Tragedy on the Horizon: Climate Change, Coastal Erosion, and the Pricing of Losses in the Distant Future.

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Abstract

The accurate pricing of climate risk in real estate and other assets hinges critically on the choice of discount rate. This study exploits the predictable and gradual nature of coastal erosion to estimate discount rates over extended time horizons. Using a unique dataset of 102,855 property transactions along England's eastern coast from 2010-2023, we show that property prices reflect anticipated losses occurring up to 250 years in the future. By comparing the present values of properties expected to disappear at different points in the future, we find that the implied discount rate schedule exhibits a downward-sloping pattern, with net discount rates (r-g) of 2% for 100-year horizons declining to 1.4% for 175-250 year horizons. These results contribute to our understanding of market efficiency, temporal asset pricing, and the term structure of discount rates in the context of housing and environmental risk, with implications for financial valuation of long-lived assets and investments in climate change mitigation and adaptation.

Keywords: Long-Run Discount Rates, Declining Discount Rate, Asset Pricing, Coastal Erosion, Flooding, Real Estate, England, Climate Finance.

JEL-codes: G12, H43, Q51, Q54, R30.

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1. Introduction

How far in advance are expected losses due to environmental effects capitalized into real estate? With hundreds of billions of dollars in real estate at risk from climate change-induced sea level rise (SLR) over the coming centuries (Gourevitch et al., 2023), this is a question of crucial importance for investors in long duration assets like real estate, and for governments and central banks in the context of financial stability (Battiston, Dafermos & Monasterolo, 2021; Campiglio et al., 2018; Carney, 2015): Will these losses be gradually reflected in asset values, or should we anticipate a sudden, destabilizing collapse in transaction prices?

This paper investigates whether markets are capable of pricing losses over very long horizons. In doing so, it sheds new light on the term structure of discount rates, a topic that remains highly relevant in the context of valuing climate mitigation and adaptation efforts (Nordhaus, 2008; Stern, 2006; Weitzman, 2007). While earlier debates have focussed on the theoretical and ethical arguments informing the level and shape of the social discount rate (Arrow et al., 2014), this paper seeks to establish the prevailing market discount rate for losses resulting from future natural events, a discount rate that can help establish the market value of climate-related losses and inform private investments in climate adaptation.

For empirical estimates of how real estate prices reflect cashflows expected in the distant future, we have previously been reliant on discount rates inferred from very long-duration leaseholds (Bracke, Pinchbeck, & Wyatt, 2018; Giglio, Maggiori, & Stroebel, 2015) as losses due to environmental effects can rarely be expected with a reasonable degree of certainty a century or more from now. This paper uses the case of coastal erosion to price losses expected in the very far future; Losses that can be timed with much greater accuracy than those anticipated from SLR, as they result from processes that depend far less on the still-uncertain future trajectory of global warming. Compared to leaseholds, a major advantage of this approach is that horizons are distributed more evenly, whereas leaseholds durations of more than a century are very rare, and the few traded contracts are clustered around a small number of horizons.

The study area selected for this paper, the East Coast of England, is especially vulnerable to coastal erosion driven by wave and surge action due to its soft cliffs. Land loss is measured in meters per year in some areas (Pye & Blott, 2015). Starting in the 1990s, the UK government

has formulated policies to manage erosion and flooding along England's coast, deciding to protect some areas while leaving other stretches of coastline to be naturally eroded or flooded as part of a strategy known as 'managed retreat' or 'no active intervention'. This approach balances environmental concerns with economic considerations, accepting that not all areas can be defended indefinitely against the forces of nature. Under these policies, the total number (mid-estimate) of residential properties at risk from coastal erosion in England is expected to increase from 3,535 currently, to 58,800-67,500 by the end of the century (CCC, 2018).

By exploiting variation in the local rate of erosion, policy interventions, properties' distance to the eroding shoreline, and the time of sale, it is possible to estimate the transaction price discount associated with different horizons while controlling for confounders using a hedonic regression. We find that losses are priced into residential real estate values up to 250 years before they are expected to occur. Comparing estimates for different horizons reveals that discount rates decrease as maturity increases, with a 2% net discount rate for a 100-year horizon, dropping to 1.4% for horizons of between 175 and 250 years. Additionally, this paper presents new estimates of the discount associated with flood risk in coastal areas in the UK, which is found to increase with proximity to the shoreline.

Roadmap The remainder of this paper is structured as follows: First, the extensive literature on the topic of intergenerational discounting in the context of climate change is briefly discussed in Section 2 along with relevant empirical work on the pricing of erosion risk and flood risk. Next, the setting of the study is presented, and the dataset is described in detail in Section 3. The empirical analysis starts with showing that erosion and flood risk are priced into transaction prices, and that the results are not driven by recent weather-shocks. Subsequently, the discount rate schedule is estimated in the remainder of Section 4. Section 5 finally, features an extensive discussion of the validity of the results and how they compare to estimates found in other settings.

2. Background and Related Literature

Long-run intergenerational discount rates, needed to value climate change mitigation efforts, can be derived from social welfare calculations or a market discount rate can be inferred empirically (Arrow et al., 1996).[1] While the latter is easily done for shorter periods due to the ample availability of cashflows with varying degrees of certainty maturing within 30 years or less, maturities with longer horizons are rare. This has led to a vigorous debate about both the level and shape of discount rate schedule, with different compelling arguments having been formulated in favour of a declining discount rate (DDR) by Gollier (2008, 2012) and Weitzman (1998, 2001).

Empirical estimates for long-run discounts rates are available only from studies comparing the prices of freehold and leasehold properties with different maturities. In the cases of England and Singapore, the seminal study by Giglio, Maggiori, and Stroebel (2015), hereafter GMS, infers that cashflows up to 150-300 years away are reflected in the present values of real estate assets, finding a gross discount rate of 2.6% for horizons beyond 100 years. Using a similar study-design, Bracke, Pinchbeck, and Wyatt, (2018), hereafter BPW, find slightly lower discounts for central London properties with the same leasehold durations, and show that the discount rate schedule is declining.[2] Bernstein, Gustafson, and Lewis (2019) also find that events expected to take place a century or more from now are reflected in real estate values, estimating a 4% discount to properties not projected to be lost to SLR before 2100. Further related to this study are Koster and Pinchbeck (2022) who estimate average tax discount rates in England in the context of mis-optimization, and Gautier and van Vuuren (2020) who study Amsterdam land leases and find strong heterogeneity in the short-term discount factor.

2.1. Erosion

Erosion studies in the context of real estate economics have so far been rare and limited in scale, likely due to the lack of hazard maps comparable in quality and accessibility to those for flooding. Coastal erosion is therefore usually considered indirectly, looking at proximity to the coast or the width of the coast rather than the time left until a property is expected to disappear

[1] For a good overview of this debate, see Stern and Taylor (2007). Arrow et al. (2014) provides a more recent overview focused on the term-structure of the discount rate.
[2] Other authors using the same approach include Wong, Chau, Yiu, and Yu (2008) for Hong Kong, Tyvimaa, Gibier, and Zahirovic-Herbert (2015) for Helsinki, and Fesselmeyer, Liu, and Salvo (2016) for Singapore.

into the sea. Landry and Hindsley (2011) find a $71-$196 premium for an additional meter of high-tide beach width and $52-$132/m of dune width, implying that houses exposed later to coastal erosion are more expensive. For properties close to the shore, Jin, Hoagland, Au, and Qiu (2015) estimate a 0.18% reduction in price per meter of annual erosion rate. Most recently, Catma (2021) found that properties located in an area subject to erosion transact for significantly lower values up to 214 meters from the shore. Filippova, Nguyen, Noy, and Rehm (2020) studied the publication of detailed projections of coastal erosion in New Zealand in 2012 and found no significant effect on transaction prices of coastal homes.

2.2. Flooding

An extensive literature centerer on the United States studies the capitalization of flood risk. The comprehensive meta-analysis by Beltrán, Maddison, and Elliott (2018) found an average discount of 4.6% for properties located in 100-year flood zones. The more recent meta-analysis as part of Contat, Hopkins, Mejia, and Suandi (2024) found a slightly lower discount of 3.9%. An additional price-discount in the wake of a flood event is found by the majority of authors (Atreya & Ferreira, 2015; Atreya, Ferreira, & Kriesel, 2013; Bin & Landry, 2013; Mutlu, Roy, & Filatova, 2023; Ortega & Taşpınar, 2018). This discount disappears again after 4-12 years, although some studies find that the discount doesn't disappear for properties that were actually inundated (Daniel, Florax, & Rietveld, 2009; Yi & Choi, 2020).

Despite the considerable differences between the US and UK in terms of climate change beliefs, attitudes towards prevention, and the role of the state in society, there have been surprising few studies on flooding in the UK. The only published study on the pricing of ever-present flood risk by Belanger and Bourdeau-Brien (2018) finds a 1.5% discount for houses located in a 100-year flood zone, with a larger discount for waterfront properties.

Because the Land Registry transaction-dataset used in all UK flooding-studies to date contains a limited number of property-level controls, other authors have limited themselves to event studies using a repeat-sales approach. Beltrán, Maddison, and Elliott (2019) find a 24.9% post-flooding discount for inland properties located in an entirely inundated postcode, and 21.1% for coastal flooding. Discounts are short-lived, disappearing in 4 or 5 years for inland- and coastal flooding respectively. Garbarino and Guin (2021) meanwhile, find a 2.6-4.2% discount to properties that were flooded for more than 49 days following the 2013-2014 winter flood.

3. Setting and Data

This study examines property pricing along the English coast in the presence of coastal erosion and flooding risk. Due to an abundance of data, the study area is restricted to 10km from the east coast of England between the northern border of North Yorkshire at Staithes and the river Orwell at Felixstowe. This area contains around 90% of the country's private properties at risk of coastal erosion under the assumption that current policies are implemented (Sayers, 2018), as well as many flood-prone areas. The study period is 2010-2023, starting with the publication of the latest shoreline management plans (see Section 3.2).

3.1. Transaction data

The Land Registry's Price Paid dataset (PPD) was first merged with the Energy Performance Certificates (EPC) dataset to obtain crucial dwelling characteristics such as floor area, year of construction and of course the EPC-bands on a scale from A (best) to G (worst).[3] Irregular transactions are removed from the dataset (fire-sales, repossessions, transfers to non-private individuals, etc.), as are transactions for which important variables were missing, and property types other than houses and bungalows (see Appendix A for more details on the merging process and data cleaning). Removing flats was done as they are often leaseholds, and including both apartments and houses in the same hedonic reduces fit.[4] Caravans are excluded because they are less durable and more mobile than houses, and therefore not suitable for the pricing of location-specific future risks.

Geocoding was done in two steps to save time and costs. First, the combined PPD-EPC dataset was merged with the National Statistics Postcode Lookup (NSPL) dataset from the Office for National Statistics (ONS, 2024) containing latitude and longitude for each postcode in England, giving an imprecise geolocation for each transaction.[5] Using ArcGIS, it was determined whether the postcode-boundary is located within 100m of the coastline. If this was the case and/or no postcode-location was given, the transaction was geocoded using its exact address. Only unique matches with a score of >95 have been kept,[6] even higher standards have to be met in some contexts as outlined in the remainder.

[3] Match rate is approximately 58%
[4] Flats are also very rare in the study area, especially along sparsely populated NAI-shorelines.
[5] These postcode units cover small areas with around 15 addresses.
[6] https://doc.arcgis.com/en/arcgis-online/reference/geocode.htm

3.2. Erosion and Coastal Management

Erosion is driven by wave and surge action. Differences in the rate of erosion, however, are primarily the result of the significant geomorphological diversity along the English coast, including hard and soft rock cliffs, sand and gravel barriers and beaches, dune systems, estuaries, tidal flats, and salt marshes (Kirby et al., 2021; Scott, Masselink, & Russell, 2011). The studied east coast, bordered by the North Sea, is characterized by soft, unconsolidated cliffs and extensive sandy beaches, experiencing rapid coastal cliff erosion.

3.2.1. Coastal Management

A Shoreline Management Plan (SMP) is a non-statutory policy document that provides the basis for coastal defence management planning for a stretch of coastline in England or Wales (DEFRA, 2011). It is a large-scale assessment setting out the risks from flooding and erosion to people and the built, historic, and natural environment within the SMP area and it formulates policies for managing risks from floods and erosion over a century. There are four main policy-options as detailed in Table 1: Hold the Line (HTL), Managed Realignment (MR), No Active Intervention (NAI), and Advance the Line (ATL), with the latter policy being very rarely selected. The choice is informed by technical, environmental, social, and economic factors. Management is further divided into three epochs: short- (2005-2025), medium- (2025-2055) and long-term (2055-2105).

Table 1: SMP policies. Source: Ballinger and Dodds (2020).

SMP2 Policy	Description
No Active Intervention (NAI)	No public investment in coastal defences or operations. Coast will be allowed to develop naturally.
Managed Realignment (MR)	By allowing the shoreline to move backwards or forwards, with management to control or limit movement (such as reducing erosion or building new defences on the landward side of the original defences).
Hold the Line (HTL)	By maintaining or changing the standard of protection. The standard of protection could increase or decrease.
Advance the Line (ATL)	By building new defences on the seaward side of the original defences, the advancement of the existing defence line assumes land reclamation and increased standard of protection from flooding and erosion to the current assets.

SMPs were first formulated in the 1990s (SMP1) and reviewed in 2006, with publication in 2010 (SMP2). SMPs were ‘refreshed’ again starting in 2019, but this refresh was not meant to

change policies.[7] Flooding and coastal protection schemes as well as planning guidelines are supposed to be consistent with SMPs. However, policy implication of SMPs such as the construction of sea walls are not guaranteed funding by the national government.

Insurance against losing a property to coastal erosion is currently not available in the UK (CCC, 2018). While no-one is legally obliged to inform buyers of the presence of erosion risk, building surveys conducted by mortgage companies should report on this. Even cash buyers are unlikely to be unaware however, given how clearly visible an eroding coastline is.

3.2.2. Climate Change and Erosion

Climate change affects coastal erosion and geomorphology, primarily through sea-level rise and alterations in wave climate, including storminess and prevailing wave direction (Masselink & Russell, 2013; Nicholls & Cazenave, 2010). While no marked increase in storminess or wave height has been observed to date, SLR is expected to result in increased coastal erosion in England (Masselink et al., 2020; Vousdoukas et al., 2020). The magnitude of this effect, however, remains highly uncertain and no models incorporating climate change were available until early 2025.[8]

This study, therefore, ignores the effects of climate change as no information on any such effects was available when the property transactions included in this study occurred. For the estimation of very long-run discount rates, this is a crucial advantage: as opposed to studies on the capitalization of SLR, estimates are not sensitive to the choice of emission scenario by the researchers as no such choice is available in the first place. The implicit assumption is that buyers and sellers disregarded climate change in the same way, although it cannot be ruled out that (long-term) erosion risk-discounts are increased due to climate change concerns if agents nonetheless expected SLR to exacerbate coastal erosion.

3.2.3. Methods

Using ArcGIS, the distance to the closest SMP-segment (and thereby the coastline) was calculated for each property within a kilometre of the coastline in the dataset. Given that the

[7] Changing an SMP-policy is not impossible but it rarely happens in practice.
[8] The latest 2024 National Coastal Erosion Risk Map includes three climate scenarios: Present Day climate, Higher Central allowance, and Upper End allowance. The latter accounting for SLR under the worst-case RCP8.5 scenario (70th and 95th percentiles respectively), resulting in a doubling of at-risk properties by 2105 (Environmental Agency, 2024).

maximum annual coastal retreat in the long-term epoch is 4.56m in this sample, the shortest theoretically possible time until a property located a kilometre from the shoreline would be lost is well over two centuries. SMP projections by epoch are subsequently converted into erosion rates and the time affected properties have left under the active policy scenario is calculated. Between 1km and 10km from the coast 6 distance buffers are created and the remainder of the transactions is located within them. Effect for coastal proximity beyond 10km are not expected to be found (Atreya & Czajkowski, 2019; Belanger & Bourdeau-Brien, 2018; Conroy & Milosch, 2011).

3.3. Flood Maps

The Environmental Agency (EA) assesses risk of flooding from rivers and the sea and publishes this information as maps with 50x50m resolution. This flood map takes flood defences and their condition into account but does not distinguish between fluvial and coastal flooding. The flood risk definitions are shown in Table 2, along with the corresponding UK flood zone level for riverine flooding, which does not distinguish between high and medium flood risk. In total, almost half a million properties in England face a >1% risk of flooding (Environmental Agency, 2023).

Table 2: Flood risk categories and definitions.

Flood Risk	Definition	Flood Zone
High	Greater than 1 in 30 (3.3%)	**3**
Medium	Between 1 in 30 (3.3%) and 1 in 100 (1%)	
Low	Between 1 in 100 (1%) and 1 in 1000 (0.1%)	**2**
Very Low	Less than 1 in 1000 (0.1%)	**1**
None	No flood risk	**-**

The EA's flood maps were updated in February 2014 following the widespread flooding occurring in the months prior. Flood risk information is also available in the form of a dataset containing all at-risk properties in England with the respective flood risk and the accuracy of the mapping in that area, which has been merged with the EPC-PPD dataset. Flood accuracy in this context is not about the accuracy of the location of the property or the resolution of the map but indicates how well the model performs at that location and how good the input data is. The result is a suitability rating indicating at which spatial scale the results are reliable. Recorded flood outlines are publicly available as GIS layers. Previously flooded properties were identified by overlaying this layer with the transaction locations in ArcGIS.

The 'High' and 'Medium' flood risk categories are merged because there are relatively few (738) observations in the former category, and the 100-year return period is conventionally used in the literature. This new variable is called flood zone (FZ) as the categories correspond to the UK flood zone levels. The difference between the definition of FZ used here and the UK flood zone levels is that the same return periods are used regardless of the source of flood risk, whereas original UK flood zone definitions differ based on the source of flooding, with coastal flooding having half the threshold of riverine flooding (i.e., flood zone 3 is >1% for riverine flooding and >0.5% for coastal flooding). This differential definition is the reason why the flood risk dataset was used in the first place, thereby assuring comparability both within the sample and with other studies globally, where 100-year flood zone dummies are the standard.

3.4. Controlling variables

2021 Census data is obtained at the level of Lower layer Super Output Areas comprising between 400 and 1,200 households and a resident population of 1,000-3,000 persons. Population density, share of deprived households, tenure shares, and shares of young (<25 years) and old (>64 years) people are added to the dataset.[9] Lastly, proximity to rivers/streams is included in the form of a categorical variable, obtained using ArcGIS. The Haven in Boston and The Humber are treated as rivers for this purpose despite being tidal.

Table 3: Descriptive statistics of key variables (N=102,855).

Variable	Mean	Std. dev.	Min	Max
Transaction Price (£)	204,955.7	107,935.8	20,000	3,075,000
Real Price (2023)	246.600.5	123,564	28,208.7	3,947,368
Price/m2	2,238.33	928.53	221.8	22,760
Real Price/m2	2,693.39	1,034.98	263.95	24,226.81
Floor Area (m2)	94.7	37.8	15	917
EPC-band (A-G)	3.98	0.98	1 (A)	7 (G)
Leasehold	0.0095	0.097	0	1

3.5. Final dataset description and transformations

After removing transactions with unrealistic prices as described in Appendix A, the complete dataset contains 102,855 transactions of 84,772 unique properties (18% repeat sales, up to 5 times). Figures in the remainder will be for transactions unless stated otherwise. Table 3 shows

[9] It worth noting that deprivation is relatively common in the study area: 56.7% of households is deprived in at least one dimension against 51.7% in all of England and Wales.

descriptive statistics of price and size for the sample. Real prices are calculated for 2023 price levels using headline consumer price index as published by the ONS.

3.5.1. Properties at risk of Erosion

After visually inspecting the geocoded locations of all properties that could be at risk under current SMP policies and manually correcting their location where necessary,[10] the number of years left before the coastline is expected to be at the location of the centroid of the building is calculated for all properties along an erodible stretch of coastline. This is done through simple interpolation, taking account of the movement of the shoreline between dates of measurement and sale. Erosion rates after the end of the long-term epoch in 2105 are assumed to be the same as during that last epoch. The sample contains no ATL-areas, meaning negative erosion rates are impossible.

The final sample contains 376 sales of 304 unique properties with an expected time until loss (ETL) of a century or less under their respective SMP policy and another 3,550 sales within 1000 years (mid-estimate). Under active policies and mid-estimates of erosion rates, there are 7 transactions with minus 1-4 years left, implying the property should have disappeared already when it was sold. Given that the value at the 95% confidence level is positive for all these transactions, this probably just means that the coast there eroded more slowly than expected. All negative values are converted to zeros, as it is impossible for buyers to expect a negative asset-life. A histogram of all transactions of properties located no more than a kilometre from the shoreline with an ETL of a thousand years or less is shown in Figure 1.

Around 3% of properties in the sample located between 990-1000 meters from the coast are expected to disappear within a millennium due to coastal erosion. From this, we can infer that less than 3% of properties exposed to coastal erosion (in the broadest sense) was missed by limiting the search to 1km. The corresponding figure for an ETL of 500 years is <1%. This means that endogenous selection of properties into the group of unaffected properties can be excluded.

[10] For this purpose, ‘at risk’ means that the distance to the coast is smaller than 1.2 times the maximum (5% likelihood) retreat distance in 2105.

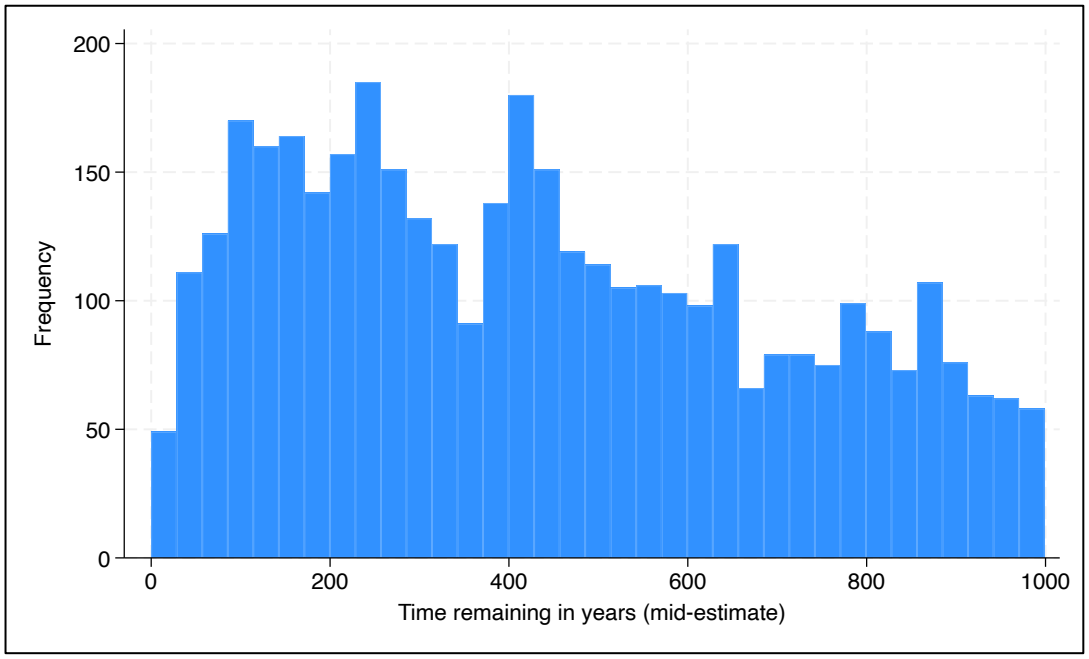


Figure 1: Histogram of ETL.

Calculating ETL for the different likelihood levels also allows us to assign properties to risk categories comparable to those used for FZs, whereby ETL is the return period. While erosion zones (EZ) 2 & 3 are not prone to selection bias, the opposite is true for EZ1 which consists of properties that are not at meaningful risk of coastal erosion but just happen to be within a kilometre of an erodible stretch of coastline.

3.5.2. Properties at risk of Flooding

Table 4 shows the number of observations in the different erosion- and flood zones, zone 0 designates no risk. Given the distribution, similar concerns about FZ1 can be raised as about EZ1: these properties were likely in areas selected for closer examination but turned out to not be at serious risk of flooding. Unlike EZ1 however, these properties are publicly designated as being at risk of flooding and estimates could therefore tell us something about the discount associated with such a designation.

Table 4: Joint frequency of exposed properties.

Flood Zone	Erosion Zone				Total
	-	**1**	**2**	**3**	
-	68,365	2,788	3,532	375	*75,060*
1	3,587	139	15	0	*3,741*
2	19,448	3	2	0	*19,453*
3	4,594	5	1	1	*4,601*
Total	*95,994*	*2,935*	*3,550*	*376*	102,855

The number of recorded sales after the event of properties that were located within the 2013-2014 flood outline is 384 only. There is virtually no overlap between flooding and coastal erosion risk (under current SMP-policies): the sample just contains just four observations that are meaningfully exposed to both risks (Zone 2 or higher). This is to be expected as erosion affects cliff-top homes which are usually perched high above the sea or beach.

4. Empirical Analysis

To estimate the price associated with exposure to coastal erosion, a hedonic framework is used where a residential property is seen as a bundle of characteristics from which consumers derive utility (Lancaster, 1966; Rosen, 1974). The price of a house i is regarded as the present value of its discounted annual flow-amenities $\boldsymbol{Z}_i = (Z_i^1, \dots, Z_i^n)$ or rent R_i. Two cases can be distinguished: transacted houses i behind a stretch of coastline j that is either protected or not eroding ($T_{ij}^{SMP} \to \infty$) and properties along coasts that will be allowed to erode ($T_{ij}^{SMP} < \infty$).

A property exposed to coastal erosion can be thought of as an annuity that matures when the property disappears due to coastal erosion at a given date in the future. The number of years left T_{ij} is dependent on the rate of coastal erosion η_j (given the SMP policy in place along stretch of coast j) and distance from the coast D_i:

$$T_{ij}^{SMP} = f\left(\eta(SMP)_j, D_i\right)$$

Following GMS, we assume that flow-amenities $\boldsymbol{Z}_i$ accruing in each future period are discounted at constant nominal (net of growth) discount rate $r - g$. This means that the T-period discount factor is given by $e^{(r-g)T}$. Further assuming that the annual amenity-value remains unchanged in the future, the value of a property exposed to coastal erosion is given by:

$$P_t^T = \int_t^{t+T} e^{-(r-g)(s-t)} \boldsymbol{Z}_t ds = \frac{\boldsymbol{Z}_t}{r}(1 - e^{-(r-g)T})$$

A perpetuity, in this case a property that is unaffected by coastal erosion (or an HTL-property), is valued at $P_t = \boldsymbol{Z}_t/(r-g)$. The discount Δ_t^T for a property exposed to future erosion relative to an otherwise comparable unaffected property is:

$$\Delta_t^T \equiv \frac{P_t^T}{P_t} - 1 = -e^{-(r-g)T}$$

In equilibrium, buyers are indifferent between properties with different remaining lifespans and the prevalent net discount rate for various horizons can be derived. The capitalization horizon, defined as the period beyond which expected losses due to coastal are no longer priced in, is given by the T for which $P_t^T = P_t$. By observing properties with different T in the same market, this horizon can be found. Unlike Landry and Hindsley (2011), we do not assume that agents differ in their knowledge of coastal processes given that estimated erosion rates for the English coast are publicly available information and erosion can be easily observed.

4.1. The pricing of erosion- and flooding risk

Before estimating how far in the future erosion losses are priced in and what the implied discount rates are over very long horizons, the analysis starts with the simple question of whether erosion risk is priced into transaction prices in England in the first place and how estimates compare to those found for flooding. This section thereby serves as a replication of the previous studies on flood-discounts in England and the rest of the world, and presents the first estimates for erosion risk. Whether erosion risk discounts are constant over time, notably in the wake of the 2013-2014 winter storm, is examined in Section 4.2. Section 4.1.3. investigates if flood zone discounts are higher in areas closer to the sea, as found by Belanger and Bourdeau-Brien (2018).

4.1.1. Identification

The following model is estimated using Ordinary Least Squares (OLS) regression:

$$P_i = \beta_0 + \boldsymbol{\beta_{1-3}} \boldsymbol{EZ}_i + \boldsymbol{\beta_{4-6}} \boldsymbol{FZ}_i + \sum_{k=7}^{K} \beta_k X_{ki} + \gamma_i + \delta_i + \epsilon_i$$

Where P_i is the natural log of the real transaction price in transaction i. The coefficients for erosion capture the average discount for that erosion zone: $\beta_1 = \overline{\Delta_t^{1-100}}, \beta_2 = \overline{\Delta_t^{100-999}}, \beta_3 = \overline{\Delta_t^{>1000}}$. Due to endogenous selection, estimates for β_3 should be interpreted with caution. The coefficients for flood zones capture the marginal implicit hedonic price for flood risk: $\boldsymbol{\beta_{4-6}} = \partial P_i / \partial \boldsymbol{FZ_i}$ as first derived by MacDonald, Murdoch, and White (1987).

Apart from the usual property-level controls including size, leasehold, newbuild, and a series of construction-era*building-type dummies, several crucial variables controlling for characteristics known to correlate with erosion risk and flooding are included. Distance to the coast and rivers are included as two separate categorical variables, controlling for the amenity value of coastal and riverside living. To control for location and time related factors, postcode-sector dummies (γ_i) and year*quarter-dummies (δ_i) are included. Further time-invariant locational factors are captured by the socio-economic indicators from the UK Census at a very granular level. This way, it is possible to control for neighbourhood effects associated with living along an erodible coast. Heteroskedasticity-robust standard errors ϵ_i are used.

As properties at risk of coastal erosion are often built or maintained to lower standards, the building material used for the walls is included as a categorical variable, as are the EPC-bands on an A-G scale. This latter variable is a good predictor of non-decent state (mouldy, state of disrepair, etc.), something that is substantiated using data from the English Housing Survey in Appendix B. As a further robustness check, the model is estimated using a sample that excludes likely non-decent and non-durable homes; sales of properties with EPC-band F or G and buildings made using a timber frame or 'system built' structures.

It is possible that owners invest less in properties at risk of coastal erosion and/or properties in flood-prone areas. To control for this factor, the difference between the energy rating and the potential EPC-band as given by the EPC-dataset is included in the regression as a discrete variable. The idea being that this difference proxies the scope for further improvements.

As the results for flooding serve in part as a replication of the findings by Belanger and Bourdeau-Brien (2018), estimate without the property-level controls obtained from the EPC-dataset are included to make them comparable in terms of specification and to show the importance of including such controls.

Lastly, two weighted regression models are estimated where the observation-weights w_i correspond to the reliability of the building-characteristics obtained from the EPC dataset and to the quality of the geocode. In the former case w_i is determined by the time in days between the sale and the date of inspection: $w_i^{EPC} = 3652 - (sale\ date - inspection\ date)$, whereby $w_i^{EPC} = 1$ if the inspection happened within a month of sale and $w_i^{EPC} = 0$ if the difference is

10 years of more. In the case of geocoding-quality: $w_i^{Geo} = 1 - (100 - geocode\ score)/5$. This way, observations that are more likely to be erroneous in terms of characteristics or location have less influence.

4.1.2. Results

Table 5 below shows estimates for erosion and flood risk using categorical variables corresponding to the same return periods for both risks. Model 1 shows estimates excluding property-level controls from the EPC-dataset, while Model 2 is the preferred specification that includes all relevant controls. Model 3 includes only durable and likely decent homes, while Models 4 and 5 show the weighted regression estimates. Residual plots for Model 2 can be found in Appendix C.

The average discount for a house that is expected to disappear due to erosion within 100 years is 16% in the preferred specification. There is even a small discount for houses expected to disappear between more than one hundred years from the date of sale. The discount associated with 1% flood risk is 2.6% and significant discounts are found even for properties exposed to small flood risks of less than 1%. The difference in discount between 2 and 3 is insignificant. It is remarkable how similar the discounts for low levels of erosion and flooding risk (EZ2 & FZ2) are, despite the differences in terms of expected losses.

Table 5: Regression estimates for erosion- and flooding risk.

	(1)	(2)	(3)	(4)	(5)
Erosion Zone 1	-0.0225***	-0.0146**	-0.0155***	-0.0161**	-0.00563
	(0.00647)	(0.00472)	(0.00467)	(0.00491)	(0.00477)
Erosion Zone 2	-0.0802***	-0.0250***	-0.0244***	-0.0265***	-0.0253***
	(0.00662)	(0.00482)	(0.00479)	(0.00498)	(0.00506)
Erosion Zone 3	-0.263***	-0.163***	-0.147***	-0.172***	-0.164***
	(0.0226)	(0.0162)	(0.0171)	(0.0169)	(0.0163)
Flood Zone 1	-0.0262***	-0.0154***	-0.0130***	-0.0154***	-0.0137**
	(0.00539)	(0.00392)	(0.00393)	(0.00412)	(0.00422)
Flood Zone 2	-0.0490***	-0.0293***	-0.0309***	-0.0289***	-0.0300***
	(0.00491)	(0.00370)	(0.00372)	(0.00392)	(0.00390)
Flood Zone 3	-0.0622***	-0.0261***	-0.0277***	-0.0275***	-0.0237***
	(0.00673)	(0.00498)	(0.00505)	(0.00526)	(0.00516)
Controls	Some	All	All	All	All
Restrictions	No	No	Quality	No	No
Weights	No	No	No	Matching	Geocoding
R-squared	0.669	0.826	0.833	0.830	0.828
N	102,855	102,855	94,359	100,493	102,854

Notes: Dependent variable is the natural log of the real transaction price. Estimates are relative to location outside EZ or FZ respectively. Quarter and postcode-sector fixed effects are included. Standard errors in parentheses. *p 0.05; **p 0.01; ***p 0.001.

4.1.3. Flood risk and proximity to the sea

Next, we investigate whether there are spatial differences in the pricing of flood risk. An interaction term $FZ * f(D)$ is added to the model. Table 6 shows results for models 2 & 4 where $f(D) = ln(D)$,[11] while models 1 & 3 use distance-dummies in line with previous specifications (only 500-750m and less are displayed). Quality restrictions and weights are not used as flood zone-estimates were found to be highly robust to those factors (see Table 5).

Table 6: Flood Zone capitalization and distance from the coast.

	(1)	(2)	(3)	(4)
Flood Zone 1	-0.00940*	-0.00919*	-0.00962*	-0.00871*
	(0.00393)	(0.00423)	(0.00397)	(0.00426)
Flood Zone 2	-0.264***	-0.264***	-0.00144	-0.00393
	(0.0208)	(0.0215)	(0.00883)	(0.00915)
Flood Zone 3	-0.262***	-0.229***	-0.00914	-0.00852
	(0.0259)	(0.0268)	(0.0155)	(0.0162)
Flood Zone 2*ln(dist. coast)	0.0298***	0.0303***		
	(0.00255)	(0.00266)		
Flood Zone 3*ln(dist. coast)	0.0311***	0.0271***		
	(0.00336)	(0.00347)		
Flood Zone 2*Dist. coast (0-100m)			-0.189***	-0.174***
			(0.0292)	(0.0317)
Flood Zone 2*Dist. coast (100-250m)			-0.139***	-0.136***
			(0.0119)	(0.0128)
Flood Zone 2*Dist. coast (250-500m)			-0.0751***	-0.0740***
			(0.00918)	(0.00974)
Flood Zone 2*Dist. coast (500-750m)			-0.0402***	-0.0394***
			(0.00881)	(0.00945)
Flood Zone 2*Dist. coast (1000-1500m)			-	-
Flood Zone 3*Dist. coast (0-100m)			-0.154***	-0.128**
			(0.0359)	(0.0401)
Flood Zone 3*Dist. coast (100-250m)			-0.0968***	-0.0871***
			(0.0183)	(0.0192)
Flood Zone 3*Dist. coast (250-500m)			-0.0397*	-0.0380*
			(0.0161)	(0.0168)
Flood Zone 3*Dist. coast (500-750m)			-0.0259	-0.0303
			(0.0174)	(0.0188)
Flood Zone 3*Dist. coast (1000-1500m)			-	-
Controls	All	All	All	All
Dist. Coast variable	Dummies	ln(dist. coast)	Dummies	ln(dist. coast)
Restrictions	No	No	No	No
Weights	No	No	No	No
R-squared	0.826	0.828	0.826	0.829
N	102,810	102,809	102,855	102,854

Notes: Dependent variable is the natural log of the real transaction price. All controls, quarter, and postcode-sector fixed effects are included. Estimates for EZ are not displayed. Standard errors in parentheses. *p 0.05; **p 0.01; ***p 0.001.

[11] For D>1km, the natural log of the mid-point of the distance-bucket is taken for calculations instead. D is centered on the sample-mean D for easy comparison of FZ estimates.

Like Belanger and Bourdeau-Brien (2018), we find that discounts for flood risk in England are higher in areas closer to the sea. Estimates for EZ2 and EZ3 are slightly smaller than those found previously, suggesting that the effect of erosion is underestimated when not controlling for the differential pricing of flood zones. Properties located close to the shoreline are often either exposed to flooding or erosion, underestimating the flooding discount can therefore mean an underestimation of the price-differential with properties at-risk of coastal erosion.

4.2. Trends and Shocks

As many authors have previously found an increased discount for flood risk in the wake of extreme events such as the series of storms and floods that hit the UK in the winter of 2013-2014, we examine if discounts differ significantly before and after this event. First, regression estimates with year*EZ and year*FZ interaction terms are shown in Table 7 to check for trends in the discounts over time.

Table 7: regression with year-risk zone interaction terms.

Year	EZ2	EZ3	FZ2	FZ3
Mean (2016)	-0.0263*	-0.167***	-0.0272***	-0.0380***
2010	-0.00386		0.0169	0.0408*
2011	-0.0113		0.00257	-0.0139
2012	-0.00464		0.0163*	-0.0148
2013	-0.0125		0.0168*	0.00383
2014	-0.0186		0.0110	0.00633
2015	-0.0182		0.0109	-0.00275
2016	-		-	-
2017	0.0112		-0.0102	0.00480
2018	0.00837		-0.0108	0.0143
2019	-0.0263		-0.0204**	0.0240
2020	0.0139		-0.00889	0.0102
2021	0.00596		-0.0176**	0.0276*
2022	0.0547**		-0.0171*	0.0189
2023	0.0241		-0.00112	0.0371*

Notes: Dependent variable is the natural log of the real transaction price. Estimates are relative to location outside EZ or FZ respectively. All controls, quarter, and postcode-sector fixed effects are included. Standard errors in parentheses. *p 0.05; **p 0.01; ***p 0.001.

Some evidence is found of trends in the flood-discounts over the study period, with the FZ2 discount becoming larger over time, and the FZ3 discount becoming smaller. Although the parallel trends assumption (PTA) underlying Difference-in-Differences (DiD)-estimation cannot be tested formally in a simple 2×2 setup (Marcus & Sant'Anna, 2021), the existence of trends in the FZ-estimates both before and after the storm makes it unlikely the PTA hold for flooding. For erosion however, there is no observable trend forcing us to reject the PTA.

Additionally, we check whether the composition of the EZ-groups in terms of ETL has changed after the storm, making sure differences in erosion-discount are not driven by objective differences in risk, which is not the case.[12] For flooding, it is not possible to make such comparisons as exact return periods are not known.

Table 8: Effect of the 2013-2014 winter storm.

	(1)	(2)	(3)
Erosion Zone 1	-0.0167*	-0.0168*	-0.0168*
	(0.00807)	(0.00808)	(0.00808)
Erosion Zone 2	-0.0347***	-0.0349***	-0.0349***
	(0.00794)	(0.00794)	(0.00794)
Erosion Zone 3	-0.223***	-0.224***	-0.224***
	(0.0308)	(0.0308)	(0.0308)
Flood Zone 1	-0.0215**	-0.0216**	-0.0216**
	(0.00714)	(0.00714)	(0.00714)
Flood Zone 2	-0.0136**	-0.0138**	-0.0138**
	(0.00488)	(0.00488)	(0.00488)
Flood Zone 3	-0.0349***	-0.0353***	-0.0353***
	(0.00821)	(0.00821)	(0.00821)
Post-storm*Erosion Zone 1	0.00296	-0.0215	-0.0389*
	(0.00825)	(0.0112)	(0.0154)
Post-storm*Erosion Zone 2	0.0126	-0.0167	-0.0353*
	(0.00813)	(0.0107)	(0.0147)
Post-storm*Flood Zone 1	0.00731	0.00402	0.00848
	(0.00749)	(0.00976)	(0.0131)
Post-storm*Flood Zone 2	-0.0197***	-0.00629	0.00743
	(0.00379)	(0.00494)	(0.00677)
Post-storm	0.113***	0.112***	0.113***
	(0.00936)	(0.00939)	(0.00937)
Post-storm*Erosion Zone 1*f(time)		0.00451**	0.0240**
		(0.00141)	(0.00752)
Post-storm*Erosion Zone 2*f(time)		0.00546***	0.0277***
		(0.00136)	(0.00723)
Post-storm*Flood Zone 1*f(time)		0.000579	-0.000742
		(0.00121)	(0.00632)
Post-storm*Flood Zone 2*f(time)		-0.00247***	-0.0155***
		(0.000601)	(0.00325)
Flooded	-0.0333**	-0.0328**	-0.0328**
	(0.0128)	(0.0127)	(0.0127)
Controls	All	All	All
Time function	None	# years	ln(years)
Restrictions	No	No	No
Weights	No	No	No
R-squared	0.826	0.826	0.826
N	101,597	101,597	101,597

Notes: Dependent variable is the natural log of the real transaction price. Estimates for EZ and FZ are relative to location outside EZ or FZ respectively. All controls, quarter, and postcode-sector fixed effects are included. Standard errors in parentheses. *p 0.05; **p 0.01; ***p 0.001.

[12] Mean ETL for EZ2 and EZ3 were 476.5 and 63.5 before, and 477.8 and 61.6 after the storm respectively.

4.2.1. Storm

Although there is no break visible at the first glance, a DiD model is estimated to check whether estimates change due to a major storm striking the study area. The traditional 2x2 DiD model is used where properties falling inside the floodplain or are located along an erodible stretch of coastline are the treatment groups and properties in other areas form the control group (Atreya et al., 2013; Bin & Landry, 2013). The variable $Flooded_i$ is also included, a dummy indicating that property i was sold after the event while being located within the 2013-2014 flood outline, thereby controlling for the impact of flood-damage on the property's value (McKenzie & Levendis, 2010).[13] Given that the PTA is unlikely to hold in the case of flooding, the results for FZ2 and FZ3 should be interpreted with caution.

Results of the DiD-estimation displayed in Table 8 show no consistent significant post-storm discount for flooding, and a small additional discount for erosion risk in some specifications only. This discount, if significant at all, disappears in around a year in Model 3. In general, the results confirm the trends we saw earlier; with FZ2 decreasing over time and FZ3 increasing. Trends for EZ are primarily driven by the final years (2022-2023) of the sample and are otherwise weak. In conclusion, the 2013-2014 winter storm does not lead to a structural change in the discounts for flooding or erosion. However, a significant discount of 3.3% is found for properties that were inundated.

4.2.2. Flood Re

As a further robustness check, we include the introduction of the UK flood reinsurance scheme (Flood Re) in 2016 as a second shock, as that might have caused the estimates for FZ to change over time. Under this scheme, insurers can reinsure policies at a price that is tied to the council tax band of the property, rather than the exposure to flood risk, thereby assuring that properties in high-risk areas remain insurable.[14] Flood Re applies to properties built before 2009 only, and succeeds a similar arrangement from 2002 known as the "Statement of Principles" (Surminski, 2018).[15] Flood coverage is included as standard with home insurance and take-up rates are around 95% for homeowners (HM Government, 2016).

[13] For erosion no such variable was included as a property that was destroyed cannot be sold again.
[14] Flood Re is supposed to remain in force until 2039, after which insurers should be free to charge risk-dependent premiums.
[15] The introduction is therefore not a break with the past, and the policy is also not unexpected; it is not a shock comparable to a storm.

Table 9: Effect of the Flood Re introduction.

	(1)	(2)
Flood Zone 1	-0.0208**	-0.0212**
	(0.00712)	(0.00713)
Flood Zone 2	-0.0127**	-0.0127**
	(0.00487)	(0.00487)
Flood Zone 3	-0.0344***	-0.0345***
	(0.00820)	(0.00820)
Post-Flood Re*Flood Zone 2	-0.0261***	-0.0261***
	(0.00385)	(0.00385)
Post-Flood Re *Flood Zone 3	0.0122	0.0121
	(0.00795)	(0.00795)
Flooded	-0.0335**	-0.0332**
	(0.0127)	(0.0127)
Constructed Pre-2009		-0.0393
		(0.0304)
Controls	All	All
Restrictions	No	No
Weights	No	No
R-squared	0.826	0.826
N	101,106	101,106

Notes: Dependent variable is the natural log of the real transaction price. Estimates for FZ are relative to location outside FZ. All controls, quarter, and postcode-sector fixed effects are included. Estimates for EZ are not displayed. Standard errors in parentheses. *p 0.05; **p 0.01; ***p 0.001.

4.3. Erosion and time structure of discount rates

Now that we have established that erosion risk is priced into residential property in England, and that this discount is not driven by recent shocks to a substantial degree, this case is used to estimate how far into the future losses are priced into real estate, and what the implied very long-run discount rates are.

4.3.1. Identification

The identification strategy rests on exploiting three main sources of variation: difference in distance to an erodible stretch of coastline, differences in the local erosion rate, and differences in shoreline management policies, as well as one minor source in the form of difference in transaction dates. The identifying assumption is that conditional on controls, the only source of differences in discounts are differences in ETL. The same model for identification is used as before, where the erosion zone-dummies are replaced with k dummies for the number of years left:

$$P_{ij} = \beta_0 + \boldsymbol{\beta_{1-k}} \boldsymbol{T}_{ij} + \sum_{k+1}^{K} \beta_k X_{ki} + \gamma_i + \delta_i + \epsilon_i$$

The horizon-categories are selected as follows: 0-39 years forms the category containing the properties expected to be lost soonest, chosen because 40 years is the maximum duration of mortgages offered by retail banks in England. Theoretically, it is therefore possible to offload erosion risk onto the mortgage-provider by defaulting when the property is lost, something that is impossible when purchasing properties that are expected to exist for longer periods.[16] The rest of the first century is divide into two epochs of equal length: 40-69 and 70-99. Subsequently, additional 50-year epochs are added until we no longer obtain significant discounts relative to the control group. This way, the cut-off between properties at risk from erosion and unaffected properties is not set explicitly by the authors, or implicitly through the 1km limit on remaining-life calculations.[17]

Flood zone is still included as a controlling variable, and we control for the spatial differences in the flooding discount established in the previous section. Estimations that don't control for the interaction of flood and distance, and estimates accounting for the storm-shock, can be found in Appendix D.

4.3.2. Results

Table 10 shows estimation results for the preferred specification (1), a model restricted to durable and decent homes (2), and models using matching-weights (3), and geocoding weights (4). Model 5 uses geocoding weights and is restricted to point-address and manual geocodes only as a further robustness check for measurement errors.[18] This restriction comes at the cost of introducing a selection bias towards addresses that are easier to find for whatever reason. Residual plots for Model 1 can again be found in Appendix C.

[16] Bakkensen and Barrage (2022) find that households with higher SLR-exposure are more likely to be leveraged and that their mortgages have a longer maturity, showing that this concern is not entirely unfounded.
[17] Real perpetuities, like the freeholds in GMS, don't exist in the case of coastal erosion, necessitating a flexible approach.
[18] When using EZs previously imposing such a restriction was unnecessary as the locations of all observations in EZ1 were manually checked and corrected. However, the volume of transactions with an ETL between 100 and 300 makes that approach too time-consuming here.

Table 10: ETL and transaction prices.

	(1)	(2)	(3)	(4)	(5)
0-39 years	-0.280***	-0.248***	-0.279***	-0.282***	-0.294***
	(0.0313)	(0.0408)	(0.0295)	(0.0312)	(0.0327)
40-69 years	-0.189***	-0.154***	-0.207***	-0.177***	-0.194***
	(0.0289)	(0.0286)	(0.0318)	(0.0286)	(0.0295)
70-99 years	-0.147***	-0.140***	-0.148***	-0.141***	-0.156***
	(0.0209)	(0.0221)	(0.0221)	(0.0211)	(0.0219)
100-149 years	-0.0989***	-0.0941***	-0.106***	-0.0926***	-0.116***
	(0.0155)	(0.0165)	(0.0163)	(0.0163)	(0.0195)
150-199 years	-0.0950***	-0.0759***	-0.0979***	-0.0888***	-0.0977***
	(0.0157)	(0.0155)	(0.0158)	(0.0163)	(0.0180)
200-249 years	-0.0506***	-0.0413**	-0.0581***	-0.0393**	-0.0465**
	(0.0126)	(0.0130)	(0.0131)	(0.0128)	(0.0158)
250-299 years	0.00889	0.00408	0.00121	0.0253	0.0401*
	(0.0145)	(0.0150)	(0.0150)	(0.0152)	(0.0174)
Controls	Yes	Yes	Yes	Yes	Yes
Restrictions	No	Quality	No	No	Geocoding
Weights	No	No	Matching	Geocoding	Geocoding
R-squared	0.826	0.833	0.831	0.829	0.822
N	102,810	94,316	100,452	102,809	55,869

Notes: Dependent variable is the natural log of the real transaction price. Estimates are relative to an ETL of 300+ years. All controls, quarter, and postcode-sector fixed effects are included. Estimates for FZ are not displayed. Standard errors in parentheses. *p 0.05; **p 0.01; ***p 0.001.

The results shown in Table 10 imply that the capitalization-horizon lies at around 250 years, beyond which we find no discount to properties exposed to coastal erosion relative to all other properties within 10km of the east coast of England. Given how close the estimate for the 250-299 years-bucket is to zero, this finding is not influenced by the choice of significance level. Estimates, especially for horizons of 100 years or more, are robust to model specification. Importantly, the relative size of the estimates is highly robust which allows us to make strong claims about the shape of the discount schedule, as is the capitalization-horizon. Figure 2 below plots the implied gross discount rates for each horizon, including estimates for staggered intervals (see Appendix D). We can clearly see that the discount schedule is declining. It appears to level-off past 175 years.

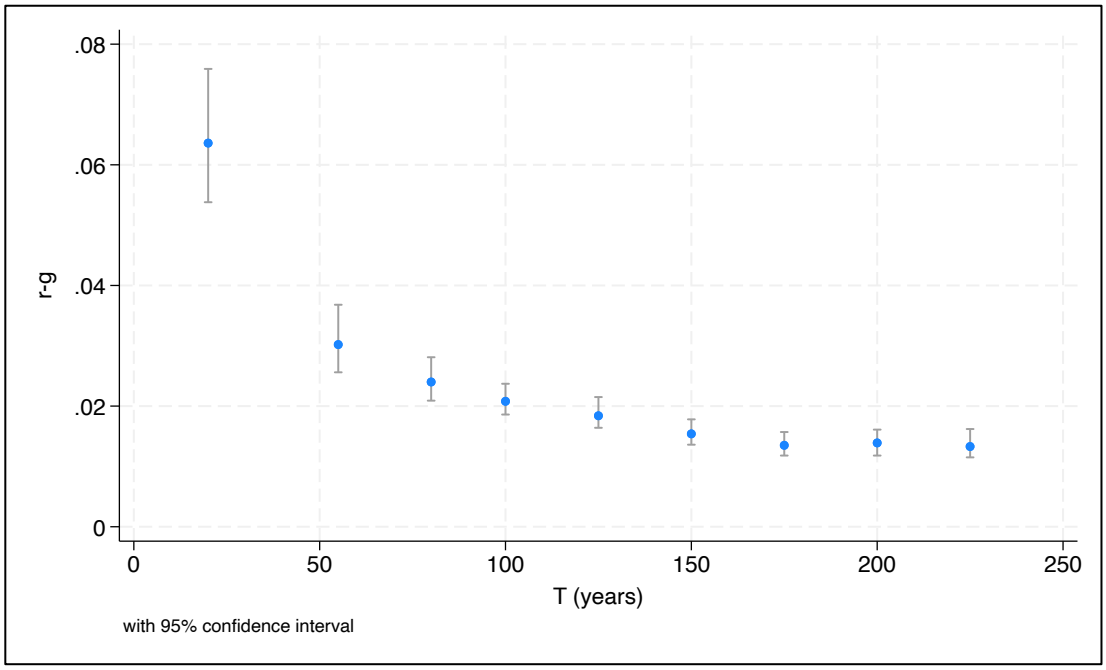


Figure 2: horizons and discount rates.

4.3.3. Comparison of estimates

To easily compare the estimates found in this paper to those found by GMS, the model is estimated using the same horizons as in that seminal paper. Table 11 below shows this study's results side-by-side with both GMS and BPW, our estimates are identical to the former for horizons of 100-150 years,[19] and a bit higher for the 150-300 year period. This paper's estimates for 80-99 years are lower, but the sample also has less statistical power for this short interval. BPW's estimates are consistently lower than mine and GMS', but not significantly so.

Table 11: comparison of estimates.

Horizon	GMS estimates	BPW estimates	Own estimates
80-99 years	-0.176	-0.105	-0.144
	(0.007)	(0.016)	(0.022)
100-124 years	-0.110	-0.080	-0.109
	(0.008)	(0.016)	(0.022)
125-149 years	-0.089	-0.043	-0.083
	(0.008)	(0.021)	(0.020)
150-300 years	-0.033	-0.037	-0.044
	(0.010)	(0.056)	(0.009)
N	1,373,383	15,907	102,855

Notes: GMS estimates can be found in Table III (column 1), and BPW estimates in Table 4 of their respective papers. Own estimates use a specification otherwise identical to the one used in Table 10, column 1. Standard errors in parentheses.

[19] However, GMS' discounts obtained using a sample excluding London (Table III, column 7) are smaller than those presented here.

5. Discussion

This study sought to answer five key research questions: First, whether erosion risk is priced into transaction prices; second, the magnitude of price discounts associated with properties located in flood zones in England; third, whether flood discounts increase with proximity to the coast; fourth, the longest horizon over which environmental effects are priced into real estate; and fifth, the implied discount rate for losses expected to materialize in the distant future.

5.1. Erosion risk

We find strong evidence that erosion risk is reflected in transaction prices of houses. EZ3, expected destruction within a century from sale, is associated with a 16-19% discount depending on the model specification, slightly less (15%) if likely non-durable or damaged homes are excluded from the sample. EZ2 (100-1000 years left) carries a highly significant discount of 2.5-3.5%. The 2013-2014 winter storm had a short-lived, small negative effect on transaction prices of homes at risk of coastal erosion. These results are consistent with previous research that finds that erosion risk is priced into residential real estate (Catma, 2021; Jin et al., 2015; Landry & Hindsley, 2011).

5.2. Flood zone capitalization

Compared to the erosion-estimates, estimates for flood zone discounts are less consistent across time and space. In the preferred specification, the discounts associated with a location in FZ1, FZ2, and FZ3 are 1.6%, 2.9%, and 2.6% respectively. The validity of these results does not extend to non-coastal areas of England, given the clear relationship found between distance to the sea and flood zone discounts.

Estimates are slightly higher than those found by Belanger and Bourdeau-Brien (2018) overall, but this might just reflect that this sample is biased towards coastal areas. Using a model specification that is more comparable to Belanger and Bourdeau-Brien (2018) a much higher discount is found, something for which we have no satisfying explanation.

No increased discount for flood zone-location is found after the 2013-2014 winter storm, just a clear downward trend for FZ2 over time, and somewhat weaker evidence for an upwards trend for FZ3 estimates. We do find however, that properties flooded during the event are sold

at a 3.3% discount after controlling for flood zone location. This figure is very similar to the discount Garbarino and Guin (2021) found for inundation periods of 50 days or more.

Discounts for lower flood risk levels FZ1 and FZ2 are far larger than any reasonable estimate of the present value of the expected costs given the extremely long return periods. They are also high compared to estimates for FZ3 although the similar estimates for FZ2 and FZ3 could simply reflect the fact the Flood Re equalizes insurance costs across flood risk levels. The discounts for flood risk in England therefore probably reflect the stigma associated with flood zone location more than the actual expected costs borne by homeowners.

5.3. Flooding and proximity to the sea

The finding that flooding discounts are higher in areas closer to the sea aligns with Atreya and Czajkowski (2019) and Belanger and Bourdeau-Brien (2018). Bosker, Garretsen, Marlet, and van Woerkens (2019) however, find no such effect in the Dutch case. Possible explanations include the greater expected damage from salt water, expectations of future increases in risk due to SLR, and presence of a form of availability bias when the sea is nearby. Future studies that are better able to separate the source of flooding from distance to the coast could perhaps shed more light on this.

5.4. Capitalization horizon

Expected losses due to coastal erosion are capitalized into residential real estate up to around 250 years into the future. This assumes that agents do not take any potential increases in erosion rate due to climate change into account. The 250-year horizon would be an overstatement if this assumption is incorrect, as discounts would reflect losses expected to occur at an earlier date in the future. Future research could potentially use the publication of updated erosion mapping in January 2025 to shed more light on the role played by (expectations of) climate change on coastal erosion pricing.

Of course, it is possible that properties are lost sooner (or later) than expected for reasons unrelated to climate change, and agents might not care exclusively about the mid-estimate, but also about the worst-case scenario, especially if they are myopic. Erosion differs in this respect from leaseholds which are not the result of stochastic processes. SLR however, is similar in this regard as local sea levels fluctuate with the tide and wind. We therefore argue that the

capitalization horizon for inundation due to SLR can be assumed to be the same, *ceteris paribus*.

No good previous estimates are available of the capitalization horizon, but the fact that GMS found a significant discount for leaseholds maturing between 150 and 300 years from the transaction date lends credibility to the finding of a 250-year horizon. The finding by Bernstein et al. (2019) that properties not expected to be lost to SLR before the end of the century sell at a discount is of course also consistent with a 250-year horizon for the capitalization of environmental losses, although the discount we find is substantially bigger than 4%.

Regardless of the precise length of the capitalization horizon, this study demonstrates that economic agents factor distant future events into their decision-making processes, suggesting that the 'Tragedy of the Horizon' (Carney, 2015) is not inevitable. The evidence indicates that when authorities clearly delineate which coastal areas will receive protection and which will be surrendered to natural processes, market prices efficiently incorporate this information. This finding has significant implications for climate adaptation policy, suggesting that transparent, long-term planning can effectively guide market responses to environmental challenges, even when the consequences lie generations in the future.

5.5. Very Long-run discount rates

The net discount rates implied by the discounts found for properties expected to be lost at different points in the future are 2.4% for horizons of 70-99 years, 2% for 75-125 years, 1.8% for 100-150, 1.5% for 125-175 years, and 1.4% for 175-250 years. The resulting discount rate schedule is clearly declining before levelling off when the horizon exceeds some period between 150 and 175 years. This finding aligns with BPW. To calculate the gross discount rate r, the rate of real rent or price growth should be added to these figures. In the case of England, estimates of the historic annual real rate of growth range from 0% (Chambers, Spaenjers, & Steiner, 2021) to 0.6% (GMS), 1% (Knoll, Schularick, & Steger, 2017), and 1.6% (Jordà, Knoll, Kuvshinov, Schularick, & Taylor, 2019). Taking the average of g=0.8% gives a gross discount rate that levels off at 2.2% for the longest horizons.

A major advantage of the use of coastal erosion to infer discount rates over the leaseholds used by GMS and BPW is that the observations in the sample used in this study are more evenly

distributed in terms of time-remaining, whereas leaseholds are clustered around a select numbers of (round) years. Moreover, the number of observations in this study does not increase in horizon and therefore confidence intervals are not wider for higher values of ETL. The main disadvantage of the current setting is the much smaller sample-size resulting from the limited number of properties exposed to coastal erosion, giving less statistical power for horizons <150 years.

Despite the different settings, our estimates are strikingly similar to those found by GMS. For equivalent horizons beyond a century, estimates are within a percentage-point of each other and do not differ significantly. This means that the discounts rate they found are not due to some peculiarity about leaseholds such as the obligation to pay ground rents; whereas GMS' subsample of 'exposed' properties consisted entirely of leaseholds, the treatment group in this study is comprised nearly entirely (99%) of freeholds.

In contrast to Bernstein et al. (2019), our approach benefits from the fact that coastal erosion rates are far less dependent on the trajectory of climate change, eliminating the need for assumptions about future climate scenarios. Because of the differences in correlation between expected losses and the state of the wider economy, their results are not directly comparable to those presented here.

One potential criticism of this study is that it assumes erosion only affects property value when the property is completely lost, overlooking the gradual impact erosion may have on a property's amenity value well before its disappearance. For example, the road in front of the house could become unusable or part of the garden could be lost (on the other hand, the house will have direct access to the sea). This might mean estimates are a slight underestimate (i.e., the real discount is smaller) as part of the discount captures the neighbourhood effects of living in the vicinity of destruction. Although fixed effects and other local controls should capture most of this, there might be a remaining effect at the lowest geographical scale that can't be controlled for.

Two things will mitigate this bias, however. First, this neighbourhood-effect will be partly a function of distance for which we can control, ETL varying in erosion rate as well. Second, neighbourhood effects are stronger when ETL is smaller, meaning any bias should decrease with horizon and is therefore unlikely to affect estimates for very long-run discount rates.

Finally, it is worth pondering the correlation between erosion risk and the state of the wider economy, and what that implies about the discount rates found. Unlike flooding risk exacerbated by SLR, erosion risk does not correlate strongly with shocks to the wider economy. During storms, more properties and infrastructure will be lost than during other times as larger chunks of the coast get washed away, but as a share of the local housing and capital stock it remains small. This suggests that the gross discount rate should be close to the risk-free rate (Greenstone, Kopits, & Wolverton, 2013).

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Appendix A: Data sources and processing

Table A1 lists all data sources, with the edition used identified by the publication date. The EPC-dataset and PPD are merged based on postcode and address. In case a transaction matches with multiple EPC entries, it is merged with the entry that is closest in time (smallest difference between date of sale and date of inspection). Transactions are not matched with EPC inspections conducted after the transaction date unless the inspection happened within 31 days of the sale. The absolute difference in time between transaction and inspection is kept as an indicator of match-quality.

Table A1: Data sources

Name	Type	URL	Release
PPD	Dataset (.csv)	https://www.gov.uk/government/statistical-data-sets/price-paid-data-downloads	20 January 2024
EPC	Dataset (.csv)	https://epc.opendatacommunities.org	31 January 2024
National Statistics Postcode Lookup	Dataset (.csv)	https://opendata.camden.gov.uk/Maps/National-Statistics-Postcode-Lookup-UK-Coordinates/77ra-mbbn/about_data	14 June 2024
Flood Risk by Property	Dataset (.mdb)	https://www.data.gov.uk/dataset/f126da9d-d4c4-48b8-8fa3-9a7bf6ac98bc/risk-of-flooding-from-rivers-and-sea-properties-in-areas-at-risk	9 February 2024
SMP	GIS-layer	https://www.data.gov.uk/dataset/7564fcf7-2dd2-4878-bfb9-11c5cf971cf9/national-coastal-erosion-risk-mapping-ncerm-national-2018-2021	5 January 2024
Historic Flood Outlines	GIS-layer	https://environment.data.gov.uk/dataset/8c75e700-d465-11e4-8b5b-f0def148f590	2018
Statutory Main River Map	GIS-layer	https://www.data.gov.uk/dataset/4ae8ba46-f9a4-47d0-8d93-0f93eb494540/statutory-main-river-map	11 January 2023
Census	Datasets	https://www.nomisweb.co.uk/query/select/getdatasetbytheme.asp?opt=3&theme=&subgrp=	2021

All matched transactions with missing values for price, floor area, year of construction, and UPRN (unique property reference number) are removed. If the year of construction is missing and the building is a new-built, the year of the EPC-inspection is taken as the year of construction. Furthermore, all transactions with a price below 10,000 GBP, above 10,000,000 AND price/m2 above 15,000, as well as transactions with a price/m2 above 25,000 are removed, along with transactions marked as irregular (*ppd_categorytype* = "B"). If the price per square meters is more realistic (closer to the postcode-district yearly average) when assuming square feet are given rather than m^2, the floor area is changed accordingly (unless the number of rooms is given and changing the size would yield unrealistic average room sizes).

The combined dataset is subsequently merged with the National Statistics Postcode Lookup-dataset, the Flood Risk by Property-dataset, and the census-data using the UPRN. Next, the

subset of addresses that needs to be geocoded is uploaded into ArcGIS to obtain coordinates, and then downloaded again and merged back into the complete dataset. Transactions with geocode-scores of less than 95 are removed at this point. The dataset was then re-uploaded into ArcGIS to create a feature-layer, transactions that were not geocoded in the previous step are located using the coordinates of their postcode. In ArcGIS, the dataset is merged with the Historic Flood Outlines-layer (overlap), the Statutory Main River Map-layer (buffer-overlap), and the SMP-layer (find closest), thereby calculating distance to the coast in the process.

Appendix B: Housing Standards

The 2021 English Housing Survey (2024)[20] is used to check whether EPC-bands, material used for the walls and dwelling age are good predictors non-decent home standard and renovation costs. In Table B1 below we can see that ratings F and G almost perfectly predict non-decent standard, while A, B & C predict decent standard.

Table B1: joint frequency of EPC-bands and decent homes in EHS

EPC-band	Decent Homes	Non-decent Homes
A/B	156	5
C	3,348	155
D	3,314	468
E	413	221
F	4	184
G	0	38
Total	7,235	1,071

[20] https://beta.ukdataservice.ac.uk/datacatalogue/studies/study?id=9229

Appendix C: Postestimation

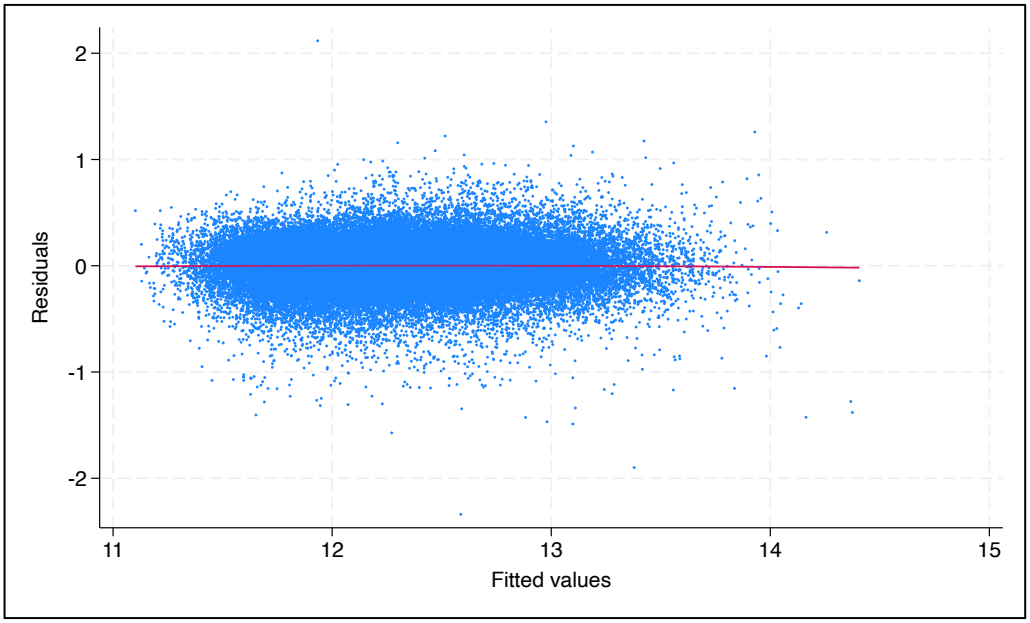


Figure C1: Residual plot of baseline model (Table 5 (2)) with fractional polynomial fitted in red.

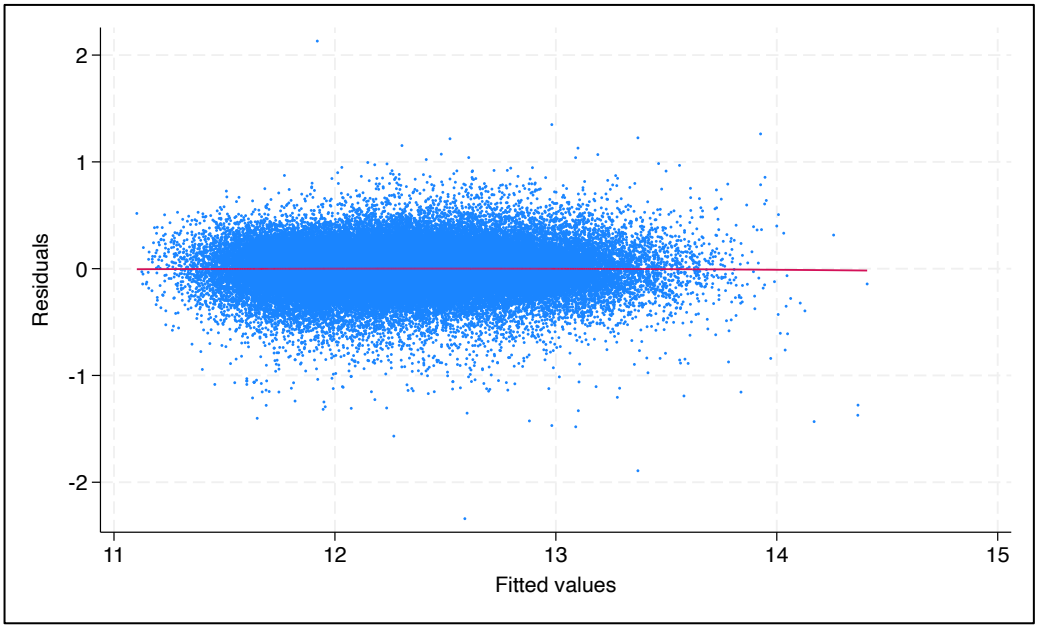


Figure C2: Residual plot of baseline model (Table 10 (1)) with fractional polynomial fitted in red.

Appendix D: Discount rates (further estimates)

Table D1: estimation results when not including flooding*distance interaction term.

	(1)	(2)	(3)	(4)	(5)
0-39 years	-0.259***	-0.232***	-0.259***	-0.267***	-0.280***
	(0.0312)	(0.0408)	(0.0293)	(0.0311)	(0.0326)
40-69 years	-0.172***	-0.140***	-0.191***	-0.165***	-0.183***
	(0.0288)	(0.0285)	(0.0317)	(0.0285)	(0.0294)
70-99 years	-0.130***	-0.125***	-0.131***	-0.128***	-0.145***
	(0.0208)	(0.0221)	(0.0220)	(0.0210)	(0.0219)
100-149 years	-0.0831***	-0.0804***	-0.0897***	-0.0805***	-0.105***
	(0.0154)	(0.0164)	(0.0162)	(0.0162)	(0.0194)
150-199 years	-0.0832***	-0.0658***	-0.0861***	-0.0800***	-0.0898***
	(0.0157)	(0.0154)	(0.0157)	(0.0163)	(0.0180)
200-249 years	-0.0401**	-0.0320*	-0.0476***	-0.0314*	-0.0400*
	(0.0125)	(0.0129)	(0.0130)	(0.0127)	(0.0158)
250-299 years	0.0189	0.0132	0.0112	0.0331*	0.0464**
	(0.0145)	(0.0150)	(0.0150)	(0.0152)	(0.0174)
Controls	Yes	Yes	Yes	Yes	Yes
Restrictions	No	Quality	No	No	Geocoding
Weights	No	No	Matching	Geocoding	Geocoding
R-squared	0.826	0.833	0.830	0.828	0.821
N	102,855	94,359	100,493	102,854	55,869

Notes: Dependent variable is the natural log of the real transaction price. Quarter and postcode-sector fixed effects are included. Standard errors in parentheses. *p 0.05; **p 0.01; ***p 0.001.

Table D2: estimation results for offset horizons.

	(1)	(2)	(3)	(4)	(5)
0-39 years	-0.281***	-0.249***	-0.281***	-0.283***	-0.295***
	(0.0313)	(0.0408)	(0.0295)	(0.0312)	(0.0328)
40-74 years	-0.198***	-0.159***	-0.220***	-0.186***	-0.203***
	(0.0283)	(0.0274)	(0.0312)	(0.0278)	(0.0288)
75-124 years	-0.125***	-0.116***	-0.126***	-0.119***	-0.138***
	(0.0160)	(0.0175)	(0.0166)	(0.0167)	(0.0183)
125-174 years	-0.0999***	-0.0944***	-0.110***	-0.0911***	-0.123***
	(0.0155)	(0.0154)	(0.0162)	(0.0159)	(0.0194)
175-224 years	-0.0673***	-0.0563***	-0.0648***	-0.0606***	-0.0525**
	(0.0138)	(0.0142)	(0.0139)	(0.0144)	(0.0164)
225-274 years	-0.0134	-0.0118	-0.0257	0.00484	0.00822
	(0.0134)	(0.0140)	(0.0140)	(0.0143)	(0.0168)
275-324 years	-0.0238	-0.0312*	-0.0313*	-0.0163	-0.0235
	(0.0136)	(0.0135)	(0.0138)	(0.0135)	(0.0161)
Controls	All	All	All	All	All
Restrictions	No	Quality	No	No	Geocoding
Weights	No	No	Matching	Geocoding	Geocoding
R-squared	0.826	0.833	0.831	0.829	0.822
N	102,810	94,316	100,452	102,809	55,869

Notes: Dependent variable is the natural log of the real transaction price. Quarter and postcode-sector fixed effects are included. Standard errors in parentheses. *p 0.05; **p 0.01; ***p 0.001.