Hydrologic flow regimes in humid tropics river basin

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ABSTRACT

The study is carried out to understand the impact of the land-use change in terms of alteration in flow regimes, which are understood to be a leading cause of ecological and environmental deterioration in riverine systems. Meenachil river in the humid tropical region of Kerala, India, is one of a kind river with human settlement along the banks for all its 78 kms of flow through the Kottayam District. The analysis of stream-flow from four stream gauge stations was done using Range Variability Approach. The analysis was down as a two-time period analysis with the parametric approach with the period separation taken according to prior studies on land-use change. The analysis shows a high degree of alteration, which can be attributed to the land-use change and can be understood as the root cause for the deterioration of water quality and also the ecological distress, which is well documented in the downstream and watershed regions of the river.

Key words: environmental flow, humid Tropics, hydrologic alterations, land-use change, range variability

HIGHLIGHTS

- Anthropogenic changes in tropical river basins.
- Extreme water conditions.
- Modification indicators Hydrological study.
- Environmental flow components.
- Flooding and its repercussions.

INTRODUCTION

Water is the lifeblood of planet Earth (Acreman 2004). The hydro-ecological systems such as lakes, rivers, saline, and freshwater bodies, are systems that need protection. In the total available water on Earth, which is of 1,400 million km$^3$, only 2.5% or 35 million km$^3$ is freshwater. The primary freshwater sources are the permanent ice caps of Antarctica and Greenland. Another portion is also locked in deep underground aquifers. Lakes, rivers, soil moisture, and shallow groundwater basins are the primary source of usable freshwater. The available and potable volume of freshwater sources is around 200,000 km$^3$ of water, less than 1% of all freshwater available on Earth (UNEP 2002). The available freshwater renews by rainfall and snowfall at a volume of 40–50,000 km$^3$ per year. According to UNESCO (2019), the water demand globally was found to be increasing about a percentage from the 1980s, which is caused due to population growth, socio-economic development, and increased consumption. This level of water demand increase is expected to follow the same trend up to 2050. More than 2 billion are expected to be under increased water stress, and another 4 billion people may experience severe water scarcity due to increased consumption and demand. The freshwater crisis is gradually unfolding in India in a significant way. The access to a safe supply of water is in crisis due to the inadequate management of water sources and subsequent destruction to the surroundings. The economic and social development of India is correlated with the water crisis in the country. There is temporal and spatial variation in the water crisis in different parts of India. Due to human action, most of the freshwater ecosystems in India are degrading.

The intense competition among the agricultural, industrial, and domestic sectors, which are dependent on groundwater, has left the depletion of groundwater levels. Pollution to the surface water and groundwater has damaged the freshwater quality. Large dams and riverine alteration along with the deforestation and land-use changes along the river banks are threats to the freshwater system. Sand quarrying and riverbank agriculture with land reclamation and construction are

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physically changing the flow path and regime of rivers. The bacteriological contamination in the drinking water sources and increased industrial and agricultural water use are causing stress in the quality of water available. The long-term changes in rainfall, overfishing, and exotic species booming in lotic ecosystems, are hard to reverse (Sauque et al. 2021; Siddiqui et al. 2021); desalination isn’t always feasible to obtain drinking water.

According to Kant (2018) in the NITI Aayog report, almost half of the Indian population faces high to extreme water stress. Almost two-thirds of households don’t have drinking water in their premises, almost two-thirds of the water available is contaminated, and among the 122 countries ranked on water quality, India ranks at 120.

The increased stress on the water by human population growth and the increased dependence of modern economies on hydropower has paved the way for the exponential increase in the number of storage and diversion facilities along the rivers. This was vital to the economies, especially the Indian economy, which was extremely dependant on large dam projects and irrigation structures. The boom in the dam construction spree globally and nationally has led to the alteration in the natural flow system. The studies done in the United States of America by Ritcher et al. (Richter 1996; Richter 1997; Richter 1998) have paved the way for understanding the alteration in flow regimes.

This study carries forward the Indicators of Alteration Hydrological study using the IHA software tool published by The Nature Conservancy (The Nature Conservancy 2009). The software uses the Range Variability Approach established by Ritcher et al. (Richter 1996). The study of Meenachil River was utilized for the IHA analysis. The data from 1984 to 2017 was used with a separation period of 1995 due to the already established high level of land-use change (Vincy & Brilliant 2014). The study has found a high degree of deviation of later flow patterns from the earlier period. This can be attributed to the rampant land-use change in the region. The high degree of hydrologic variation can be associated with the deteriorating condition of the river and subsequent environmental (Nair & Singh 2010) and ecological stress (Padmakumar 1999; Narayanan & Thapanjith 2004) in the watershed regions. Aims of the current study include improving understanding of the impact that land use and cover changes have on the hydrological regimes of the Meenachil river.

Study area: Meenachil river

Kerala is a South Indian State with a land area of 38,863 km², with its borders along the Arabian Sea on the west side and Tamil Nadu and the Karnataka States on the east side. The state is 560 km long and has a width between 70 and 125 km at various sections. The state lies between 08°18' and 12°48' north latitudes and 74°52' and 77°22' east longitudes. The state has 44 rivers that flow through it, of which 41 are west flowing, and three are east flowing.

The more significant rivers in the state are Bharathapuzha, Periyar, Pampa, and Chaliyar, which exceed 160 km in length, while other rivers are relatively small with an average length of about 64 km (Menon 1997). Both snow melting and rains do not perennially feed the rivers in the state, unlike its northern counterparts. This causes the rivers of the state to be short and fast-flowing with dry spells in the summer months. Kerala is a state that owes its beauty and comfort in living in comparison with other Indian states to the abundance of water and water bodies. The destruction of these systems that are essential due to factors such as land-use change, diversions, and encroachment are significant concerns and cause catastrophic imbalances.

Meenachil River originates from Araikunnunumudi at an elevation of 1,097 m above MSL. Its watershed extends from 9°25’ to 9°55’N latitudes and 76°20’ to 76°55’ E longitudes (Figure 1). The river has a length of 78 km. Meenachil River basin has an area of 1,272 km², within 57 panchayats and three municipal towns in Kottayam as well as in Vaikom, Kanjirappally, Meenachil, and Changanacherry taluks. The entire river basin falls within the district of Kottayam.

Meenachil river, which flows from the hills, passes major towns in the Kottayam District in Kerala, feeds the agrarian and economic needs for those towns and flows down into the Vembanad backwater. This entrance region was once a river trading route between Erattupetta and Allepey ports.

The Meenachil River, according to Vincy & Brilliant (2014), is one river that has human settlement along the course of its flow right from the source to the cessation at Vembanad Lake. Due to the excessive anthropogenic activity along the course, there is notable land-use change along the river course. The towns along the course empty their waste and dirt into the river and flooding during the monsoon season and acute water shortage during the summer season are also prevalent.

Land use/land cover change in the watershed area

The Meenachil River Basin is entirely on the Kottayam District in Kerala, India. There have been documented extensive land-use and land cover changes in Meenachil River Basin as studied for the year 1967, Figure 2, for the year 1996, and for the year...
Figure 1 | Stream gauge site locations (Google Images).

Figure 2 | Monthly flows for June.
2013 by Vincy et al. (Vincy & Brilliant 2014). The extent of the change in the basin is nothing short of enormous. The agricultural area comprised of rice fields, palm, areca nut, and seasonal crops has decreased significantly, while rubber plantations increased. This level of change has a dangerous impact on the quantity of water released, and also on the quality of water due to increased consumption and contamination (Ziegler 2009).

The studies on the Kuttanad wetland ecosystem showed species vanishing due to the Thanneermukkam regulator, due to the disturbance in development phases (Padmakumar 1999). The increased weed and invasive species populations and reduction in ecologically sustainable fishing are prevalent. The real estate encroachment and reclamation for tourism purposes, and the vanishing mangroves, which are the habitat for migratory birds, and the drying wetlands, are understood as irreversible ecosystem impacts. Padmini et al. (Padmini 2000) studied the daily streamflow and bimonthly groundwater fluctuations of the Meenanthara watershed of Meenachil River Basin using 1993–1997 data. The study found that the water balance values reflect the soil moisture deficit in the summer months. The Ichthyofauna of the Vembanad wetland is the watershed region of the Meenachil river, with 9 out of 34 freshwater species threatened, and one exotic species (Narayanan & Thapanjith 2004). There is also a notable increase in the invasive species growth and spread in the Meenachil River basin, namely the Limnocharis Flava Buchenau weed (Abhilash & Singh 2008).

The Chalakkudy river system, which is situated north of the Meenachil River, faces sustainability issues due to inter-basin water transfer and other anthropogenic activities (Sunny George 2001). The increased flow alteration has led to increased occurrence of salinity intrusion into the drinking water systems. The Pannagon River, which is a major tributary of the Meenachil River, exhibits a high degree of sinuosity with complex and convoluted loops with a large area of flood plain on either side when compared to other major tributaries of the Meenachil River (Satheesh 2008).

The presence of heavy metals, namely zinc, manganese, iron, lead, copper, and cadmium, for a period from May 2009 to September 2009 in the Meenachil river was studied by Indu et al. (Nair & Singh 2010). The study found levels of iron and lead in higher concentrations than permissible by the Bureau of Indian Standards during the post-monsoon season. The cause of this discharge was found to be domestic and municipal waste along with terrestrial runoff from seepage and agricultural sites.

Types of floods
There are numerous distinct types of floods, and the damage they may cause to your house might be quite varied depending on which one you are dealing with. Knowing which of the several sorts of floods might impact your house is essential to
understanding what you can do to better prepare for the catastrophe while also ensuring that you and your family can get to safety as fast as possible once it occurs.

Coastal flood
Flooding along the shore is caused by a buildup of water on land as a result of waves, tides, storm surge, or excessive rainfall. Because of their proximity to the water, coastal regions are particularly vulnerable to flooding, and the threat of flooding is anticipated to increase as a result of climate change.

River flood
When water surges above the tops of riverbanks, it is referred to as a river flood. Any size river or stream has the potential to flood, with rivers having a greater chance of flooding once every two years than smaller rivers and streams. In most cases, river flooding is caused by heavy rainfall brought on by tropical storm systems, prolonged thunderstorms, heavy rainfall mixed with snowmelt, and ice jams. It is precisely these bursts of melting snow or rain that cause water to flow above the riverbanks and flood the surrounding communities. A dam or dike failure, even if river floods may typically be forecast in advance, has the potential to cause significant property damage that would otherwise be unforeseeable. However, the majority of the time, river floods are caused by storms that provide ample warning for residents in the surrounding region to get away safely before the flood occurs.

Flash flood
Storms, hurricanes, tropical storms, and other weather patterns can create flash floods, which begin within 6 hours of the onset of heavy rainfall and can last for days. Additionally, flash floods can occur as a result of dam or levee failure or mudslide activity.

Groundwater flood
Groundwater floods are often caused by flooded drainage systems as a consequence of heavy rains, causing water to overflow into streets and neighboring houses and into the surrounding environment. They are equally likely to occur in both urban and rural locations, according to the data. Groundwater flooding, on the other hand, occurs gradually, when the water level is low and residents have ample time to relocate their belongings. It is important to note that this groundwater flooding may be problematic since it may last for several weeks or months before the soil is able to absorb the standing water. Therefore, they can...
pose a substantial threat to homeowners’ safety, increasing the possibility of structural damage to their houses as well as the potential of long-term hazards such as mold exposure.

Sewage flood
Flooding from sewage systems or treatment plants occurs when unexpectedly strong rainfall overwhelms the system or treatment plant, leading it to fail and to the release of untreated sewage into nearby water bodies. Water flooding from sewage pipes or drains is perhaps the most unpleasant, with sewage pouring through pipes or drains or leaking into toilets, sinks, or showers. Floods of this nature are the most dangerous since the water is contaminated with toxic germs and chemicals that can lead to infections and other ailments such as diarrhea, fever, vomiting, and others. In these instances, it is critical to have a quick reaction and a complete and meticulous clean-up performed by professionals who are acquainted with sewage cleanup services.

Data used for IHA analysis
The four sets of stream gauge data that are used for the IHA analysis are stream gauges in Teekoy, Pala, Kidangoor and Peroor, as shown in Figure 1. The Teekoy, Pala and Peroor data are from the Water Resources Department (WRD) of Kerala State, and the Kidangoor Stream gauge data is from Central Water Commission (CWC). The Teekoy, Pala, and Peroor stream gauge data is from 01/06/1980 and is up to 31/05/2009. The Kidangoor stream gauge data is from 01/06/1985 to 31/05/2017. The impact is taken for all the four-stream gauge locations as 1994–1996, as it is the period with a great shift in the land use pattern, as noted by Vincy & Brilliant (2014).

RESULTS AND DISCUSSIONS

Magnitude of monthly water conditions
The monthly flows for June show that the magnitude of water is seen to reduce during the post-impact period. Pala and Peroor data show most variation from the mean, which can cause stress on the ecosystem and organisms that are dependent on the water. Monthly flows for July show the Pala and Peroor data variation from the pre-impact mean. It may be
due to the excess water consumption due to the land-use change. Monthly flows for August show Pala and Peroor data mean with the largest deviation from the median while Teekoy and Kidangoor median trend is almost a continuum to the pre-impact period.

Figure 6 | Monthly low flows for June.

Figure 7 | Extreme low flows frequency.
Monthly flows for September show Teekoy and Kidangoor mean increasing from the pre-impact period, whereas Pala and Peroor data continue with the trend of a lowered mean than the pre-impact period. Monthly flows for October show Teekoy and Kidangoor mean value continues to be above the pre-impact period, whereas Pala and Peroor data means are seen to continue below the pre-impact period. Monthly flows for November show Teekoy mean value continues to be above the pre-impact period, whereas the Pala, Kidangoor, and Peroor mean values are seen to be below that of the pre-impact period. Monthly flows for December show a reversal of the existing trend after the Monsoon season, where the upstream Teekoy mean flow is seen to be below the pre-impact mean whereas Pala and Kidangoor flows can be seen to increase from the pre-impact mean value. Peroor in most of its downstream continues the trend of having a lower mean value than that of the pre-impact period.

Monthly flows for January show the reversal trend is seen to continue in the post-monsoon season where Teekoy and Peroor have a lower mean flow value, whereas Pala and Kidangoor show an increase in mean value from the pre-impact period. Monthly flows for February show Teekoy and Pala in the upstream have an increase in mean flow from the pre-impact period, whereas in the downstream, Kidangoor and Peroor show a drop of mean value from the pre-impact period.

Monthly flows for March show the mean values of Teekoy, Pala, and Kidangoor are above the pre-impact mean flow with an increased flow regime in early summer, whereas Peroor in most of the downstream still show a reduced mean flow from the pre-impact period. Monthly flows for April show Teekoy and Kidangoor data with an increase in mean flow from the pre-impact period, whereas Pala and Peroor show a decrease from the mean flow in the pre-impact period. Monthly flows for all four stations show an increase in mean flow from the pre-impact period. This may be due to increased runoff due to the land-use change or from flow being obstructed by the small check dams.

**Magnitude and duration of extreme water conditions**

Annual minima 1-day means show the mean annual minimum flow for Teekoy data remains the same as in the pre-impact period, the Pala and Peroor data are slightly above the pre-impact, and the Kidangoor data is seen to be below the mean from the pre-impact period. The 3-day annual minimum mean for Teekoy and Pala data can be seen to increase from the pre-impact period, whereas Kidangoor data is below the pre-impact mean. The Peroor data remains the same.

The 7-day annual minimum data for Teekoy and Pala in the upstream show a higher mean from the pre-impact period, whereas the downstream Kidangoor and Peroor show a decrease from the mean value of the pre-impact period.

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Figure 8 | High flow pulses frequency.
The 30-day annual minimum data for Teekoy and Pala in the upstream show a higher mean than the pre-impact period, whereas the downstream Kidangoor and Peroor show a decrease from the mean value of the pre-impact period. The 90-day annual minimum data for Teekoy and Pala in upstream shows equal to or higher than mean from the pre-impact period.

Figure 9 | Small floods frequency.

Figure 10 | Large floods frequency.

The 30-day annual minimum data for Teekoy and Pala in the upstream show a higher mean than the pre-impact period, whereas the downstream Kidangoor and Peroor show a decrease from the mean value of the pre-impact period. The 90-day annual minimum data for Teekoy and Pala in upstream shows equal to or higher than mean from the pre-impact period.
period, whereas the downstream Kidangoor and Peroor show a decrease from the mean value. The 1-day maximum mean for Teekoy and Kidangoor mean value is seen to be above that of the pre-impact period, whereas Pala and Peroor data shows mean below the pre-impact period.

The 5-day maximum mean for Teekoy and Kidangoor mean value is seen to be above that of the pre-impact period, whereas Pala and Peroor data show means below the pre-impact period.

The 7-day maximum mean for Teekoy and Kidangoor mean value is seen to be above that of the pre-impact period, whereas Pala and Peroor data show means below the pre-impact period. The 30-day maximum mean for Teekoy and Kidangoor mean value is seen to be equal to or above that of the pre-impact period, whereas Pala and Peroor data shows mean below the pre-impact period.

The 90-day maximum mean for Teekoy mean value is seen to be above that of the pre-impact period, whereas Pala, Kidangoor, and Peroor data show means below the pre-impact period.

The mean of zero flow days in Teekoy, Pala, and Peroor are seen to be below the pre-impact mean, whereas the Kidangoor data shows an increase in the number of zero flow events from that of the pre-impact period. The base flow index, 7-day minimum flow mean is seen to increase in Teekoy, Pala, and Peroor data, whereas in Kidangoor data, the mean is seen to be below that of the pre-impact period.

Timing of annual extreme water conditions
The number of days of annual 1-day maximum mean values of Teekoy is seen to increase from the pre-impact period; for Pala, it remains the same, and for Kidangoor and Peroor, the mean values are seen to decrease from that of the pre-impact period.

The number of days of annual 1-day minimum mean values of Teekoy, Pala, and Kidangoor is seen to decrease from that of the pre-impact period, but the Peroor data shows a higher mean value than that of the pre-impact period.

Frequency and duration of high and low pulses
The number of low pulses count is seen to be zero for WRD data; that is, Teekoy, Pala, and Peroor. For Kidangoor data, the mean of the number of low pulses is seen to be lower than that of the pre-impact period. The data on the duration of low pulses for WRD data is seen to be blank. For the Kidangoor data, the mean of the duration of low pulses is seen to be higher than that of the pre-impact period.

The mean count of the number of high pulses is seen to be lower in all four stations when comparing to that of their pre-impact periods. The duration of high pulses can be seen to decrease from the mean value for Teekoy, Pala, and Kidangoor, but in the downstream, Peroor has seen an increase in the mean of the duration of high pulses from the pre-impact period.

Rate and frequency of water condition changes
The mean rise rate in Teekoy and Kidangoor are seen to increase from the pre-impact period, whereas for Pala and Peroor, the mean has decreased from that of the pre-impact period.

The mean fall rates of Teekoy and Kidangoor are seen to decrease from the pre-impact period, whereas for Pala and Peroor, the mean has increased from the pre-impact period. This is an exact reverse trend to that of the rise rates.

Number of means of reversal events for Teekoy and Peroor increased from the pre-impact period, whereas Pala and Kidangoor decrease from pre-impact periods.

Environmental flow components
Monthly low flows
The mean monthly flows for the month of June at Teekoy, Pala, and Peroor are seen to be below the pre-impact period, whereas the mean of the monthly flow June at Kidangoor is slightly higher than that of the pre-impact period. The mean monthly flow for July at all four stations is below that of the pre-impact period with Peroor at the downstream showing the highest variation. The mean monthly flows for August at all four stations are below that of the pre-impact period with Peroor at downstream, showing the highest variation.

The mean monthly flows for September at Teekoy, Pala, and Peroor are seen to be below the pre-impact period, whereas the mean of the monthly flow June at Kidangoor is slightly higher than that of the pre-impact period. The mean monthly flows for October at all four stations are below that of the pre-impact period with Teekoy and Peroor showing the highest variation.
The mean monthly flows for November at all four stations are below that of the pre-impact period with Teekoy and Peroor, showing the highest variation.

The mean of the monthly flows for December at Teekoy and Peroor are below the pre-impact period, whereas for Pala and Kidangoor, it is slightly above the pre-impact period. The WRD data for January is incomplete. At Kidangoor station, the mean of the flow is seen to be higher than that of the pre-impact period. The WRD data for February is incomplete. At Kidangoor station, the mean of the flow is seen to be higher than that of the pre-impact period. The WRD and CWC data for March is incomplete.

The WRD data for April is incomplete. At Kidangoor station, the mean of the flow is seen to be higher than that of the pre-impact period. The mean monthly flows for May at Teekoy and Kidangoor are higher than the pre-impact period, whereas for Pala and Peroor, they are seen to be below those of the pre-impact period.

**Extreme low flows**

The mean value for extreme low flow frequency at Teekoy and Kidangoor is seen to be higher than that of the pre-impact period, whereas, at Pala and Peroor, it is seen to be below that of the pre-impact period. The mean value for the number of extreme low flows duration at Teekoy and Peroor is seen to be lower than that of the pre-impact period, whereas, for Pala and Kidangoor, it is seen to be higher than that of the pre-impact period.

The WRD data show a continuum of the mean value of extreme low flow peaks, and CWC data for Kidangoor show a lower mean value from the pre-impact period. The mean value of the extreme low flows timing for all four stations wherein WRD stations shows a higher shift from that of the pre-impact period.

**High flow pulses**

The mean value for the high flow pulses at Teekoy, Pala, Kidangoor, and Peroor is seen to be below that of the pre-impact period with Peroor at downstream, showing the higher shift. The mean value of the number of days of high flow pulses at all four stations is seen to be below that of the pre-impact period. The means of the high flow pulses at Teekoy, Kidangoor, and Peroor are seen to be lower than those of the pre-impact period, whereas, at Pala, it seems to be higher than that of the pre-impact period.

The mean values of the high flow pulses peaks at all four stations are below those of the pre-impact period. The mean values of the high flow rise rate at Teekoy and Pala are seen to be below those of the pre-impact period, whereas at Kidangoor and Peroor, they are above those of the pre-impact period. The mean values of the high flow rates at Teekoy, Kidangoor, and Peroor are seen to be below the pre-impact period, whereas at Pala, it is seen to be above the pre-impact period.

**Small floods**

The mean values of the small flood frequency at Teekoy, Pala, and Peroor are seen to be lower than that of the pre-impact period, whereas, at Kidangoor, it is seen to be above that of the pre-impact period. The data for small flood duration for WRD data is incomplete, whereas, for CWC station at Kidangoor, the mean value is seen to be higher than that of the pre-impact period. The data for WRD stations for small flood timings seems incomplete, whereas, at CWC station at Kidangoor, the mean is slightly lower than that of the pre-impact period.

The data for WRD stations for small floods peak seems incomplete, whereas, at CWC station at Kidangoor, the mean is slightly higher than that of the pre-impact period. The data for WRD stations for small floods rise rate seems incomplete, whereas, at CWC station at Kidangoor, the mean is slightly higher than that of the pre-impact period. The data for WRD stations for small floods fall rate seems incomplete, whereas at CWC station at Kidangoor, the mean is slightly lower than that of the pre-impact period.

**Large floods**

The mean value of the large flood frequency is seen to be higher than that of the pre-impact period at all four stations as shown in Figures 3–10. For Large Floods Duration, the data for all four stations is incomplete. Large floods timing, the data for all four stations is incomplete. Large floods peak, the data for all four stations is incomplete. Large floods rise to rate, the data for all four stations is incomplete. Large floods fall rate, the data for all four stations is incomplete.

Climate fluctuation and change have garnered considerable interest from the scientific community worldwide. The fundamental reason that climate change is the most often debated subject in every forum is that it impacts all the realms to which all
living creatures are exposed. The negative consequences of severe climate change have the potential to destabilize all elements of the environment, and therefore the relationships between the abiotic and biotic components of any ecosystem.

CONCLUSION
The IHA analysis of 67 flow parameters shows there are alterations in the flow regime of the Meenachil river, which is the lifeblood of the Kottayam District in Kerala. The change in flow pattern attributes to the land-use change along the watershed region of the river. The current knowledge of the anthropogenic impacts such as heavy metal accumulation, stress on native species, growth and spread of invasive species can be associated to the alteration in hydrologic regimes, as seen in this study. The precise causes and impacts of the changes in the alteration in the flow regime are a matter of further research. The alteration in the flow regime, as seen in this study, may indicate large scale anthropogenic influence in the river, which may be causing a slow death to the river by the same society that is very much dependent on it. The missing data in the Water Resource Department stream gauge stations is a matter of concern, as proper data research is dependent on data from the site, which is complete.

DATA AVAILABILITY STATEMENT
All relevant data are included in the paper or its Supplementary Information.

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