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Sub-Recent Changes in Annual Average Water Level in the Shannon Estuary, Western Ireland

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ABSTRACT

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This paper describes results to date on work to reconstruct the pattern of sub-recent water level changes within the Shannon Estuary, western Ireland. The main database for the study covers the period 1949 to 2002, and includes observed tide gauge data and hydrological data. Routine statistical analyses are used to plot the relative position of the water surface through time, and to assess the relative significance of the components of an averaged water level curve that has been developed for Limerick City Dock at the head of the estuary. The findings form part of a larger project that aims to develop a time series of Mean Water Levels, Mean High Water Levels, Mean Low Water Levels and Mean Tidal Range in the context of human modification of the estuary since the mid-19th C, including land reclamation and environmental responses to predicted sea level changes. The newly assembled data presented indicate that average water levels have changed significantly between 1949 and 2002, including a clear overall rise in water surface elevation within the study period and particularly within the last decade. This paper quantifies the degree and rate of change evident from the averaged water level curve and explores the possible causes of the trend.

ADDITIONAL INDEX WORDS: *Tide gauge data, hydrological data, reclamation, relative sea-levels.*

INTRODUCTION

This paper presents newly assembled data for the Shannon Estuary as an averaged water level curve for the period 1949 to 2002, assesses the relative importance of factors contributing to the trend exhibited by the curve, and evaluates its significance and implications in the context of the Intergovernmental Panel on Climate Change (IPCC) projections for future sea levels.

Projections made by the IPCC (2001) suggest that sea levels will rise substantially in the 21st century. Tide gauges on a global level have shown an average relative sea level rise of between 0.1 and 0.2 m during the 20th century. The IPCC suggests that between 1990 and 2100 globally averaged sea level will rise by between 0.09 m to 0.86 m, with a 'best estimate' of 0.49 m for global sea level change in the next 100 years. Considerable uncertainty remains on how these averaged values will translate in terms of coastal process-response systems at the local level. This is particularly the case where significant geologic, oceanographic, tidal or climatological differentials occur at the regional to local level, or where there has been significant engineered modification of the coastal environment. Estuarine environments in particular have been the subject of considerable human pressures, as demonstrated by DAVIDSON *et al.* 1991 for sites in the UK, where the combined demands of land reclamation, industrial, commercial, infrastructural and settlement land use are shown to have altered the morphometrics and functioning of most estuarine systems in Wales and England. Similar patterns have occurred in other estuaries in Europe and elsewhere (VILES and SPENCER, 1995; FRENCH, 1997; ALLEN, 2000).

The Shannon Estuary is an extensive water body situated on Ireland's Atlantic coast. It comprises the lower reaches of the Rivers Shannon and Fergus, extending *c.* 96 km from Limerick City to its mouth at Loop Head Co. Clare. Its hinterlands incorporate parts of County Kerry, County Limerick and County Clare. The outer estuary consists of the area to the west of Aughinish Island on the south bank, and west of Kildysart on the north bank, while the inner estuary comprises the remainder of the water body eastward to Limerick City and northward to Clarecastle on the River Fergus (Figure 1). The Shannon Estuary is subject to permanent marine inundation and tidal flows through a generally southwest - northeast aligned main channel. The estuary is macrotidal, with a tidal range of 5.44 m, the largest on the Irish coast. Water depths vary from *c.* 37 m at the estuary mouth to less than 5 m at some points near Limerick City. The estuary receives a substantial freshwater input from the River Shannon and its tributaries (draining *c.* 15,700 km^2) as well as lesser amounts from several other rivers and streams.

Aspects of the estuary's physical setting (WHEELER and HEALY, 2001), ecological attributes (HEALY, 2002) and changing morphology (HEALY and HICKEY, 2002) have been the subject of a number of recent studies. The estuary system has extensive associated inter-tidal mudflats, fringing reed-beds, salt marshes, wet marsh habitats and reclaimed wetlands. Substantial parts of its environs have been modified significantly as a consequence of land reclamation and commercialisation since the mid-19th C. Much of the relatively low-lying land around the inner estuary is subject to intermittent flooding during periods of high rainfall and coincident storms occurring at spring tides, such as the storms that occurred in October 1961 and more recently in February 2002. Record high tides were recorded on both occasions and much of the reclaimed land that relies on embankments and revetments for flood protection was extensively flooded. These embankments are serviced and occasionally improved by the Irish Office of Public Works (OPW) and others in an effort to maintain their effectiveness as flood defence systems.

The studies described in this paper focus primarily on variations in the averaged annual water levels within the Shannon Estuary in the latter half of the 20th C based on observed data for this period. It is significant, however, that in common with many similar areas on the European Atlantic fringe and elsewhere, Holocene relative sea levels in south-west Ireland have risen inexorably, on the evidence of chronostratigraphic data. DEVOY (1990) argues that in Ireland the evidence for coastal environmental change indicates that marine flooding and associated land erosion has been continuous since the end of the last (Midlandian/Devensian) glaciation *c.* 14,000 years ago. Approximately 30-40 km of Ireland's coastline has become submerged since then, when the sea surface was some 60 m below present levels. Averaged rates of relative sea level recovery between 10,000 and 5,000 BP achieved approximately 6 mm/year before slowing to 1 mm/year, and relative sea level had reached to within 2 m of present day levels by 3,000 BP (TAYLOR *et al.*, 1986; CARTER *et al.*, 1989).

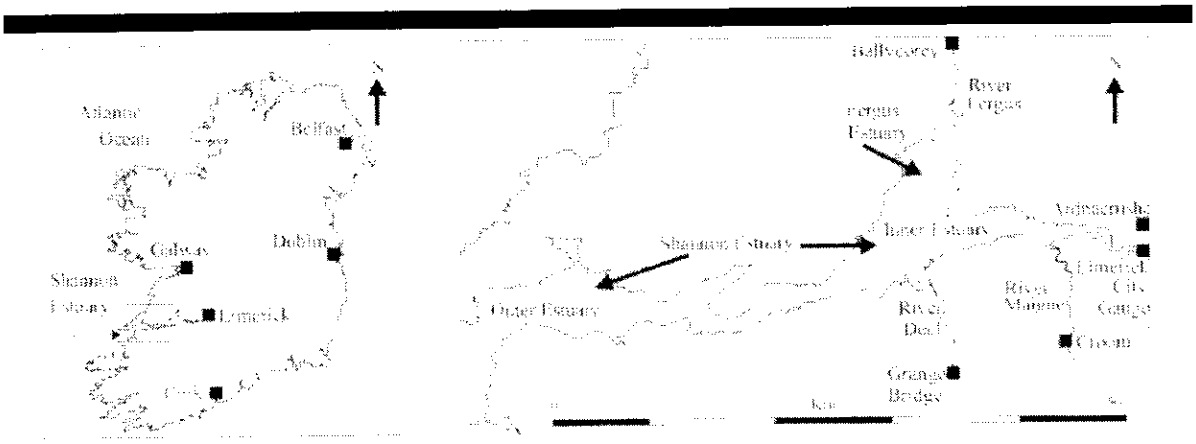

Figure 1. Location of the Shannon estuary, western Ireland and outline of estuary showing freshwater flow stations and tide gauge station.

The rate of rise has been computed at 0.8 to 1.1 mm per year over the last 2,000 years (CARTER *et al.*, 1989). Regional complexity resulting from isostatic readjustment is embedded within this general situation. Tide gauge data from Malin Head, County Donegal, on the north coast of Ireland have shown that relative sea level was falling as land levels were rising, though recent studies suggest that land level may now be static. On the south coast land levels appear to be sinking gradually, producing relative sea level rise of 0.5 mm/year. Land levelling data from the south-west region quoted by DEVOY (1990) suggest that there may be a more rapid rise of sea-level in the south-west relative to other regions, possibly indicating crustal sinking at rates of *c.* 0.1 m/100 years and an overall relative sea level rise of *c.* 0.15 m/100 years since 1842.

In a review of the implications for Ireland of projected sea level rise under the scenarios published by the Intergovernmental Panel on Climate Change (1990), CARTER (1991) surmises that coastal areas subject to relative sea level rise from the combined effect of crustal sinking and eustatic water level rise are likely to experience significant environmental changes. In the instance of the Shannon Estuary, these include a higher-energy environment, producing increases in tidal currents and amplitude, high water mark erosion, sediment displacement and channel siltation erosion cycles. Under these circumstances, the estuary environs may experience socio-cultural and socio-economic losses, such as land and housing losses, infrastructural damage and disturbance of facilities adjacent to the estuary (CARTER, 1991). These may include urban disruption at Limerick City, industrial, commercial and settlement loss around Shannon town and communications and transport displacement around Shannon International Airport, as well as more general problems associated with flooding and water intrusion in the hinterland, which has a population of *c.* 122,000.

Aims

This paper describes the development of an averaged water level curve for the Shannon Estuary for the period 1949-2002 based on observed tide gauge data from a station in Limerick City docklands. The function of the curve is to assess the extent to which the elevation of the average water level within the estuary has changed in the course of the study period. Assuming that the volume (water storage capacity) of the estuary basin is constant in the study period, the volume of water stored within the estuary basin per unit of time determines observed surface water level, and water volume change is primarily controlled by variations in the combined effect of tidal and freshwater flow through the estuary basin.

The relative significance of the tidal and freshwater components of the water level curve is assessed. The approach used in the assessment involves plotting the observed tide gauge data against the metered freshwater flow record from the main freshwater feeder rivers in the inner estuary. The findings are interpreted against a backdrop of large-scale human modification of the Shannon estuary for purposes of land reclamation from the mid-19th C onwards.

METHODOS

Data sources

The analysis of water level records is based on two primary data sources available for the Shannon Estuary. The first is the observed tide gauge record from the 'Ted Russell' dock at Limerick City, referred to here as the Limerick City Gauge (LCG).

This comprises a continuous record of daily water levels from 1949 to 2002, generally consisting of two high tide readings and one low tide reading, but some discontinuities occur in the record of low tide levels. The majority of the observations are recorded manually in tide ledgers, but from 1996 to 2002 automated data is available in a digitised format showing hourly records. Elementary statistical manipulation of these data allows the production of periodic water surface elevation curves using the high water observations. Annual average water levels were calculated for the LCG, as illustrated in (Figure 2). The resulting water level curve represents the compound influences of the various components that contribute to determining water surface elevation.

The second data source is provided by freshwater flow meters located on the main feeder rivers that debouche into the inner estuary (Table 1). Freshwater flow data are recorded as the daily mean flow in cubic metres per second (m^3/s) at discharge recording stations located at Ballycorey on the River Fergus, Croom on the River Maigue, Grange Bridge on the River Deel and Ardnacrusha Hydro-Electric Power (HEP) Station on the River Shannon. The Irish Electricity Supply Board (ESB) maintains the Ardnacrusha data, while the OPW has provided data for the other sites. These data are plotted as time/discharge curves that describe freshwater flow on an annual basis.

Table 1. *Freshwater flow recording stations around the inner Shannon Estuary.*

Name of station	Station reference No.	River Catchment	Duration of recorded data
Ardnacrusha		Shannon	1949 - 2002
Ballycorey	24001	Fergus	1956 2002
Grange Bridge	24012	Deel	1954 2002
Croom	27002	Maigue	1972 - 2002

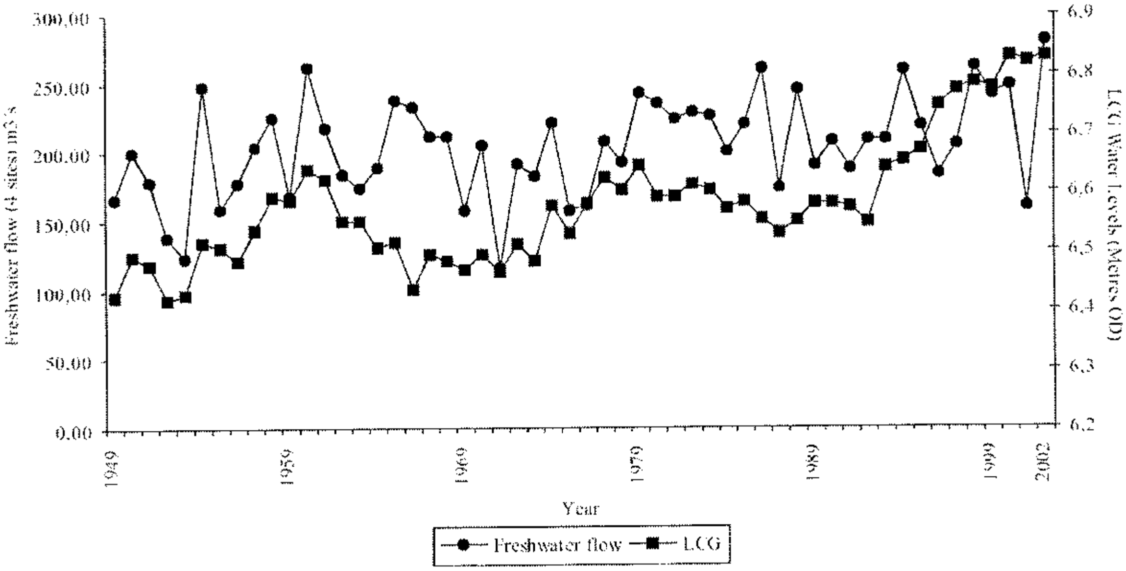

Figure 2. Combined Annual Average Freshwater Flow Values and LCG Water Level Values.

RESULTS

Observed Tide Gauge data 1949-2002

The water surface elevation curve for the LCG (Figure 2) shows that the secular trend in water surface elevation has changed significantly in the period 1949-2002, with the overall trend of average high water values exhibiting a pronounced rise. In total, average water levels have risen by 0.406 m in the study period. However, this rising trend has within it an embedded oscillation, with rising and falling patterns of water level change. In the period 1949-1960 water levels achieve an overall increase in elevation of 0.214 m, notwithstanding that this period includes the lowest mean high water recording for the entire data set (6.417 m) in the year 1952. Conversely, water surface levels display a falling tendency (-0.156 m) between 1961 and 1971, despite the occurrence of Storm Debbie in October 1961, which produced some of the highest recorded high water readings for the Shannon estuary.

From 1972 to 1981 water levels increase by 0.078 m, followed by a decrease of 0.040 m from 1982-1991, which, while significant, represents a rate of decrease considerably less than that exhibited in the 1961-1971 period. From 1992 onwards there is a progressive increase in water levels that continues through to 1998. The most striking feature of the LCG water level curve is the sustained rise in water surface elevation in the period 1992 to 2002, during which an increase of 0.282 m occurs. This represents an annual average increase of 0.026 m per year in this decade, which is more than three times the rate of 0.008 m per year for the overall period of 1949-2002. This compares with an increase of 0.129 m from 1973 to 1982 and an increase of 0.123 m. between 1953 and 1962. Values for a number of individual years are notable within the data, such as 1992-1993 with a rise of 0.10 m, from which point the LCG water level curve begins a sustained rise through to 2002. Similar individual annual increases occur in 1953-1954, 1973-1974 and 1995-1996.

Freshwater Input

The cumulative freshwater flow data for the period 1949 to 2002 is derived from adding together the annual average values for Ardnacrusha, Ballycorey, Croom and Grange Bridge to produce the freshwater flow curve shown in Figure 2. This shows that freshwater input to the inner estuary has oscillated in the study period, producing a pattern similar to that observed for the LCG data. There is good general correspondence between the water level curve and the freshwater flow curve. The latter suggests that freshwater is reaching the inner estuary at increasing rates through the study period, while the former demonstrates that the elevation of the water surface within the inner estuary has risen significantly through the same period.

The river Shannon (illustrated by the Ardnacrusha curve) is the main contributor of freshwater to the estuary, supplying *c.* 80% of the total freshwater volume in the period 1949 to 2002. The Grange Bridge flow record for the River Deel begins in 1954, while data for the River Fergus at Ballycorey is available from 1956 and for the River Maigue at Croom from 1972. Figure 3 shows the annual average freshwater flow data for each of the metering stations, and it indicates a significant degree of correspondence in relative flow rate among the four main rivers that approach the inner Shannon Estuary. Examples

Table 2. *Changes in water surface elevation for the LCG and freshwater flow based on trend and decadal analyses.*

Period	Change in water surface elevation (metres OD)	Change in freshwater flow (m³/s)	Decadal Analysis	Change in water surface elevation (metres OD)	Change in freshwater flow (m³/s)
1949-60	+0.214	+95.40	1953-1962	+0.123m	+60.48
1961-71	-0.156	-102.72	1963-1972	-0.122m	+17.40
1972-81	+0.078	+32.41	1973-1982	+0.129m	+46.80
1982-91	-0.040	-42.47	1983-1992	-0.013m	-17.85
1992-02	+0.282	+72.48	1993-2002	+0.188m	+72.51
1949-02	+0.406	+114.48	1953-2002	+0.403	+157.60

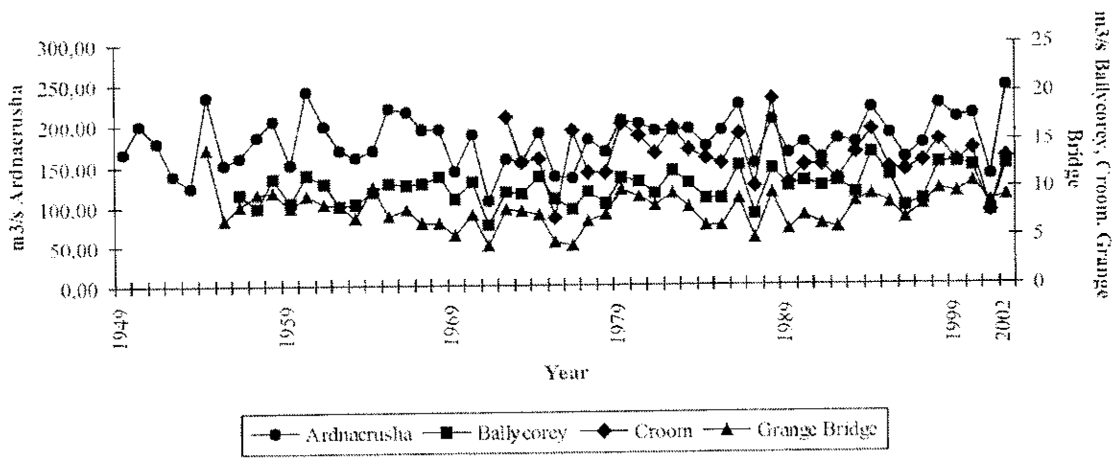

Figure 3. Annual Average Freshwater Flow at Ardnacrusha, Ballycorey, Croom & Grange Bridge.

of coincident increases in annual average values are particularly evident in 1988, 1994, 1998 and 2002, while coincident decreases in average flow are strikingly apparent for the years 1975, 1987, 1996 and 2001. An exception to the pattern of correspondence occurs between 1964-1969, where the Ballycorey data suggests an increase in freshwater flow while the Grange Bridge and Ardnacrusha records show decreasing flow levels. FIGURE 2 illustrates that there is a general lack of correspondence between the LCG curve and the combined freshwater flow curve in the same period.

The period 1949-60 shows the greatest cumulative increase in freshwater flow throughout the study period. However, there is a remarkable degree of oscillation in the record, as demonstrated in Figure 2. A decrease of 102.72 m³/s in annual average flow occurs in the period 1961-71 with the lowest annual average flow record in the study period occurring in 1971. A slight increase in annual averaged flow levels is evident between 1972 and 1981, followed by a decrease of 42.47 m³/s from 1982-91. The 1992-2002 period shows a rise in flow of 72.48 m³/s, an annual average increase of 6.59 m³/s for this period.

DISCUSSIONS

The data available for the LCG illustrate that the elevation of the water surface in the Shannon Estuary has experienced a sustained non-linear rise between 1949 and 2002. Water surface elevation in the inner Shannon Estuary appears to have risen more dramatically in the 1992-2002 period than in any previous period. This rise may be represented as an annual average increase in water surface elevation of 0.026 m per year, compared to 0.008 m per year between 1949 and 2002, suggesting that the rate of water level increase within the estuary has been accelerating in recent years.

Consistent with the findings of SWEENEY (1997) on changing precipitation levels in the Irish environment, freshwater flow data demonstrate that the quantity of freshwater reaching the inner Shannon estuary has increased in the period 1949-2002, with an annual average increase of 2.16 m³/s. This suggests that a relationship may exist between the overall water level recorded at the LCG and freshwater flow. The 1992-2002 period also shows an acceleration in the rate of annual average increase of 6.59 m³/s in freshwater flow into the inner estuary, which is approximately three times the rate of 2.16 m³/s for the 1949-2002 period. This demonstrates that the rate of rise in water surface elevation equals the rate of annual average increase in flow data over the course of the last decade. It may be concluded, therefore, that while there may be a relationship between increased freshwater input to the inner estuary and overall water surface elevation, other forcing factors are responsible for differentials in the trends exhibited in Figure 2.

There is a general consensus that global tide gauge data indicate that sea levels have risen measurably in the course of the last century, notwithstanding the regional influence of tectonic and isostatic influences on relative sea level patterns. The IPCC (2001) predicts that sea level will continue to rise in the future, estimating a rise of between 0.09 m and 0.88 m by the year 2100 with a 'best estimate' of 0.49 m. The annual average increase in water levels of 0.008 m per year in the Shannon Estuary is compatible with IPCC projections on changes in sea level on both a European and worldwide scale, and corresponds with findings at other European sites such as the North German coastline (JENSEN and MUDERSBACH, 2002). In an analysis of secular trends in UK mean sea level based on four UK tide gauges (1830's to 1982), WOODWORTH (1987) concluded that variations in the sea-level component of the tide gauge records is consistent with estimates for sea-level rise. The UK data correspond well with the LCG curve in the 1949-1982 period, with decadal patterns of rise and fall being reasonably consistent in both studies. In this context, it is likely that changes in relative sea level are a contributory factor in determining the overall trends evident in the LCG water level curve. The factors responsible for the rapid acceleration in the rate of water level rise in the 1992 2002 period are currently unclear, but the sustained year-on-year annual average increase between 1992 and 1998 is unlikely to relate to data errors, particularly given that the values for the 1999 2002 period are consistent with the accelerating trend.

There is as yet insufficient data for the Shannon region and the Irish mid-west generally to evaluate the possible contribution of many other process-related factors in influencing the LCG data. The significance of land level variations, which may occur as a result of isostatic re-adjustments cannot be calculated for this region in the absence of substantial and detailed chronostratigraphic data. A similar paucity of data relating to local and regional sediment supply and displacement, as well as an absence of information on sediment compaction and consolidation within and around the estuary, make it difficult to identify with precision the primary controls on water surface elevation changes.

Human modification of estuarine systems involving reclamation and flood defence technologies can significantly alter basin morphometrics and hydrologic characteristics. HEALY and HICKEY (2002) have shown that reclamation of a substantial part of the Shannon Estuary intertidal wetlands has taken place, primarily in the 19th C. The total area of estuarine wetland reclaimed was at least 6500 ha, which is now protected from flooding by a chain of embankments. The effect of reclamation works was to remove large areas of intertidal wetlands from the functional area of the estuary complex, and thereby significantly constrict the surface area of the water body. The tidal wetlands that were once available for dissipation of tidal floodwaters are now agricultural lands. There has been a consequent reduction in water storage capacity of the inner Shannon estuary in particular. The association between reclamation engineering and water surface elevation change seems intuitively clear, with the narrowing of the waterway leading to compensatory increases in water level, the effect of which may be magnified through time as the impact of relative sea level rise and increased freshwater flow becomes manifest.

CONCLUSIONS

The record of water surface elevation changes from the LCG data indicate that a pattern of oscillating increase in annual average values has been taking place in the period 1949 to 2002. While the general rate of increase through the study period is analogous with trends occurring elsewhere in Europe and consistent with IPCC data, the acceleration in the rate of increase in the 1992 2002 period remains to be explained.

There is a good general correspondence between water surface elevation and freshwater flow data for the main rivers approaching the inner Shannon estuary. Arising from a comparison of annual average water elevation and annual average freshwater input, it may be concluded that a relationship between freshwater input to the inner estuary and overall water surface elevation exists. However, freshwater flow values for the 1992 2002 period do not explain the pronounced rise in the LCG curve. This suggests that other variables are involved in determining water levels. These may include process-response systems relating to tectonic / isostatic readjustments in land levels, changes in sedimentary budgets and sediment displacement, or alterations in compaction / consolidation characteristics of materials within the estuary. In addition, the impact of land reclamation and associated engineering may be contributory factors in the trends observed.

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