The Teifi Estuary in a Changing Climate

Background Notes

Tim Wright … August 2023

Original Presentation 9th September 2023

Small World Theatre

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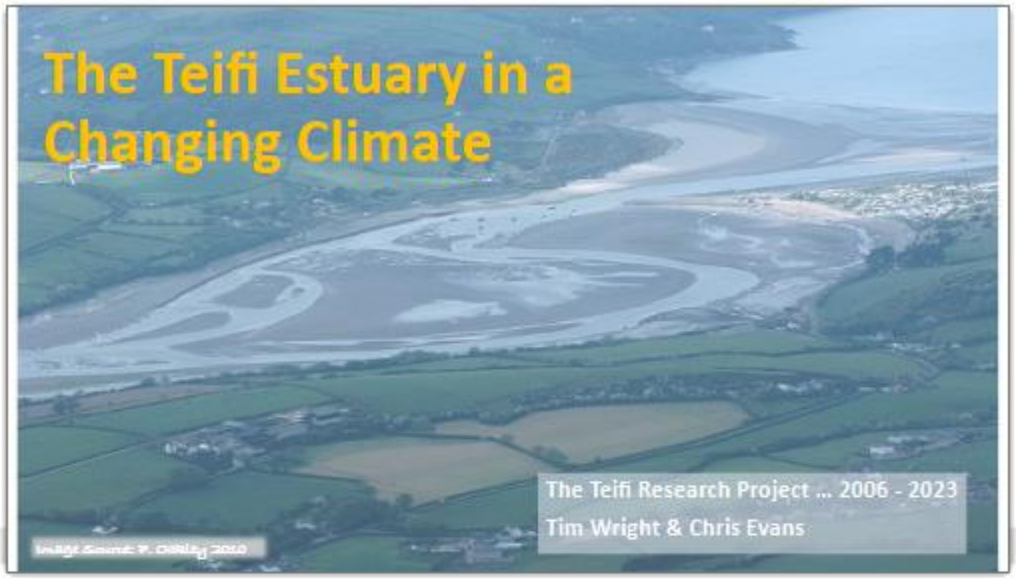
Abstract: The research project we undertake focusses on the core physical processes that operate within the estuary. Several of these processes are climate driven. Field observations, secondary data analysis and evidence gathered from research into the historical record reveal a compelling story of accelerating change. Inevitably, there is a range of complex contributory factors, but without doubt, climate change is a significant driver.

Further, small estuaries are poorly represented in terms of research focus. Much of what is understood is derived from research carried out on the larger estuary systems. Therefore, it is vitally important to continue to investigate the processes active within the Teifi estuary.

Important areas for future consideration should include:

- The changes to the tidal regime as sea level rises
- The interaction between river discharge and the tide
- Storm surge flood risk to sensitive infrastructure within the estuary and immediately upstream of Llechryd Bridge.
- Salt water penetration in the upper estuary
- The residence time of fresh water discharges into the estuary.

[This list is not exclusive however, and of note is the absence of habitat focus, which is outside of our expertise.]



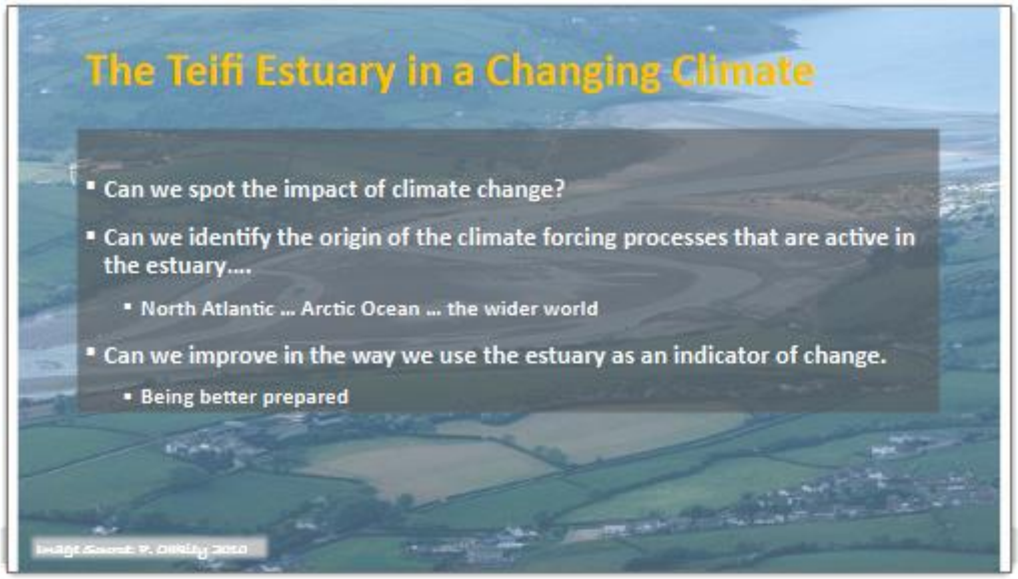
Slide 1. …

The Teifi Estuary in a Changing Climate

Introduction. **Teifi Research Project** – This is a 20 year collaborative study of the estuary carried out by Chris Evans and Tim Wright. However, both participants have been involved in separate research in the estuary and Teifi valley for over four decades. The information covered in this presentation is just a small part of the area of study.

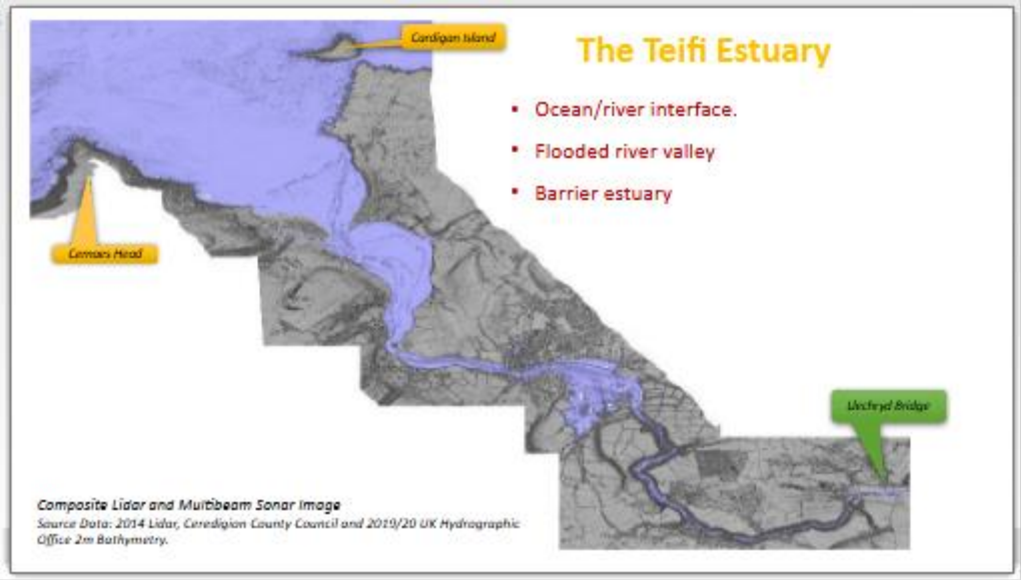
Chris Evans is a retired British Geological Survey officer who specialised in offshore aggregates.

Tim Wright is a retired local teacher and a Quaternary science specialist.



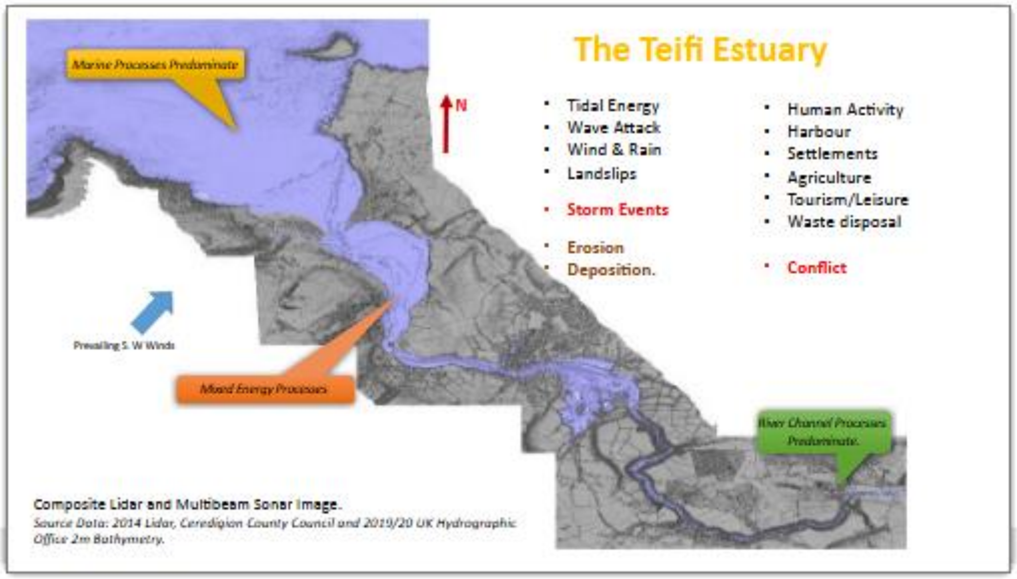
Slide 2. … **Presentaion Outline**

- Can we spot the impact of climate change? [On the processes operating with the estuary]
- Can we identify the origin of the climate forcing processes that are active in the estuary….
    - North Atlantic … Arctic Ocean … the wider world
- Can we improve in the way we use the estuary as an indicator of change.
- Being better prepared [Forecast, rather than hind-cast.]



Slide 3. … **Brief introduction to the Teifi Estuary and estuary processes**.

- The background estuary image. Lidar and multibeam sonar data. [Both formats provide accurate location detail for every data point. [An elevation value is also recorded. Lidar m ODN … multibeam sonar -m CD]
- The estuary survey area is defined by … Cardigan Island to Cemaes Head to seaward. Llechrhyd bridge as the head of navigation upstream.
- Ocean/river interface. [Rich variety of habitats, great range in energy expenditure and sediment type availability]
- Flooded river valley [Great environmental diversity during recent geological history. Marine, river, lake and glacial deposits are all present. 60m of sediments below the current surface sands to rock-head. Repeatedly inundated by the sea with the current situation only coming about in the last 5,500 years or so.
- Barrier estuary   [Form of estuary classification based upon geomorphological features rather than say the tidal characteristics. The barrier in this instance is the Bar/Lower Poppit sands.]



Slide 4. … **Physical Processes and the Use the Estuary is put to.**

- Marine processes predominate in the outer estuary
- River channel processes dominate in the upper estuary
- In between … when the tide is in, marine processes … tide out, river channel processes

Orientation of the estuary re waves and wind direction. … [Poppit in the main is more sheltered and the expanse of sand helps to dampen wave energy. Gwbert/Pen yr Ergyd is much more exposed and deeper water permits waves to be more energetic/destructive.]

Prevailing offshore winds help reduce storm surge impact, but can provoke steep adverse wave forms over the bar.

Estuary becomes more vulnerable if storms approach from the north. [Of note: North Atlantic low pressure systems are becoming much more variable in terms of energy, direction of approach and longevity over the British Isles.]

Physical Processes

- Tidal Energy … [Spring/Neap tide cycle. Tides distribute sediment. Flood tides have more energy than Neap tides. Helps explain why estuaries silt up over time]
- Wave Attack … [Constant change of energy levels and orientation.]
- Wind & Rain … [Wind moves dry sand – responsible for dune formation.]
- Landslips … [Rock falls mainly occur in the outer estuary. Rare, but becoming more prevalent in Cardigan Bay]
- **Storm Events …** [Source of dramatic change. Tail end of Hurricane Lily in the 1990s struck at low water. Even so waves had sufficient energy to cross Poppit sands and erode a 2m scarp in the face of the dune system. Took 8/10 years to repair.]
- **Erosion …** [Constant – varying scale over time]
- **Deposition**. … [Constant change depending on the availability of sediment.]

Change and time scales … minutes, hours, weeks, months, seasons, decades, century scale. The estuary exhibits them all.

Human Activity

- Harbour
- Settlements

- Agriculture
- Tourism/Leisure
- Waste disposal

Conflict … [between the various human uses and between the human uses and physical processes.]

From slide 5 we start a trip downstream from Llechryd Bridge to the sea covering a few of the processes that are climate driven and illustrate changing scales.

Slide 5. **… Flooding, Llechryd Bridge**

Flood water input into the estuary … River responding to a high rainfall event over the catchment. This may have occurred over several days, or be in response to a discrete high volume intense down pour.

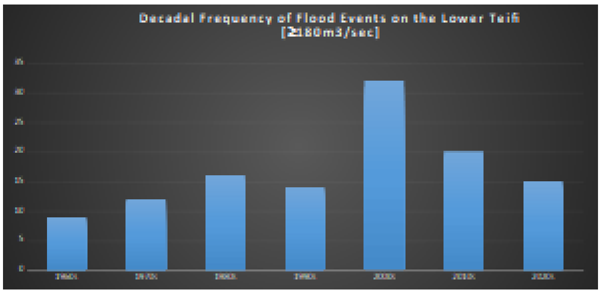
[Most of these event move into and through the estuary without causing too much of a problem to settlements, infrastructure, or other human interests. This is usually because:

- The flood duration is short. Hours/not days.
- The tide cycle is favourable … Ebb tide, low water or one of the smaller neap tides.
- There is plenty of space for the water to expand into …. Pentood marsh and the extensive area of mud and sand banks between St Dogmaels and Poppit/Pen yr Ergyd.

But if it coincides with a Spring High Water things can be very different …

Slide 6. … **November, 2014 Cardigan Floods Image**

Flooding Gloucester Row, St Mary's Street, Pwll Hai and part of the Strand. Resulted from a combination of a big Spring High Water coinciding with high Teifi discharge.



Slide 7. … **Part 1 … The data does always tell the complete story**

Data analysis … Graphic depicts the number of days per decade when the peak discharge is equal to, or exceeds 180m^3/sec. [The data is derived from the Glan Teifi gauging station located between Cenarth and Llechryd and describes events on the lower Teifi. Here a flood event occurs when a peak flow event equals or exceeds 180m^3/sec. *Data Source: National River Flow Archive*.]

Trend … an increase from the 1960s [9] through the 1970s [12] to the1980s [16] followed by a minor decline in the 1990s [14], which is significantly exceeded through the 2000s [32]. Although there is a decline in the 2010s [20] compared to the 2000s it exceeds the earlier decades. The trend appears to be continuing in the 2020s with 15 days already achieved. **This data fails to inform as to the character of the flood in terms of level, or duration.**

Interestingly, prior to the mid-1970s, flood events were confined to the November to February period. From the mid-1970s on, the distribution of these events extended into October and March. … 68 of the 120 flood days have occurred since the year 2000. Surprisingly, since 2000, a little over 30% of flood events occur in years with below average rainfall.

So what causes the lower Teifi to flood?

Somewhere over the catchment upstream, or over the catchment as a whole there has been precipitation [rainfall]. This may have been an accumulation over days, or a discrete high volume intense down pour. The outcome is that the volume of water delivered to the river channel exceeds its capacity and the water overflows the banks. Sometimes the flood lasts for a few hours, at other times it may extend to 1 or 2 days.

An exacerbating factor is the speed of run off, which leads to an interesting discussion about attributing the cause of the increase in flood days.

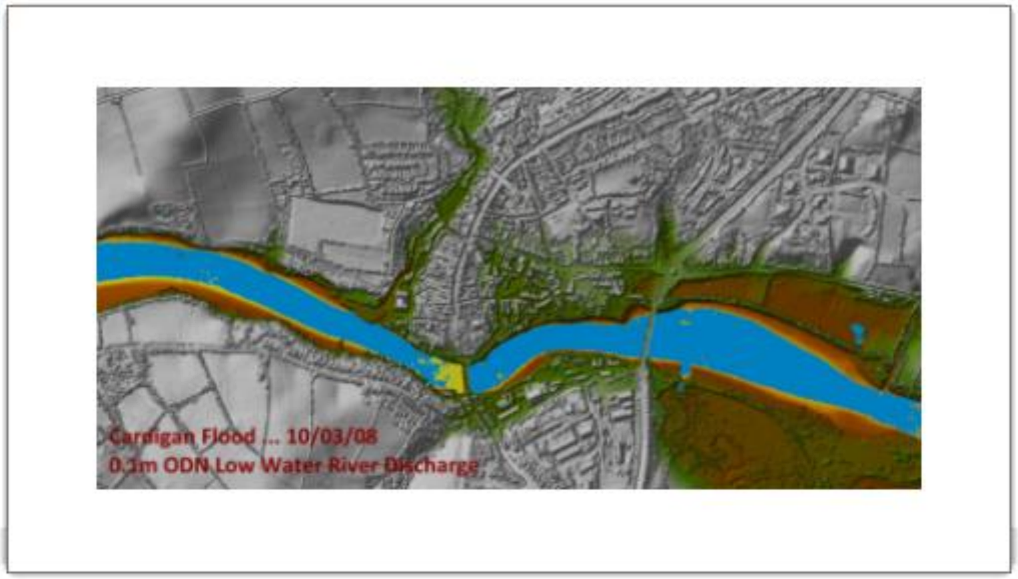
It is acknowledged here that human activity within the catchment, urbanisation, road expansion, the drainage of farmland and the clear felling of upland forestry plantations are all contributors to getting water into the channel faster. The gradual increase from the 1960s to the 1990s may well reflect this. Consequently, some of the floods occurring in more recent years might not have been flood events in the 1960s or 1970s. However, urbanisation and farmland drainage etc. are not the only changes. Precipitation has changed too. Over the past 60+ years there has been a small increase in volume. There has also been a significant modification to those protracted periods of light rain, which were characteristic of the catchment in the past; to the current regime of dry spells, followed by discrete high volume rainfall events. Current thinking suggests that these events will appear more frequently and become more energetic.

Of note: there has also been a moderating effect on river discharge following the re-hydration of Cors Caron bog at Tregaron. It is early days, but initial indications suggest that inflow from the uplands are not passing through the bog as quickly as in the past. [There is further work being carried out.]

When high rainfall events follow a dry period, water at the surface does not have time to infiltrate into the soil or rock. If the soil surface has been baked, this too prevents infiltration. Consequently, the water travels quickly and in greater volume overland to channels/drains and enters the river.

What lies behind this change is that the delivery mechanism [North Atlantic low pressure systems] are forming within a much more energised atmosphere that sits over an ocean, which is also seeing great changes. Further, the polar jet stream is changing too following the rapid warming of the Arctic. For example, large southern meanders in a weaker jet stream permit depressions to develop over, and travel across warmer Atlantic waters. This changes the character of the depressions and brings them to UK shores at unusual times of the year.

A standout here is that the 2014 flood illustrated on the previous slide was not associated with a lower Teifi flood event however. Peak river discharge was recorded between 103-130m^3/sec for this period. It was the influence of an unusually high spring high water coinciding with a significant river discharge that caused the flooding. [*See Appendix 2 below for further information on tides.]



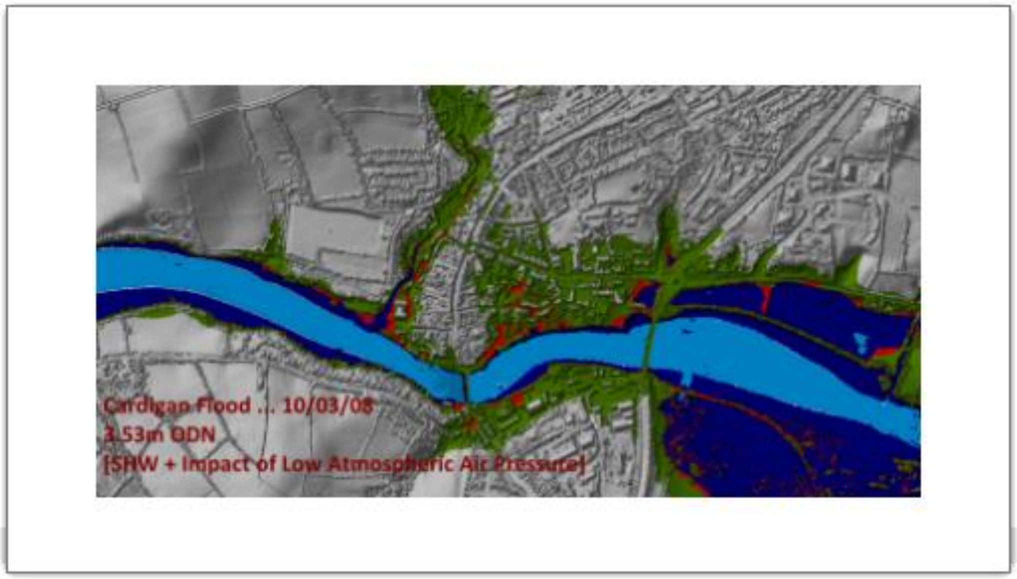
Slide 7. … **Part 2. … Lidar image of Cardigan riverside. Pentood Marsh to the Netpool.**

Low water discharge channel in blue. Also visible is the Old Town Bridge, the Bypass Bridge. Pentood marsh and the former railway embankment, now the board walk.

The lower town [shaded green] is prone to flooding, as is the lower car park at the bottom of Quay Street.

Note … The Netpool reach presents a "bottle neck" at this point in the estuary. Teifi discharge cannot spread out therefore it must go up. The narrow constraints of the rock gorge also causes the incoming tides to rise higher [0.1/0.2m] than it does in the outer estuary.

March 2008, Cardigan … Big spring high water [SHW] usually associated with nuisance flooding. E.g. Floods lower car park, but not usually a threat to the lower town. This type of SHW usually occurs in the autumn or spring.



Slide 8. … **March 2008 Flooding due to SHW & low Air Pressure**

Predicted HW of 5.4m over Chart Datum [CD]. This equates to 2.96m Ordnance Datum Newlyn [ODN]. Image of 2.96 SHW – dark blue area

On this occasion unfortunately, it happened to coincide with a vigorous low pressure system whose centre passed directly over the lower Teifi. The air pressure at the centre of this depression as it moved across was 954mb/956mb.

Sea surface elevation and air pressure has an inverse relationship. For a fall of 1millibar of air pressure, there is a rise of 1cm of the ocean surface. On this particular day at high water the sea surface was 0.57m higher due to the low air pressure. This elevated the SHW from 2.96m to 3.53m. This had the capability to flood into the lower town. Again, this was not a flood that would show up in the flood discharge data for the lower Teifi.

The expected nuisance flooding of around 0.26m in the car park actually turned out to be 0.83m. In St Mary's Street this flood event ranged between 0.3m – 0.5m in depth.

Luckily there was no storm surge as winds were offshore from the south west.

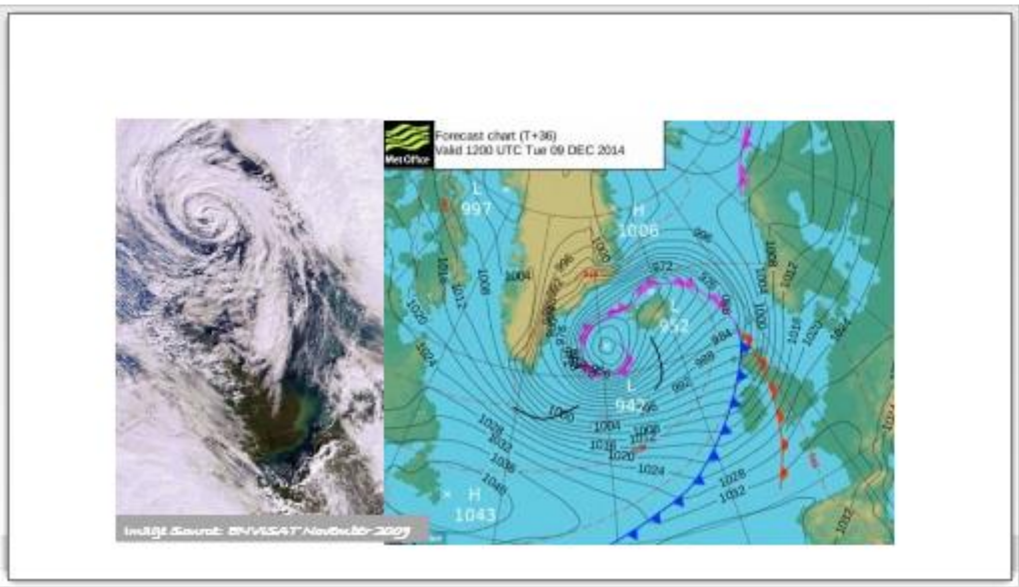
Storm water discharge in the river arrived 7 hours later. The tide had ebbed and air pressure was climbing.

Of note: Spring High Waters of 5.14m CD or greater start to flood the lower car park. [2.7m ODN]. This does not occur every year. In 2022 there were only 3 or 4 tides predicted to reach 5.0m for example. Compare this to August 31st to September 3rd 2023 when there were 7 tides predicted to be between 5.04m and 5.25m OCD. In August and September 2023, high air pressure suppressed surface elevation [1017/1027mb]

*See Appendix 1 for more information on tides and in particular Table 1 "The Influence of Falling Air Pressure on High Water, linked to Cardigan Town Flooding".

The relationship between river discharge and tide is much more complex when it comes to flooding. The timing of high discharge arriving in the estuary is critical in terms of the spring/neap cycle as well as the arrival coinciding with high water or low water.

*See Appendix 2 for more info on the interaction between high river discharge and tides.



Slide 9. … **North Atlantic Depressions**

Satellite image of a depression situated over the UK [*Source: ENVISAT, November 2009*] and an accompanying surface pressure chart for a depression. [*Source: Met Office, December 2014*]

These systems deliver the majority of the rainfall events seen in the UK. Interestingly, the orientation of the fronts associated with these depressions often align along the long profile of the catchment. Historically, these depressions delivered low intensity rainfall distributed throughout the year, but with a winter maximum. Over the past 25 years there has been an increase in the frequency of high volume events occurring at any point throughout the year. Latest research findings suggest that the number of days when high impact rainfall events occur over the UK will increase. [Met Office] This suggests that significant change is taking place in the energy levels involved in depression formation.

Track - The customary track of these low pressure systems, moving north-eastwards between Scotland and Iceland towards Northern Norway is now subject to change.

Depressions are intimately linked to the Polar Jet Stream. Think of it as the phenomena within which depressions are rooted and it is the “conveyor belt” in terms of delivery. Changes here result in depressions approaching the UK from different directions and where they originate from will change their characteristics.

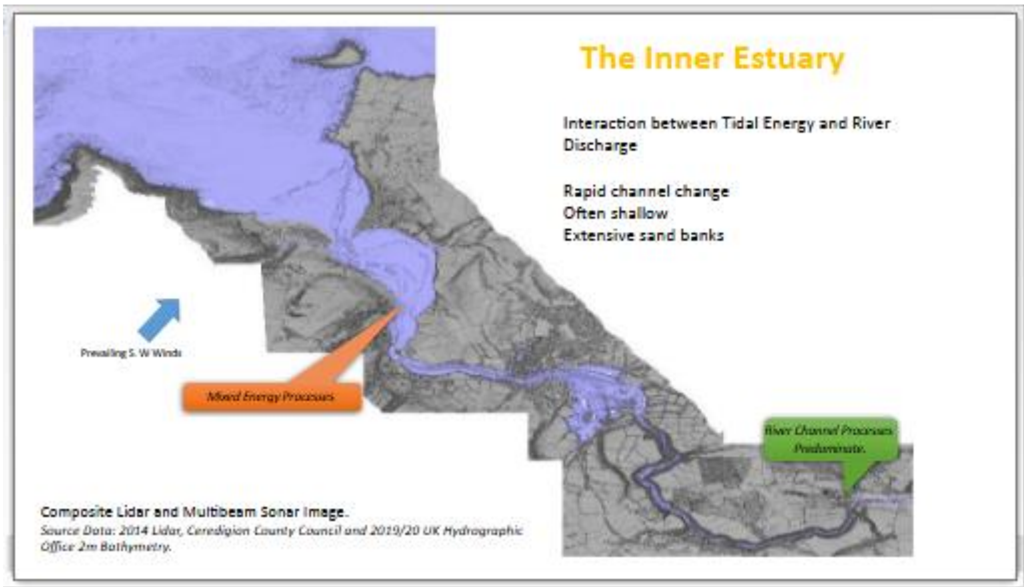
Wind speed and direction – Wind speed is determined by the pressure gradient in the main. According to the Met Office wind speeds [maximum gusts] have not increased over the UK as a whole. There is however a small spring/winter/autumn increase over western areas. Again wind storm activity is expected to become more frequent. Offshore winds help to reduce storm surge impact by pushing surface water away from the coast. Strong winds can increase wave attack within the estuary [This was very evident in front of the Teifi Boating Club prior to the rock armour being emplaced.] Strong winds also funnel along the Netpool reach. Strong winds blowing downstream reduce the height of high waters at Cardigan quay, delay the arrival of high water and reduce its duration. Strong onshore winds do the reverse.

Air pressure – An increase in storm events with low air pressure at their centre increases the possibility of higher tides through the inverse barometric effect.

Slide 10. … **Disruption to the Polar Jet Stream**

Image showing the historic track and amplitude of the Polar Jet compared to its more disrupted southern loops.

Evidence is growing that links these changes to sea-surface warming and the rapid increases in temperature in the Arctic. [The meandering waves that connect jet streams to global warming.]



Slide 11. … **The Inner Estuary –** ***The interaction between tidal energy and river discharge***

This area between St Dogmaels and Pen yr Ergyd is characterised by a meandering channel passing between extensive sand and mud banks. The channel changes position rapidly and is often shallow in certain sections.

Initially as the tide floods this part of the estuary it is confined within the channel system. As the flood tide overflows the channel, tidal energy and some wave energy become influential across the whole area. Once the ebb tide has returned to the confines of the channel, channel processes take over.

Slide 12. … **The Inner Estuary – *The interaction between tidal energy and river discharge***
2006 image illustrating the major physical features exposed at low water. Of note are:

- The lower Poppit sands/Cardigan Bar to seaward
- The upper beach and dune system at Poppit
- The Pen yr Ergyd promontory and the Pen yr Ergyd spit
- Remnants of the salt marsh along the western shore of the Inner estuary
- Extensive sand banks
- Main meandering discharge channel curving towards Nant y Ferwig
- Some minor channels.
- Box ended flood tide channel along the western shore terminating just before the Bryn Du bend.

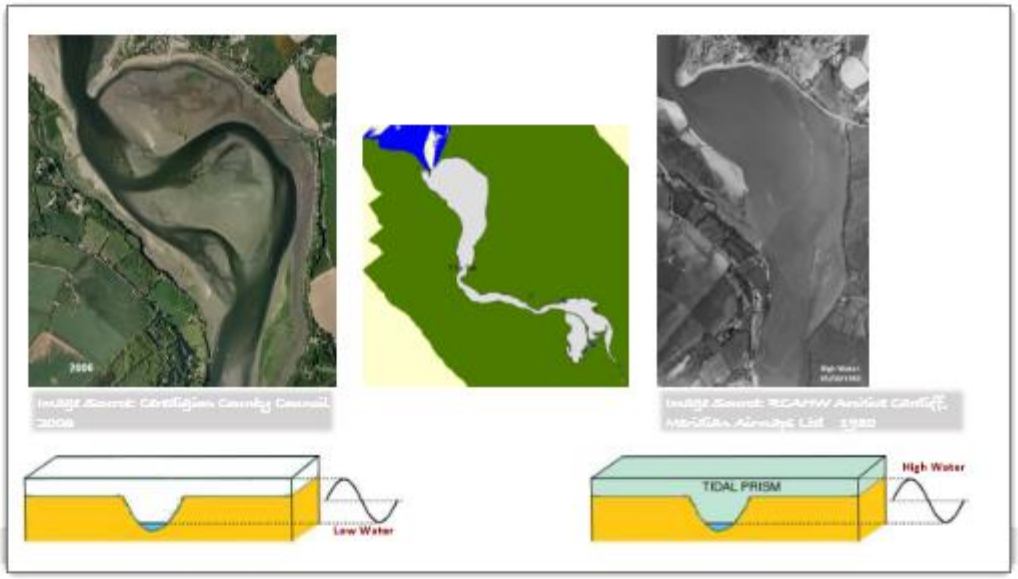
This is a tidal delta characterised by low angled gradients. It is sensitive to changes in the volume of water and sediment. The flood tide enters with more energy than the ebb tide leaves. The flood tide carries sediment into the inner estuary. The ebb tide carries a smaller amount seaward. Over time estuaries silt up. However, river discharge helps to remove sediment too.

Slide 13. … **The Inner Estuary –** ***Channel change and the shallows***

2018, 2021 and 2023 images reveal changing channel locations. The channels change much more frequently than these images suggest. They are modified by each tide. There is a strong seasonal signal and there are migrations that take place over years. In addition, one off high discharge events can divert channels if they arrive in this part of the estuary at half tide, late on the ebb flow. The channel meanders over this area because it carries more water than a straight line route could cope with. In general, narrow channels are deeper than wider channels and a single channel system is deeper than multiple channels.

The shallow zones can be clearly seen above, particularly where the flood tide starts to lose energy around the Bryn Du bend.

Question - Why do we these shallow areas persist? After all the tide ebbs with extra water from river discharge!



Slide 14. … **The Inner Estuary – *Explaining the tidal prism***

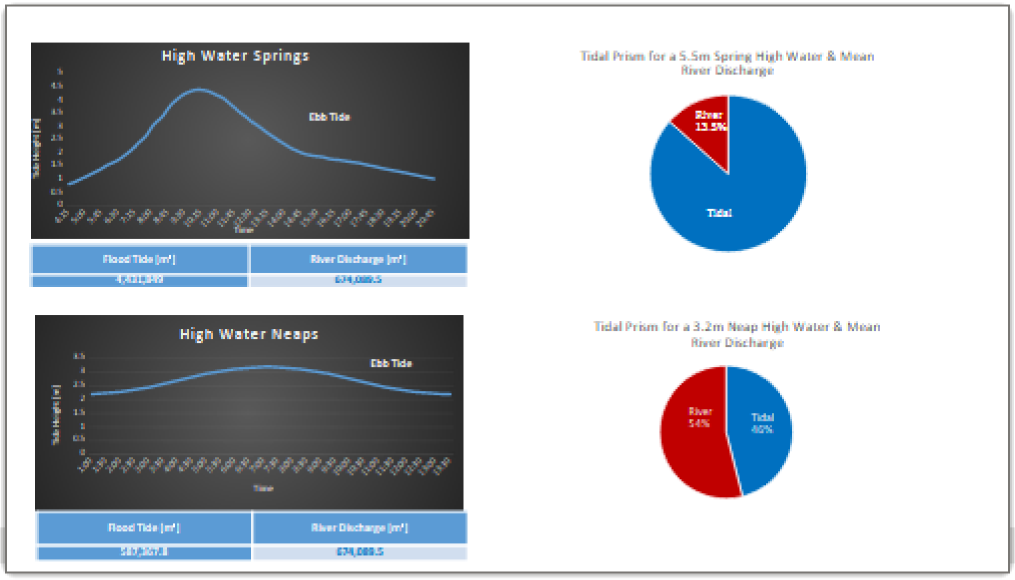
Low and high water images of the inner estuary. Tidal prism graphics. Lidar image of the inner estuary's tidal prism footprint.

To answer the question we needed to establish the volume of the tidal prism.

Supporting graphics illustrate that the tidal prism is made up of two parts in the estuary. One part is the salt water entering from the sea and the other consists of fresh water delivered by the river's discharge.

To achieve this lidar data for the estuary from Pen yr Ergyd to the downstream outfall to Cilgerran gorge was used to calculate the volume of water present for a range of tide heights. The mean discharge* of the river was then used to compute the fresh water contribution over the varying tidal cycles.

*The mean discharge 1959 – 2021 is 29.875m^3/sec [29.72m^3/sec when accounting for licenced abstraction]



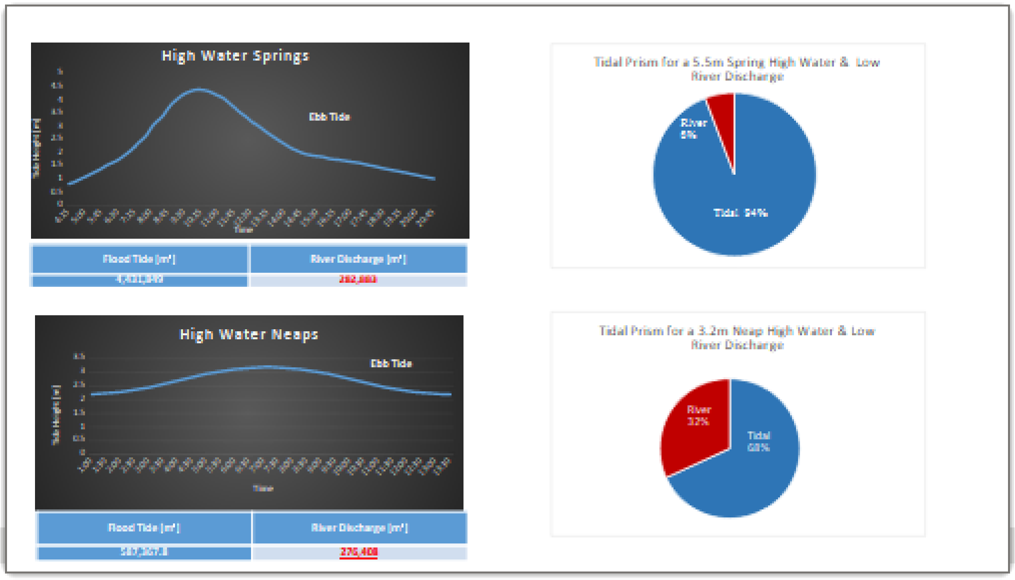
Slide 15. … **The Inner Estuary – T*idal prism volumes***

Spring & Neap tide graphs showing typical durations for the flood and ebb tides along with their heights.

Tables of data illustrating the volume of the tidal prism and pie charts depicting the contribution of salt and fresh water.

Tidal Height	Total Volume with channel water [m³]	Salt Water Influx [m³]	River Water Influx [m³]*	% Contribution of Salt Water	% Contribution of River Discharge
5.5m	5,105,938.65	4,431,849	674,089.50	86.8	13.2
3.2m	1,261,457.33	587,367.80	674,089.50	46.6	53.4

Looking at the extra volume of water leaving the inner estuary on the ebb it was not clear as to why sediment was being left in the channels. It looked like sediment should be flushed out in greater quantities than it is.



Slide 16. … **The Inner Estuary – T*idal prism volumes, further investigation***

Further interrogation of the discharge data revealed that the mean discharge only represents 2.3% of all the discharges. In fact, 63.5% of discharges are below the mean, with 50% of all discharges being below two thirds of the mean. Re-working the discharge values for the top end of the 50% of discharges, 18m^3/sec, it greatly reduced the river discharge contribution.

Just 6% on a 5.5m spring tide and 32% on a 3.2m neap tide. Clearly, for the majority of days in the year the extra river discharge is insufficient to help flush all the sediment out.

Field observations in-channel helped to identify those discharges that efficiently reduced sediment in the channel. It is important to note that the number of channels operating within the inner estuary is an important factor here too, as is the width of the main channel. Simply, the more channels there are the shallower they are and the wider the main channel is the shallower it is. However, discharges in excess of 40m^3/sec help maintain channels and flush sediment seaward. Unfortunately, these only occur on about 90 days a year and most of those occur over winter. Consequently, recreational boat users seldom experience easy channel access up to the town as they are not on the water over the winter period.

Other contributory factors to Low Flow discharge volumes … Low flow conditions are not just about protracted periods of dry weather. It remains unclear for example :-

1. How climate change is affecting evaporation rates … it may well rain but higher temperature and windier days remove water through evaporation in greater volumes.
2. Further, as growing seasons extend the demand for water from plants removes water from the soil for longer periods, which permits more surface water to enter the soil store.
3. How much water is abstracted for agricultural use is not totally understood.
4. The impact of licenced water abstraction for domestic needs has the greatest impact during periods of low flow.

Of note: In recent times, protracted periods of dry weather have started to occur at any time of the year, although they are usually more frequent during the late spring and summer months. This reflects the changes to the climate as discussed above. [Low Pressure systems dominating for periods that are then replaced by anticyclones exerting their control. These are both intimately linked to changes to the Polar jet. See above.}

Slide 17. … **The Inner Estuary – T*idal prism volumes and engineering***

Image of Afon Teifi Fairways Ltd [AFTL] channel maintenance to the pontoon and suction dredger trials just off the pontoon.

We have passed our findings across to AFTL because they had expressed concerns about shallow channels inhibiting access to Cardigan. Our suggestion was that "engineering projects" should avoid times that would coincide with low river discharges as this would introduce extra sediment into the system at a time when it was not efficiently flushing sediment out. - We have no evidence that this information influenced decision making.

Slide 18. … **The Inner Estuary –** ***Poor Flushing***

1980 High Water image and the 2023 Low Water image of the inner estuary.

The 1980 image shows the boundary between fresh and salt water bodies in the inner estuary. We suspect that on a large number of occasions there is an inadequate flushing regime operating in the Teifi estuary. Weak flushing leads to water passing to the outer estuary, but then forming part of the tidal volume which is re-introduced on the next tide. Under such circumstances effluent from sewage discharges and farms for example have a greater time to settle out on the banks and beaches. It is outside of our area of expertise, but we suspect that the large areas of algal mat growth seen across the inner estuary banks during the summer reflects the high volumes of nitrates and phosphates retained within the system. [See 2023 image]

This is a subject area which should be the focus of future research.

Slide 19. … **The Outer Estuary**

Image of Poppit sands and Cardigan Bar dominating the centre and west and the remnants of the Pen yr Ergyd promontory on the south Gwbert foreshore to the east.

This section is about changes to the coastline along the south Gwbert/Pen yr Ergyd side of the estuary.

We have spent a lot of time trawling through old maps and charts, surveyors diaries and reports on the estuary to understand the changes that have occurred over time. Difficult to know what to leave out!

The Teifi appears on a range of maps and can be found on copies of a map of the British Isles from Ptolomey's Geographia. It also appears on the Gough Map.

However, the first detailed "chart" by Lewis Morris was surveyed in 1738 and shows an estuary that shares very similar characteristics to the present day. Meandering channels, sand banks, bar. Murdoch MacKenzie surveyed the estuary in the 1770s for the Admiralty. His chart is less detailed in some respects, but spatially more accurate than Morris's. His commentary warns mariners about passing over the bar and the shallows awaiting in the channel beyond. Unfortunately, the distortions on these charts, some resulting from the survey techniques adopted at the time and others down to the engraving and printing, do not permit them to be used for spatial comparisons.

However, in the early 1800s [1811 - 1819] the Ordnance Survey accurately triangulated the Cardigan area at a scale of 2 inches to the mile. It was this base that the Admiralty used in 1838 when Sheringham surveyed the estuary. This is the first survey of quality that permits comparison with younger data and it is where the following animation starts.

The animation covers the years 1838 to 2006, although the significant change to the eastern shore finished in the early 1990s. The 1838 chart is followed by 6" OS sheets for 1888/89, 1904/07 and then by aerial photographs from 1946 to 2006.

Slide 20. … **The Outer Estuary … 1*838 – 1995 Change Animation.***

Focus on the changes to the eastern shore of the outer estuary. Note that the time period between successive images is not uniform. Change takes place continually and is not calibrated by the date of the images displayed here.

Slide 21. … **The Outer Estuary … Change**

Images of the changes between 1838 and 1946 and 1946 to 1995.

Loss dark brown … Gains yellow

It is possible to detect that the changes occurring between 1946 and 1995 are more extensive than in the previous 108 years.

Slide 22. … **The Outer Estuary … Area Loss and Rates of Change**

When interrogating the data further it is possible to see that the highest annual rates of loss occurred post 1946 and peaked in the period 1977 – 1980.

There was an intervention in 1983 by the Local Authority who had the revetment on the south Gwbert shore built. This was undertaken to protect the road above. The project also advanced the coastline seaward slightly from where it had been eroded.

A second intervention occurred in the early 1990s when the caravan park frontage was rock armoured and a series of groynes were built.

The important details are …

74,501m^2 lost through coastal erosion.

The vast majority of the loss occurred in the

20th century. Most of it post 1946 [68%]

Gwbert South & Pen yr Ergyd Coastal Change

Period	Years	Loss [m2]	% of Total Loss
1838 to 1995	157	74,501	
1838 to 1904	66	11943	16.03
1904 to 1946	42	12030	16.15
1946 to 1995	49	50528	67.82

Gwbert South & Pen yr Ergyd Coastal Change

Period	Years	Loss [m2]	% of Total Loss	Loss per Annum [m2]
1838 to 1888/89	50	7818	10.3	156.4
1888/89 to 1904/07	16	4125	5.4	257.8
1904/07 to 1946	42	12030	15.8	286.4
1946 to 1950	4	1569.6	2.1	392.4
1950 to 1953	3	5564.4	7.3	1854.8
1953 to 1964	11	11669	15.3	1060.8
1964 to 1972	8	7817.1	10.3	977.1
1972 to 1977	5	8549.5	11.2	1709.9
1977 to 1980	3	8384.5	11.0	2794.8
1980 to 1983	3	3740	4.9	1246.7
1983 to 1988	5	3234	4.2	646.8
1988 to 1995	7	1634	2.1	233.4

Slide 23. … **The Outer Estuary … Lack of volumetric data**

Early 20th century image of the Patch/Gwbert foreshore. Photographer standing about 7/10m above the beach.

Note: the picture was taken near the boundary between the Pen yr Ergyd dune system and the glacial diamicts deposited to the north. It is possible to pick out the Cliff Hotel and Cardigan Island. It is clear that there is a large amount of material aligned along the foreshore with an elevation of about 15m.

Slide 24. … **The Outer Estuary … Lack of volumetric data**

View from the same place today!

Note: Loss of elevation and shoreline deposits. Dramatic change to foreshore.

Best estimate of material lost - ~250,000m^3

Slide 25. … **The Outer Estuary … Causes**

The expectation at the outset was that change around the estuary would occur at the same sorts of rate over time.

We also expected that the eastern shore would see more change as it is exposed to the prevailing westerly set of the waves entering the estuary from around Cemaes Head.

However, the accelerating rate of change caught our attention.

The cause of the changes are multifaceted.

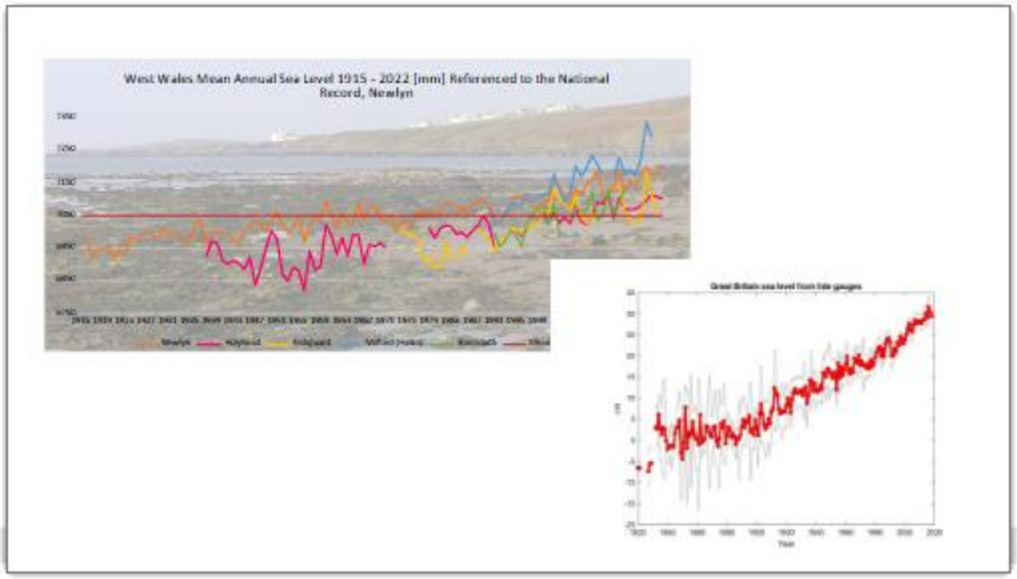
Weak sediment types, are more easily eroded. The change is focussed on the Pen yr Ergyd promontory [sand] and the south Gwbert shoreline [glacial diamicts]. Very little change is visible where the more resistant lower Palaeozoic rocks outcrop.

Increasing use of the estuary made through recreation and tourism. - Certainly, increasing footfall in dune systems damages vegetation cover, which then allows the sand beneath to become more mobile. However, that does not help explain the increase during the first half of the 20th century, or the losses associated with the glacial diamicts. Tourism was not so heavily developed then and the area of the shore associated with the diamicts was not as accessible, nor as attractive to visitors.

Post 1946, the Pen yr Ergyd promontory was increasingly developed for tourism use, which in turn made sand available for erosion. However, this again does not provide the complete answer, as what we see are periods of increasing loss punctuated with periods of more dramatic change. [E.g. 1964 – 1972 compared to 1972 – 1977]

Importantly, we have to ask why are the glacial diamicts eroding so quickly, when they aren't the focus for visitors.

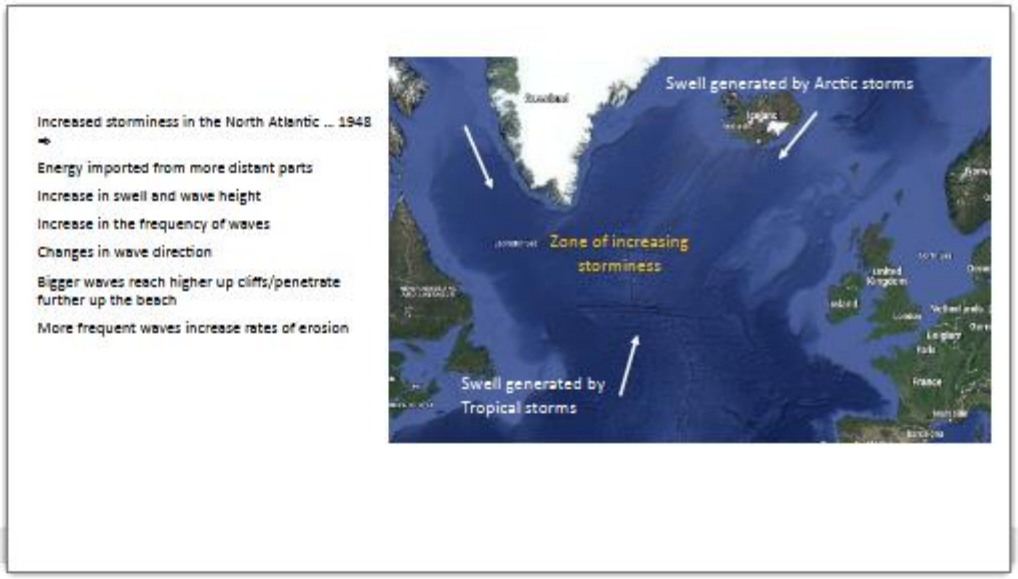
Road surface upgrades [1930s on] – We have some anecdotal evidence that as the road to Gwbert was metalled, surface water was allowed to drain into the area where the glacial diamicts are situated. It is possible that this surface water was also being gathered from a greater area than in the past. Water entering the upslope area of the diamicts would add mass to the slope and lubricate the sediments. This would greatly increase the chance of mobilising the slopes and encourage landslips. There is photographic evidence which shows small slips delivering material to the beach and it is possible to identify remnants on the current foreshore. However, we do not have any record that shows the frequency of such events increased.



Slide 26. … **The Outer Estuary … Causes**

Sea level Rise – The supporting data for global sea-surface rise is irrefutable as is the data for UK waters. The National tide gauge at Newlyn, supported by others at Milford, Fishguard, Holyhead and Liverpool confirm that sea level has risen between 0.25m and 0.30m since 1830. Of note, is that the rate of rise has increased over time. A higher sea-surface permits the tide and waves to act over greater areas, particularly in estuaries where low angled beach slopes are found. Simply, tidal energy and wave energy penetrate further up the beach and higher up the cliffs. This exposes the upper part of the foreshore to erosion for a greater length of time.

However, the spatial loss data infers that there were fluctuating high energy periods and these need to be explained.



Slide 27. … **The Outer Estuary … Causes**

We considered an increase in wave energy to be a significant contributory factor to the erosion in the estuary and the subsequent removal and redistribution of sediment. So we started to look for evidence of change. Waves are generated by surface winds blowing across the sea. So we started looking for an increase in wind speeds over the UK.

Storminess – Surprisingly, the Met Office have not found a significant increase in wind speed across the UK as a whole. [2018 online paper] There has been a small increase in Cardigan Bay and the St George's Channel over the winter months but not enough to explain this. So what's going on? As it happened we were not alone as observers all over North West Europe were reporting increasing evidence of coastal erosion.

We had to look further afield for answers. Waves and swell are not necessarily generated locally. It turns out that they combine over long distances and can distribute energy from storms in one region to areas thousands of kilometres away.

There is a growing body of research that documents increased storminess over the world's oceans with the greatest impact in the Southern Ocean. Specifically, storminess over the North Atlantic has been increasing since 1948. in brief, winter storm wave heights are increasing across all of Western Europe's coastline. At the latitude of N W Scotland & W Ireland, this comes in at 10mm/year. [0.7m since 1948] Southern Britain/France 5mm/year – while for Portuguese coastlines it is around 1mm/year.

Further research suggests there is a zone in the North Atlantic that is becoming increasingly stormy and that the track of the depressions that bring winter storms to north west Europe and the UK form and pass across it.

Interestingly, there is an exchange of energy between more distant parts of the Atlantic and this zone in terms of swell. Wave energy generated by the winds associated with the tropical storms located to the south are propagated northward into the North Atlantic. At the same time an increasingly active Arctic ocean is exporting energy through swell into the North Atlantic. The Arctic ocean is becoming more wavy as the extent of sea ice reduces. The combined impact is to make this part of the North Atlantic rougher with increasing wave heights.

Larger waves in the originating region is not the only concern. As wave sets travel down wind they combine and build water, allowing waves to climb higher. Also, wave directions are changing as is the wave period. The wave period indicates how close together the waves are. This is important as the closer they are the more energy is delivered to the coastline over a given period of time.

Observations suggest that extreme storm events are fuelling wave heights 1.7m higher that their 1948 equivalent. Interestingly, examining the Bidston Observatory records [Birkenhead] on the number of days gales occurred highlights the 1950s as being stormier than the 1960s and early 1970s. However, the early 1980s see a record number of gales and it remains pretty boisterous throughout the decade. This follows the rate of loss trends for the estuary. Pye & Neal, 1994 note the occurrence of significant storm surges and comment upon their increasing frequency in their research into coastal dune erosion at Formby just north of the river Mersey. In particular, they single out storms with significant surges in 1977, 1983, 1987 and 1990.

So, we appear to have identified the origin of increasing energy in the waves and swell that arrive upon western European coastlines. To a certain degree Cardigan Bay is aided by the shelter afforded by Ireland, but even so, 11m waves have been recorded by the Aberporth Buoy. Also the increasing frequency of waves results in more erosion being able to take place.

In summary, there are identifiable mechanisms that help deliver material to the foreshore [Tourism expansion and road improvements], but neither explain the energy increase to remove areas of the coast in an increasing fashion. Sea-level rise again helps get wave and tide energy higher up the beach, but it is the increase in storminess that has provided the energy to further erode and remove material within the estuary.

Slide 28. … **The Outer Estuary … Storm Wave Video**

North Wales slip-way video. Illustrates the risks involved with visiting the coast during a storm.

The general public underestimate the power of storm waves and the unpredictability of the waves ability to surge up-shore. Storm waves have the potential to hide ones of much greater size within the wave train.

There is also an increase in the frequency of waves arriving on the beach.

This increase in energy has the potential to strip away sand from the beach and undermine soft sediments at the top of the beach.

Of note: increased wave frequency at other times of the year can cause water to build on the upper part of the beach. At some point this water surges back seaward in the form of a rip-current. On local beaches Aberporth for example] experienced local swimmers are being taken by surprise with the increase in energy of the local rip current. On other beaches, rip currents are now present where in the past there were none.

Wave data can be found at … British Oceanographic Data Centre and Cefas. [Sadly the Aberporth buoy has recently ceased to function.]

We need to seriously start thinking about decreasing our vulnerability to extreme storm events and pro-actively adapt to a more energetic future wave climate.

Local authorities are already starting to look at high risk areas. Unfortunately, our national Government in Westminster has not seriously addressed the issue.

Slide 29. … **Concluding Summary**

There is clear evidence that changes to our regional climate are driving change in the estuary at all levels.

The evidence presented above indicates that those drivers have been operating for decades, and that the rates of change in some instances have increased.

It is important to acknowledge that other factors contribute to change in the estuary too, and in particular note the importance of human derived changes.

The immediate threats to focus on are the interaction of any of the following with high tides and particularly, Spring High Tides.

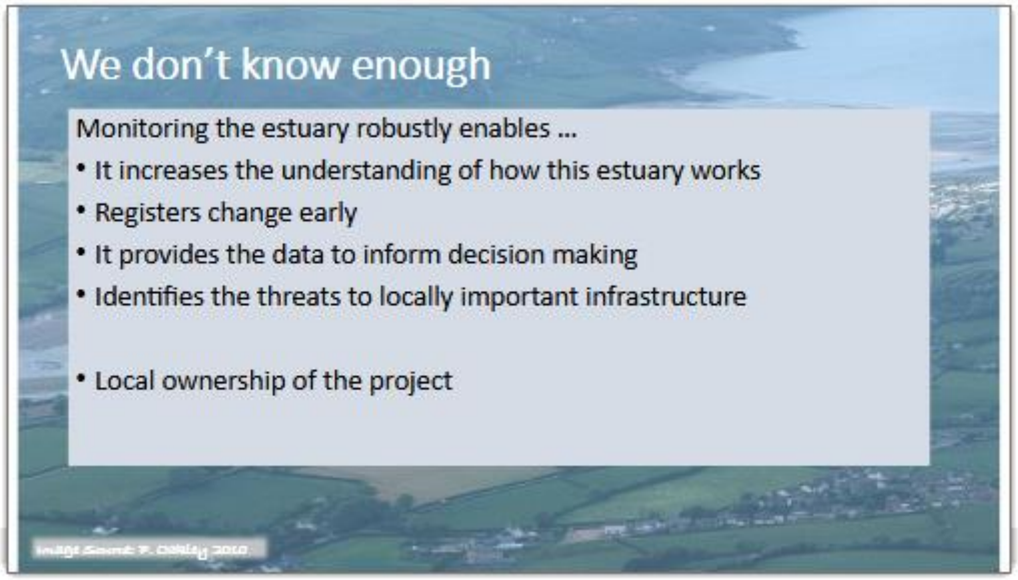
- Storm surges
- Increasing wave activity – Storm wave height and wave frequency
- High volume rainfall events acting upon the Teifi catchment
- Storm events

Current thinking suggests that all of these are set to increase in scale and frequency over the coming years.

Sea level rise is not our first priority, but it is a rapidly evolving threat. Ice sheet collapse, a threat 20 years ago, consigned to the following centuries is now presenting as a more pressing threat. Work from West Antarctica and Greenland highlight increasing instability as ice is being warmed from beneath by warming oceans.

Further, evidence is mounting for significant change in the way the North Atlantic ocean functions. The reduction in the AMOC [Atlantic Meridional Overturning Current – more familiarly know as the Gulf Stream or North Atlantic Drift] may cause significant change to the climate of Western Europe and influence other climatic factors globally.

Of note: For the Teifi estuary we do not fully understand how the current tidal regime works let alone how it will adapt to sea level rise.



Slide 30. … **Concluding Summary – We don't know enough!**

Small estuaries are not well represented in research literature and the interactions that go on in their upper reaches are poorly understood. There are a few PhD theses and an occasional research programme [E.g. Dyfi Study 2008, Mawddach, 2011], but in the main we are left to interpret phenomena based on studies carried out on the world's larger estuaries. Consequently, it is important to, not only continue monitoring the estuary, but to expand the areas of study.

Monitoring the estuary robustly …

- Increases the understanding of how this estuary works
- Registers change early – Forecast, rather than hind-cast.
- It provides the data to inform decision making
- Identifies the threats to locally important infrastructure

Local ownership of the project is important …

- Don't wait for public bodies to take the lead
  - They are understaffed for the scale of the task nationally
  - There are places around the coast with more urgent needs.

Local people can carry this project forward ...

- In this community there are people with a broad range of skills
- Where there are gaps in the skillset – we can learn.

Slide 31. … **Closing slide**

Change is continuing – the slide shows the recent loss of the Pen yr Ergyd spit and the re-working of the sand bank immediately upstream by wave action.

Appendix 1 … Tides

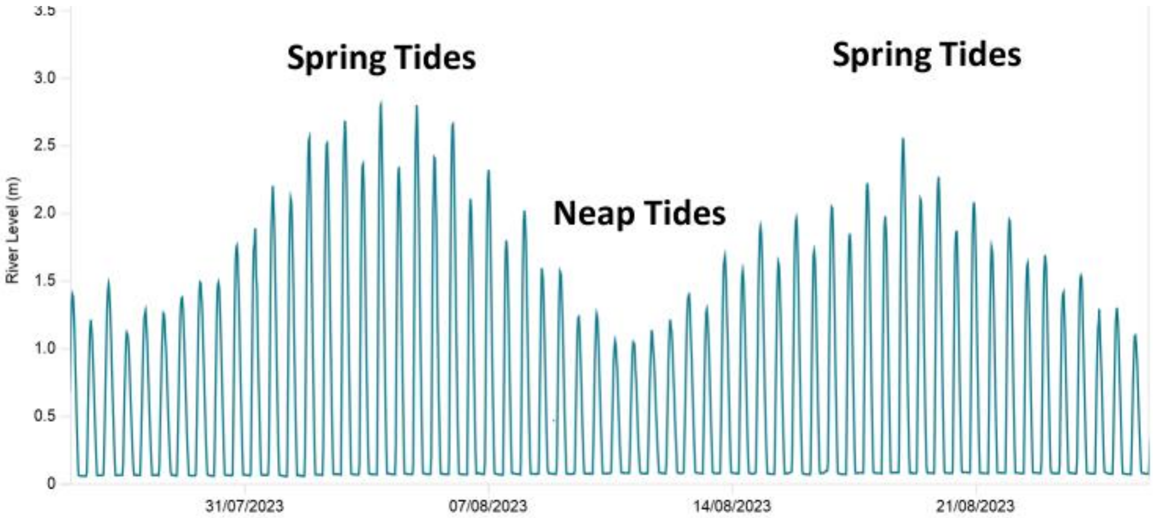


Fig.1 Diagram above illustrates the Spring/Neap tide cycle as it occurs at Cardigan Quay. Source: River levels, rainfall and sea data - Cyfoeth Naturiol Cymru/Natural Resources Wales.

Accessible at: https://rivers-and-seas.naturalresources.wales/Station/4224/?lang=en&parameterType=1

[Do not intend to get into an explanation of tide rising forces here, but am happy to respond if people require help.]

Things to note: The dip and rise between successive high waters. This results from a combination of factors, but is mainly a response to the Moon being overhead [High], or being overhead on the opposite side of the Earth [Lower] roughly 12.5 hours later. Also note that the low water part of the graph is missing. This is because low water tide heights are found further downstream and mainly in the outer estuary. The low water levels depicted above are the discharge elevation of the river as it flows past the quay.

Predicted Tide Heights & times. – The times and heights you see online, in an almanac, or you get from an app are often modified by various factors on the day. For example, winds that pile the water on our coast can make tides higher, cause them to occur a bit sooner than expected and inhibit the ebb flow. Low air pressure can also cause the tide to be higher than predicted. Strong offshore winds bring about the reverse and high air pressure can cause the tide height to be lower than predicted.

Table 1 below illustrates the impact of low air pressure upon high water at Cardigan Quay.

The Influence of Falling Air Pressure on Cardigan Town High Water, linked to Flooding																								
Air Pressure 1013mb and Height of River at the Town Bridge 0.1m ODN																↓Lower Carpark starts to flood.					↓Lower Town starts to flood			
High Water Over Chart Datum [m]		**4.4**	**4.45**	**4.5**	**4.55**	**4.6**	**4.65**	**4.7**	**4.75**	**4.8**	**4.85**	**4.9**	**4.95**	**5**	**5.05**	**5.1**	**5.15**	**5.2**	**5.25**	**5.3**	**5.35**	**5.4**	**5.45**	**5.5**
High Water Over Ordnance Datum Newlyn [m]		**1.96**	**2.01**	**2.06**	**2.11**	**2.16**	**2.21**	**2.26**	**2.31**	**2.36**	**2.41**	**2.46**	**2.51**	**2.56**	**2.61**	**2.66**	**2.71**	**2.76**	**2.81**	**2.86**	**2.91**	**2.96**	**3.01**	**3.06**
Air Pressure falling in 5mb increments	**1008mb**	2.01	2.06	2.11	2.16	2.21	2.26	2.31	2.36	2.41	2.46	2.51	2.56	2.61	2.66	2.71	2.76	2.81	2.86	2.91	2.96	3.01	3.06	3.11
	1003mb	2.06	2.11	2.16	2.21	2.26	2.31	2.36	2.41	2.46	2.51	2.56	2.61	2.66	2.71	2.76	2.81	2.86	2.91	2.96	3.01	3.06	3.11	3.16
	998mb	2.11	2.16	2.21	2.26	2.31	2.36	2.41	2.46	2.51	2.56	2.61	2.66	2.71	2.76	2.81	2.86	2.91	2.96	3.01	3.06	3.11	3.16	3.21
	993mb	2.16	2.21	2.26	2.31	2.36	2.41	2.46	2.51	2.56	2.61	2.66	2.71	2.76	2.81	2.86	2.91	2.96	3.01	3.06	3.11	3.16	3.21	3.26
	988mb	2.21	2.26	2.31	2.36	2.41	2.46	2.51	2.56	2.61	2.66	2.71	2.76	2.81	2.86	2.91	2.96	3.01	3.06	3.11	3.16	3.21	3.26	3.31
	983mb	2.26	2.31	2.36	2.41	2.46	2.51	2.56	2.61	2.66	2.71	2.76	2.81	2.86	2.91	2.96	3.01	3.06	3.11	3.16	3.21	3.26	3.31	3.36
	978mb	2.31	2.36	2.41	2.46	2.51	2.56	2.61	2.66	2.71	2.76	2.81	2.86	2.91	2.96	3.01	3.06	3.11	3.16	3.21	3.26	3.31	3.36	3.41
	973mb	2.36	2.41	2.46	2.51	2.56	2.61	2.66	2.71	2.76	2.81	2.86	2.91	2.96	3.01	3.06	3.11	3.16	3.21	3.26	3.31	3.36	3.41	3.46
	968mb	2.41	2.46	2.51	2.56	2.61	2.66	2.71	2.76	2.81	2.86	2.91	2.96	3.01	3.06	3.11	3.16	3.21	3.26	3.31	3.36	3.41	3.46	3.51
	963mb	2.46	2.51	2.56	2.61	2.66	2.71	2.76	2.81	2.86	2.91	2.96	3.01	3.06	3.11	3.16	3.21	3.26	3.31	3.36	3.41	3.46	3.51	3.56
	958mb	2.51	2.56	2.61	2.66	2.71	2.76	2.81	2.86	2.91	2.96	3.01	3.06	3.11	3.16	3.21	3.26	3.31	3.36	3.41	3.46	3.51	3.56	3.61
	953mb	2.56	2.61	2.66	2.71	2.76	2.81	2.86	2.91	2.96	3.01	3.06	3.11	3.16	3.21	3.26	3.31	3.36	3.41	3.46	3.51	3.56	3.61	3.66
	948mb	2.61	2.66	2.71	2.76	2.81	2.86	2.91	2.96	3.01	3.06	3.11	3.16	3.21	3.26	3.31	3.36	3.41	3.46	3.51	3.56	3.61	3.66	3.71

Appendix 2. The Interaction between high river discharge and tides

The interaction between river discharge and the tide is complex. Certainly, high river discharge coinciding with a high spring tide can elevate water surfaces enough to cause significant flooding. [November, 2014] However, timing and duration of the flood surge are critical factors, as are disturbances to the tide. [Air pressure, the strength and direction of wind being the most significant.] When linked to spring high waters, high discharge does not have to be a flood event as determined by the 180m^3/sec level at Glan Teifi gauging station.

Fig. 2 below shows a high discharge event that occurred on the Teifi at the end of March, beginning of April 2023.

This event interacts with neap tides over several days. It is possible to pick out the following features …

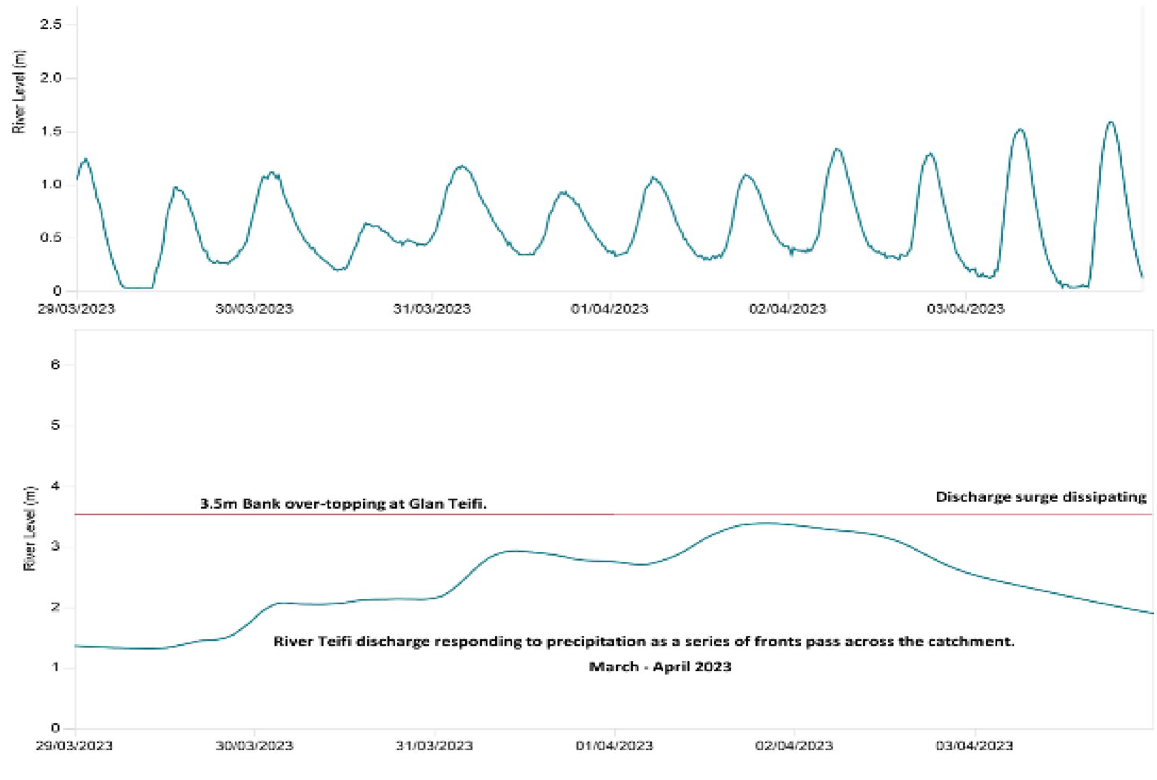
- The low water river discharge is elevated above the norm.
- The graph is irregular in nature indicating strong surge flow.
- One high water is prevented from forming
- There is a broader peak to the high water
- The ebb flow is extended

Interestingly, further research indicates that the height of high water is reduced compared to what was predicted [adjusted for air pressure] in most instances during this event. It is thought that the high discharges flowing through the confines of the Netpool reach are responsible for this. The over-running of the high water on the afternoon of the 30th March probably was the result of a surge in discharge in the Netpool reach inhibiting the full tide wave from making progress.

The duration of high water at Cardigan Quay varies greatly. Usually at neaps it lasts for around 15/20minutes. On other occasions it may stretch to 30 minutes, yet we have seen it last a brief 6 minutes. During this period of high discharge the duration ranged between 1 hour 15 minutes to 2hours 15 minutes.

The extended ebb flow illustrates the high discharge that has been "held back" by the tide.

Fig.2 Comparison of the water levels at Cardigan Quay [top] and Glan Teifi gauging station, Abercych, 29th March to 3rd April 2023.



*At a spring high water, such a precipitation event would have led to the repeated flooding of the lower parts of Cardigan town.

Table 2 below describes the changes to the times and heights of tide. It is important to acknowledge when working from predicted tide data that there are multiple factors that can influence the tide height and timing on the day.

Table 2. Changes to the Times and Heights of the Neap tides 29th March to 3rd April 2023.

	Predicted Times & Heights Source UKHO		Aberporth Met' Office	Tide Height adjusted for Air Pressure [m]	Actual Times & Heights Cardigan Quay Sour NRW	
Date	**Time**	**Height [m] ODN**	**Air Pressure [mb]**		**Time**	**Height [m] ODN**
29/03/23	01:22	1.26	1010	**1.29**	01:15	1.25
	14:02	1.02	1004	**1.11**	13:30	0.98
30/03/23	02:34	0.97	1002	**1.08**	02:15	1.12
	15:40	0.78	998	**0.93**	15:00	0.64
31/03/23	04:35	0.88	983	**1.18**	04:00	1.18
	17:29	0.86	985	**1.14**	17:30	0.93
01/04/23	06:00	1.1	1002	**1.21**	05:45	1.07
	18:33	1.15	1006	**1.22**	18:15	1.1
02/04/23	07:00	1.41	997	**1.57**	06:30	1.33
	19:14	1.46	1005	**1.54**	19:15	1.3
03/04/23	07:27	1.7	1008	**1.75**	07:15	1.52
	19:47	1.74	1028	**1.59**	19:30	1.59

Further Reading & Online Lecture Sources

The volume of literature related to this subject is huge.
There are links to some resources throughout the text.
Clearly, a lot of what is discussed above comes from our own work.

The resources here are a just a selection and more detailed references can be supplied if people are interested…

Specific to the Teifi Estuary

Data Sets

2002 – 2022 Lidar Data sets *[Incomplete]*

Air Pressure and High Water, Cardigan *… data set. Tim Wright 2008 - 2023*

Teifi Discharge Data 1959 – 2021 *… Interactive data resource. Tim Wright*

Reports

Changes to the Pen yr Ergyd Spit & TBC Bank 2017 – 2022 – *September 2022 – Tim Wright*

The Teifi Estuary – Response to the proposal to remove the Pen yr Ergyd Spit*. - June 2020 - Tim Wright and Chris Evans*

Pen yr Ergyd Spit Evaluation – October 2018 *- A response to a request for information as to how the LIDAR data provided by Ceredigion County Council is utilised to further the understanding of the processes at work in the Teifi estuary. Evans & Wright*

Interpreting Historical Map Sources - the Teifi Estuary – *December 2018 – T. Wright*

The Teifi Estuary – A review of the available options for managing its channels. *- April 2015 -Evans & Wright*

Pen yr Ergyd Spit Report 2007 *– Evans & Wright*

Presentations...

The Teifi Estuary, Tides and Channels .... TBC – April 2023 - *Wright*

The Teifi Estuary through time ... TBC – November 2022 - *Evans*

Presentation Briefing – Pembs/Ceredig/AFTL/NRW *- 2014 - Evans & Wright*

Briefing presentation NRW *– 2014 - Evans & Wright*

Briefing CCW/CCC/AFTL *– 2013 - Evans & Wright*

Symposium on the problems of small estuaries *– SEACAMS Conference – Swansea Uni April 2013 - Evans & Wright*

Spit, Sand and Channels Presentation TBC *– Sept 2008 - Evans & Wright*

Briefing presentation CCW/AFTL 2007 *– Evans & Wright*

Technical Reports

Teifi Estuary, Pen yr Ergyd Spit: the do nothing scenario. *- February 2022 – Sutherland and Dearnaley, Wallingford.*

Teifi Estuary, Advice on Changes, Coastal Defence Studies *- March 2008 – Finch, Brampton, Wallingford*

Teifi Estuary, Advice on Changes, Float Tracking Survey – *2008, Brampton, Wallingford*

2007 Lidar Survey – Environment Agency Science Enterprise Centre *- Afon Teifi Fairways Committee*

Assessment of Works Proposed on the Teifi Estuary, Environmental Report *– May 2004 – Atkins*

Teifi Estuary: Morphological Development of the Estuary and Pen yr Ergyd Spit Technical Report *- 2002 – D Brew, Royal Haskoning*

Teifi Estuary Improvement - Hydraulic and environmental assessment Report EX 3516 *- January 1998 – Wallingford*

Fieldwork

Estuary Survey 2006 – 2008 *- C. Evans - D Maynard - C Moore - N Newland - T Wright*

Fieldwork Observations 2006 – 2023 *- Evans & Wright*

Interesting Academic Papers and other Publications...

Estuaries, A Physical Introduction, *2nd Edition … Keith R Dyer, Wiley, 1997*

Estuaries Murray K. Gingras,,1 James A. MacEachern,† Shahin E. Dashtgard,† John-Paul Zonneveld,* Jesse Schoengut,‡ Michael J. Ranger} and S. George Pemberton**

UK Climate Primer *can be found at … UK Climate The Meteorological Society*

North Atlantic Oscillation – Met Office

The North Atlantic Ocean and climate change in the UK and northern Europe. *Neil C. Wells. First published: 08 January 2016 https://doi.org/10.1002/wea.2558*

The North Atlantic Jet Stream under Climate Change and Its Relation to the NAO and EA Patterns

Tim Woollings and Mike Blackburn. Print Publication: 01 Feb 2012 DOI:https://doi.org/10.1175/JCLI-D-11-00087.1

Future changes to high impact weather in the UK *… Open Access Published: 30 June 2021 volume 166, Article number:50 (2021)*

A recent increase in global wave power as a consequence of oceanic warming *Borja G. Reguero, Iñigo J. Losada & Fernando J. Méndez . Nature Communications* ***volume 10****, Article number: 205 (2019)*

Century-long cooling trend in subpolar North Atlantic forced by atmosphere: an alternative explanation, Climate Dynamics *Laifang Li et al, (2021). DOI: 10.1007/s00382-021-06003-4*

Online Lectures
Brief explanation of AMOC and its importance *… Andreas Schmittner, CEOAS, Oregon State University, 2017*
Lab-based demonstration of how the AMOC works … Prof' John Sharples, - Oceanographer , Liverpool Uni … 2020

National Oceanography Centre … Selection from the Video Library

Ocean Circulation and Tipping Points … Prof' Stefan Rahmstorf … EPA Climate Change Lecture, Dublin Mansion House, April 19th 2023.

Tipping Points in Climate and Biosphere Function … Tim Lenten - National Academy of Sciences, November 2018 Tim Lenten features in a host of other Online discussions, Webinars and lectures.

If you have not visited Cambridge Zero try this link.