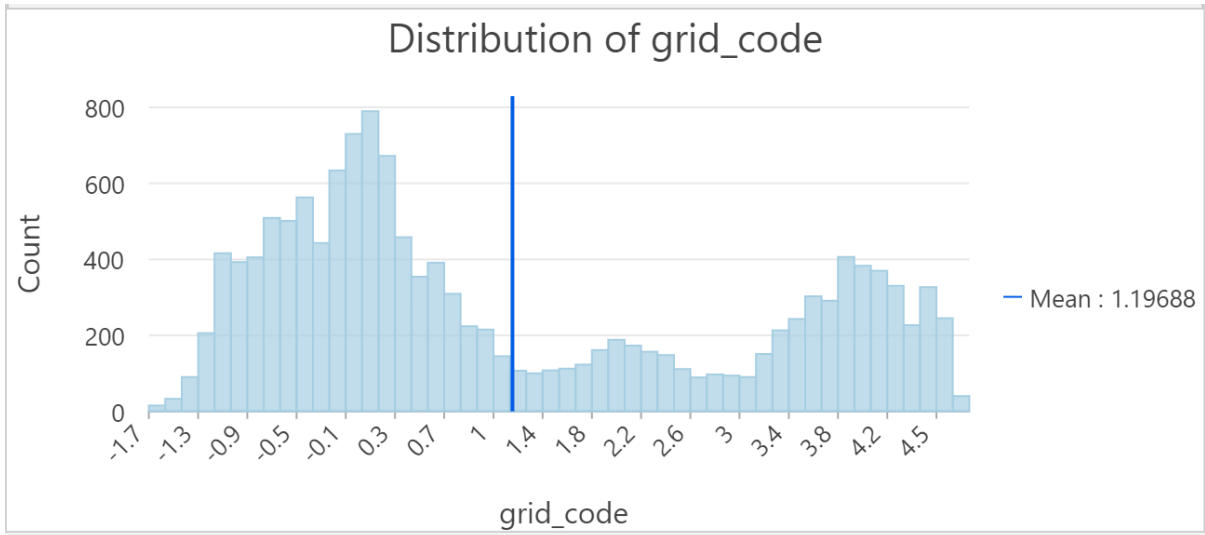
C12 2018 3m



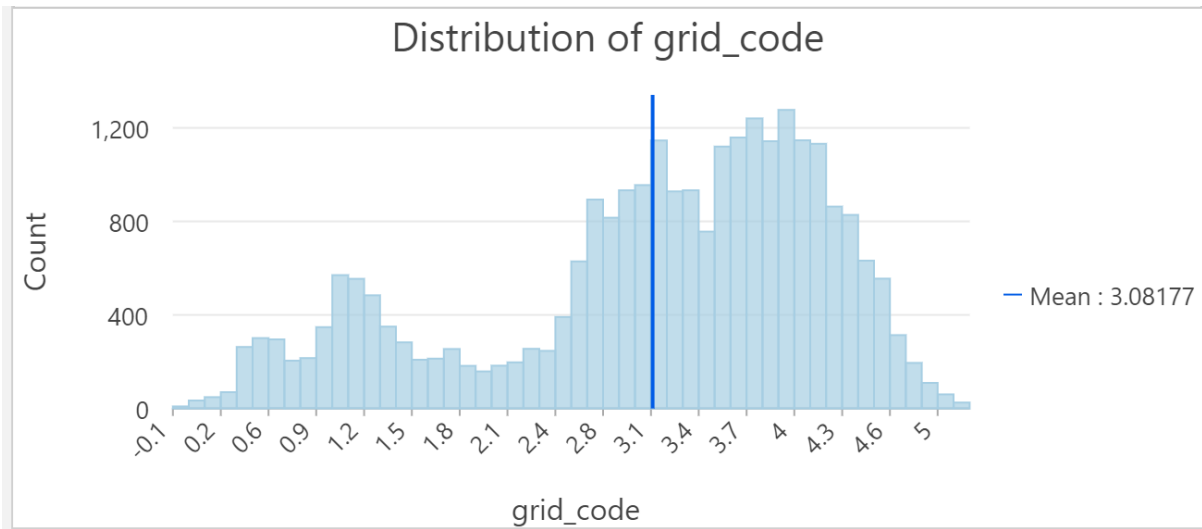
C12 2019 3m



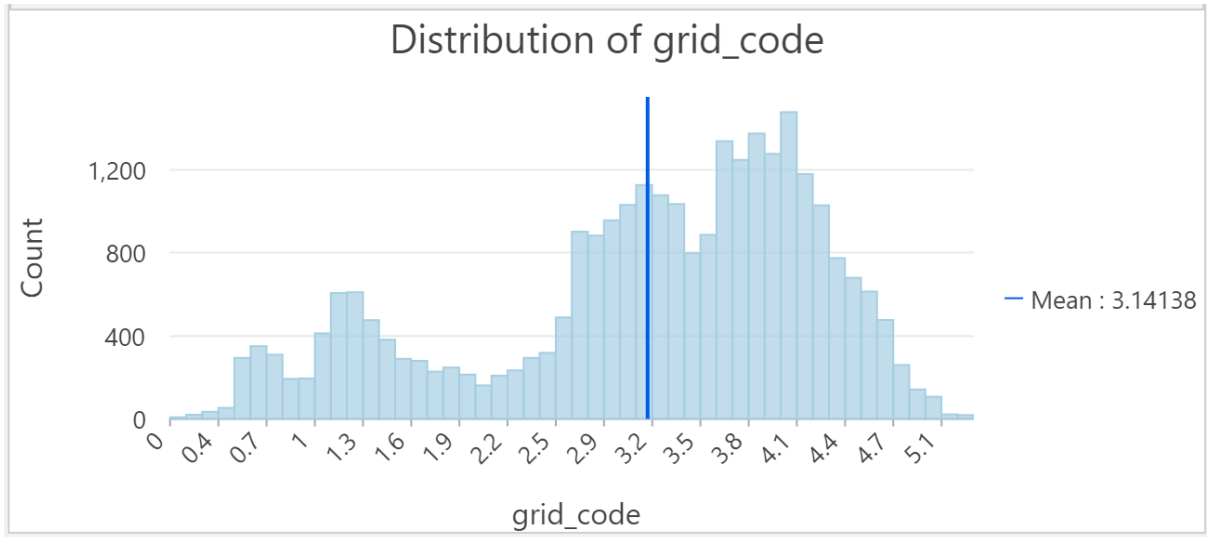
C12 2021 3m



C16 2018 3m



C16 2019 3m



C16 2021 3m

