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ESTIMATION OF TIDAL MARSH LOADING EFFECTS IN A COMPLEX ESTUARY

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ABSTRACT: The Cooper River is a complex estuarine system amidst the greater Charleston, SC, area. It experiences semi-diurnal tides, extensive flooding and drying of abandoned rice fields and marshes, and flow releases from a hydroelectric dam. The river is also heavily used as a receiving stream for industrial and municipal wastewater treatment plants. Much controversy has existed for years about the relative roles that point-source and non-point source (both anthropogenic and non-anthropogenic) oxygen-consuming constituent loads have on the river's water quality, as measured by dissolved-oxygen concentration (DO). From 1993 to 1995, the U.S. Geological Survey operated a real-time stream-gaging network that collected DO, water-level, water temperature, and specific conductance data at 15-minute intervals at several sites. One site in an upper branch of the Cooper River was known to be largely unaffected by anthropogenic sources, offering an opportunity to evaluate the impact that non-anthropogenic, non-point sources have on DO variability. Monitoring data were combined with rainfall measurements from area weather stations, and subjected to signal processing and artificial neural network (ANN) modeling techniques. Two distinct causes of DO variability were found and quantified. Rainfall was found to decrease DO concentration at a rate of approximately 0.25 mg/L per inch of rain. Depending on hydrodynamic and meteorological conditions, DO was also found to decrease 2.0 mg/L or more due to tidal flooding of the wetlands proximal to the gaging station. The approach that was used provided the benefit of an extensive accounting of the causes and DO variability under a broad range of hydrological and meteorological conditions.
KEY TERMS: estuary, tidal marsh, non-point source loading, neural network models

INTRODUCTION

Many estuaries in the Southeast United States are characterized by extensive tidal marshes that flood and drain during each tidal cycle. The loadings from these marshes are acknowledged to be a large contributor to the naturally low dissolved-oxygen concentration of these estuaries. Estimation of the effect of marsh loading on dissolved-oxygen concentration is critical to the sound management of coastal waters, especially ones receiving point-source effluent loads.

The U.S. Geological Survey (USGS) cooperated in comparing (Conrads and Roehl, 1999) artificial neural network (ANNs) models to deterministic finite-difference models of the Cooper River, a complex estuarial system (Figure 1). Both models were developed from real-time measurements of water level (WL), dissolved-oxygen concentration (DO), water temperature (WT), and specific conductivity (SC) that had been collected by a network of gaging stations (Conrads and others, 1997). The models were used to predict the river's hydrodynamic, mass transport, and water-quality behaviors. The comparison showed the ANNs to be significantly more accurate and quickly developed. The ANNs could also be deployed as compact programs that execute without iteration and a prototype control system was developed to investigate regulating wastewater discharges according to the river's assimilative capacity (Roehl and Conrads, 1999). Subsequently, ANN models and other data-mining techniques were applied to the time series

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data of the Cooper River to determine whether the effects of rainfall and other modulating factors could be quantified from the dataset.

DESCRIPTION OF STUDY AREA

The Cooper River is located in the lower Coastal Plain physiographic province in the lower part of the Santee-Cooper River Basin (Figure1). This basin covers 21,700 square miles and is the second largest drainage basin on the East Coast. The Cooper River is formed by the confluence of the West and East Branches of the Cooper River at an area referred to as the "Tee". The West Branch of the Cooper River flows 18 miles from the tailrace of Pinopolis Dam to the confluence with the East Branch of the Cooper River at the Tee. This reach is a meandering natural channel bordered by extensive tidal marshes and old rice fields in varying states of disrepair. This area contains large amounts of poorly defined overbank storage and unmeasureable flows through broken levees between the main channel and rice fields. The East Branch Cooper River is a tidal slough throughout its 8-mile reach. On the Cooper River, from the Tee to Flag Creek (Figure 1, just downstream of station 021720675), industries are located along the west bank of the river and extensive *Spartina alerniflora* salt marshes dominate the east bank. Downstream of Flag Creek, the main channel has been dredged to a depth of 42 ft by the US Army Corps of Engineers for navigational purposes. Industries dominate the west bank of the river and the east bank contains numerous dredge-material disposal areas.

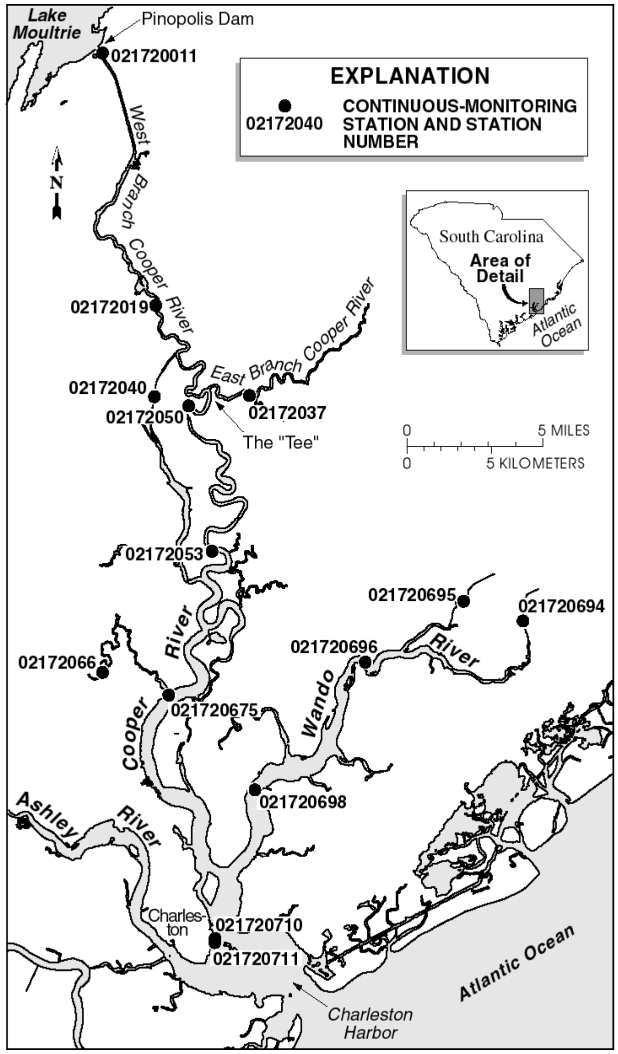

Figure 1: The Cooper and Wando River, SC.

The Cooper River is tidally affected throughout its entire reach, and has mean- and spring-tidal ranges of 5.27 and 6.11 ft, respectively, at the Customs House (Figure 1, station 021720711) on the lower Cooper River and mean- and spring-tidal ranges of 1.70 and 1.97 ft, respectively, at Pimlico (Figure 1, just downstream of station 02172019) on the West Branch Cooper River (National Oceanic and Atmospheric Administration, 1995).

APPROACH

The variability of DO in the Cooper River is a result of many factors including the quality of the water from Lake Moultie and Charleston Harbor, the loading of oxygen-consuming matter from the tidal marshes, abandoned rice fields, and other non-point sources, effluent from permitted point sources and physical characteristics of streamflow, tidal range, salinity, and temperature. To evaluate whether an ANN could be used to determine the influence of tidal marsh loadings on DO, data from a gaging station that was near extensive marsh areas and relatively distant from point-source loadings was selected for evaluation. Of the nine stations in the database on the Cooper River and its tributaries, the gage on the East Branch of the Cooper

River (02172037) was the most dominated by tidal marshes and abandoned rice fields, and farthest removed from the point-source discharges on the lower Cooper River.

The data used were comprised of hourly measurements for WL, SC, WT, and DO. The effect on DO of the decay of organics can occur over a time scale of several days. This effect can be difficult to discern when coupled with high frequency forces such as diurnal and semi-diurnal ambient temperatures and tidal flow variability. Therefore, the hourly time series were filtered using frequency domain filtering (Press and others, 1993) to remove diurnal and semi-diurnal periodic signal components. (Filtered variables are denoted by an "f" subscript, for example, DO_f.) A further processing step was taken to decorrelate variables by systematically synthesizing cross-correlation functions and computing their residuals. This step was necessary to avoid the propensity of ANN models to overfit when correlated variables are used as inputs. (Decorrelated variables are denoted by a "d" subscript, for example, $DO_{f,d}$.)

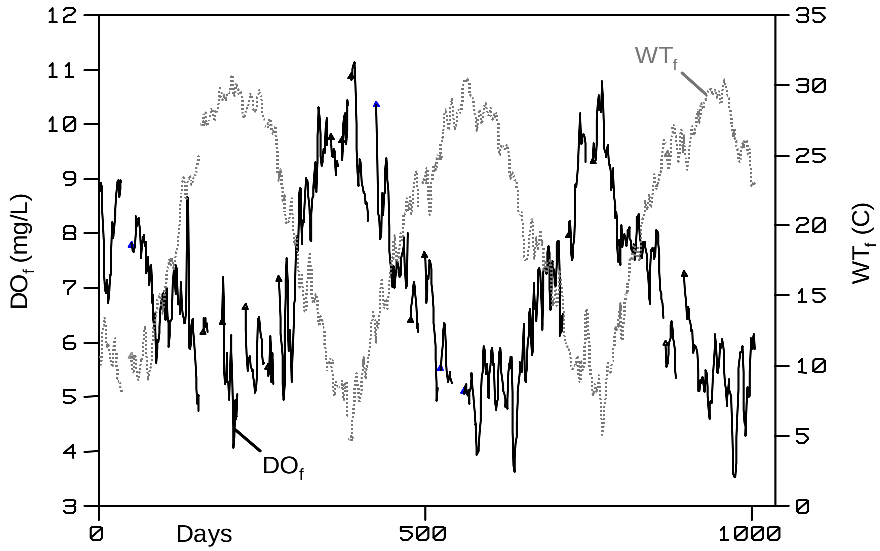

Figure 2: DO_f and WT_f for East Branch of the Cooper River (station 02172037).

Rainfall data were collected from three National Weather Service stations located in the watershed. These measurements were averaged together, and the resulting signal was converted to a 2-day moving window average "RAINAA" (AA indicating average of the average of three rainfall measurements).

The dataset was augmented with calculated variables. The dissolved-oxygen deficit "DOD" was computed as follows: $DOD = DO_{saturated} - DO_{measured}$. $DO_{saturation}$ was determined by adjusting the measured DO values for temperature and salinity (US Geological Survey, 1981). In addition, the difference between the high and low tide WL's for each tidal cycle (XWL) was computed, interpolated to produce hourly values, and then filtered as above.

Typically, the majority of the variability in DO is due to WT. Inspection of DO_f and WT_f shows their inverse relationship (Figure 2). Linear regression produces a coeffecient of determination (R^2) of 0.846, indicating that approximately 85 percent of the variability of DO is explained by WT alone (Figure 3), and that approximately 15 percent of the variability is caused by other factors. WT has two effects. One is that gas-in-liquid solubility decreases with WT, and the other is that microbial activity that consumes DO also increases with WT (given sufficient DO and nutrients).

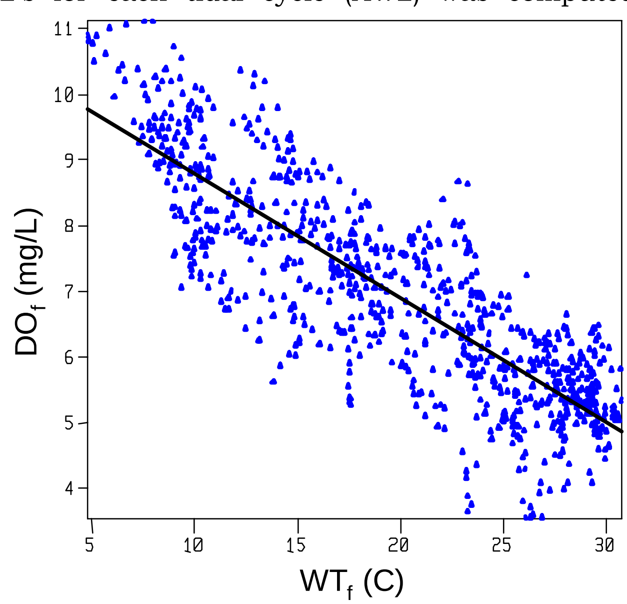

Figure 3: DO versus WT and least-squares regression. R^2 = 0.846.

The sensitivity of the response variables, DO and DOD, to the explanatory variables of interest of rainfall, tidal range, and salinity (as an indicator of water-quality transport from the lower Cooper River) was determined using ANN models. The type of ANNs used were the multi-layer perceptrons described by Hinton (1992) that were trained using the back-propagation and conjugate gradient algorithms.

RESULTS

RAINAA and $DOD_{f,d}$ vary seasonally, and upon close inspection of Figure 4, some incidents of high rainfall that coincide with spiking DOD can be seen. Figure 5 shows that an ANN, having inputs for RAINAA at multiple, time delays τ starting at 1 day, models a significant portion of the $DOD_{f,d}$ variability (R^2 = 0.281). $DOD_{f,d}$ was most sensitive to RAINAA @ τ = 3 days. (The use of the "@" symbol is used by convention to match a model input variable with a time delay relative to a model output variable.) Figure 6 shows the ANN's predicted response for $DOD_{f,d}$ versus RAINAA @ τ = 1 and 3 days (RAINAA inputs at longer delays were set to 0). Also shown are the actual data projected onto the surface. Note that the surface is relatively linear, and that the sensitivity of $DOD_{f,d}$ to RAINNAA @ τ = 1 is consistently less than @ τ = 3 days.

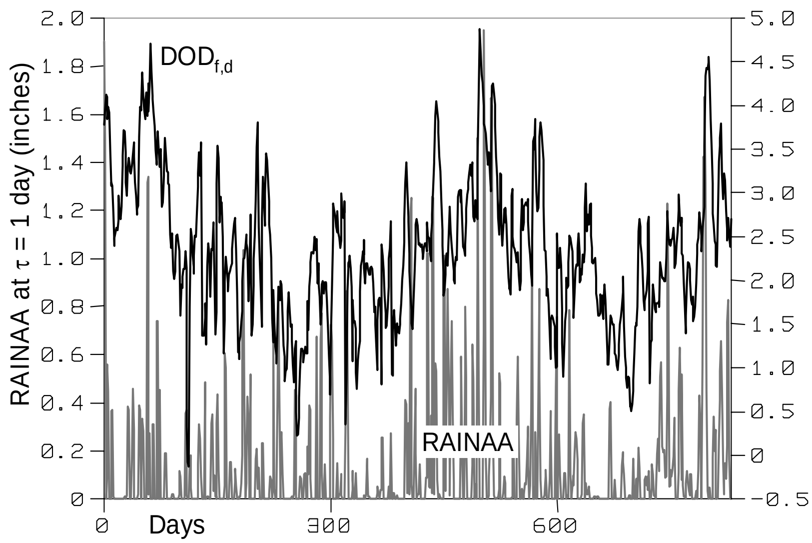

Figure 4: RAINAA and $DOD_{f,d}$ versus Days.

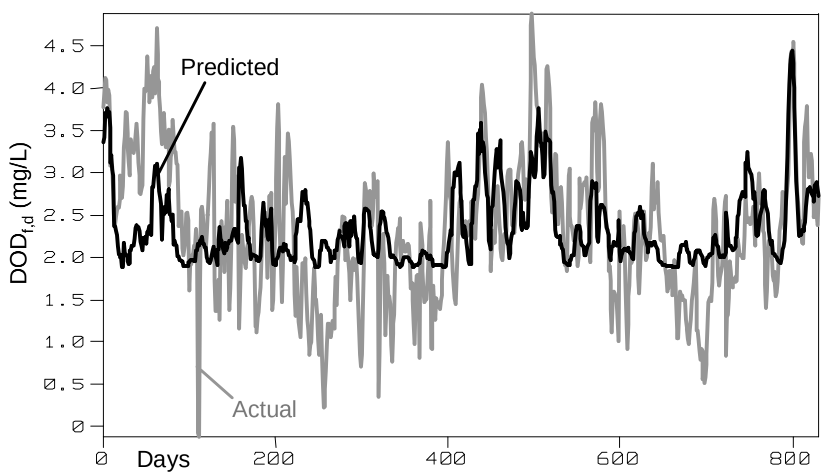

Figure 5: Actual and ANN prediction of $DOD_{f,d}$.

The overall impact of rainfall can be estimated from Figure 6 as follows. The total increase in $DOD_{f,d}$ ≈ 2 mg/L. This occurs when the RAINAA @ τ = 1 and 3 days are both ≈ 2 inches of rain. (Approximately 0.8 mg/L for τ =1 and 1.2 mg/L for τ =3 days.) Because RAINAA is a 2-day moving average, a value of RAINAA = 2.0 is equivalent to 4 inches of rainfall over 2 days, or 8 inches over 4 days. The sensitivity of $DOD_{f,d}$ to rainfall can be characterized as:

$$DOD_{f,d} \approx 2 \text{ mg/L} / 8 \text{ inches of rainfall over 2 days} \approx 0.25\text{mg/per inch of rainfall.}$$

A second neural network model was created to examine how interactions between WL, XWL, SC, and WT affect DOD. The model used filtered and decorrelated versions of these variables, plus their 1-day derivatives, plus RAINAA as inputs to predict $DOD_{f,d}$. Figure 7 shows the model prediction of $DOD_{f,d}$ versus $XWL_{f,d}$ and $SC_{f,d}$ as a response surface. (To generate the response surface shown in Figure 7, RAINAA and derivative inputs were set to 0, and WL and WT inputs were set to the midpoints of their ranges.)

A number of behavioral modes are apparent. Mode 1 shows that DOD remains low and nearly constant at high XWL. A high XWL, the difference between high and low tide, is an indicator of high tidal fluxes that would transport non-point source oxygen-consuming matter from proximal wetlands downstream to the main channel of the river. Mode 2 shows that DOD also remains low and nearly constant at high SC. A high SC indicates a reverse flow of seawater upriver so that the characteristics of the seawater dominate behavior at the gage. Mode 3 shows that at low XWL, DOD behavior is highly dependent on SC. The highest DOD value occurs at low XWL and SC, indicating conditions that have little tidal exchange. Resident fresh water is being neither aerated nor transported away, allowing non-point organic matter to decay undisturbed. Increasing SC, an indicator of reverse flow upriver, drastically reduces DOD. This is likely caused by the diversion of high quality water flowing downstream from the Cooper River's West Branch into the East Branch where the gage resides. As SC continues to increase, DOD behavior becomes that of Mode 2. Mode 4 shows that DOD declines quickly with increasing XWL and tidal flux. Mode 5 shows that DOD increases at an intermediate but low SC. The surface about Mode 5 is likely a region of transitional behavior in which lower quality water from below the Tee is forced into the East Branch by higher tidal fluxes.

In Figure 7, the actual data are projected onto the response surface, showing

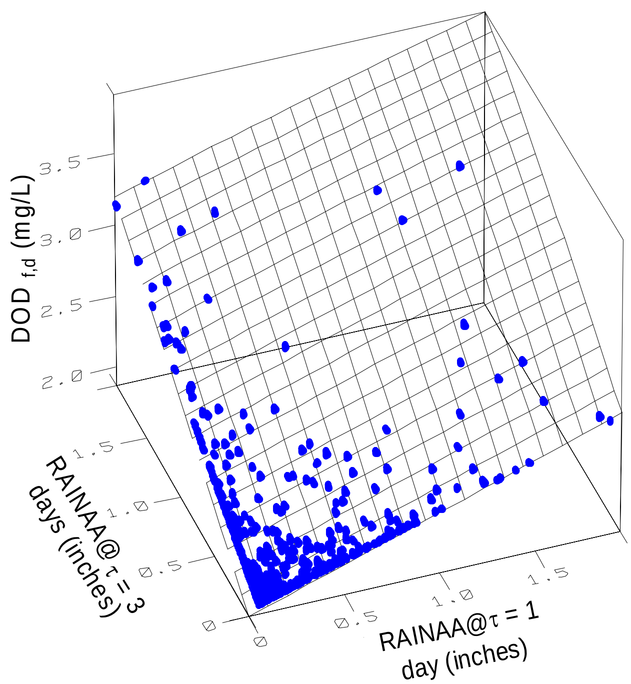

Figure 6: $DOD_{f,d}$ versus RAINAA @ τ = 1 and 3

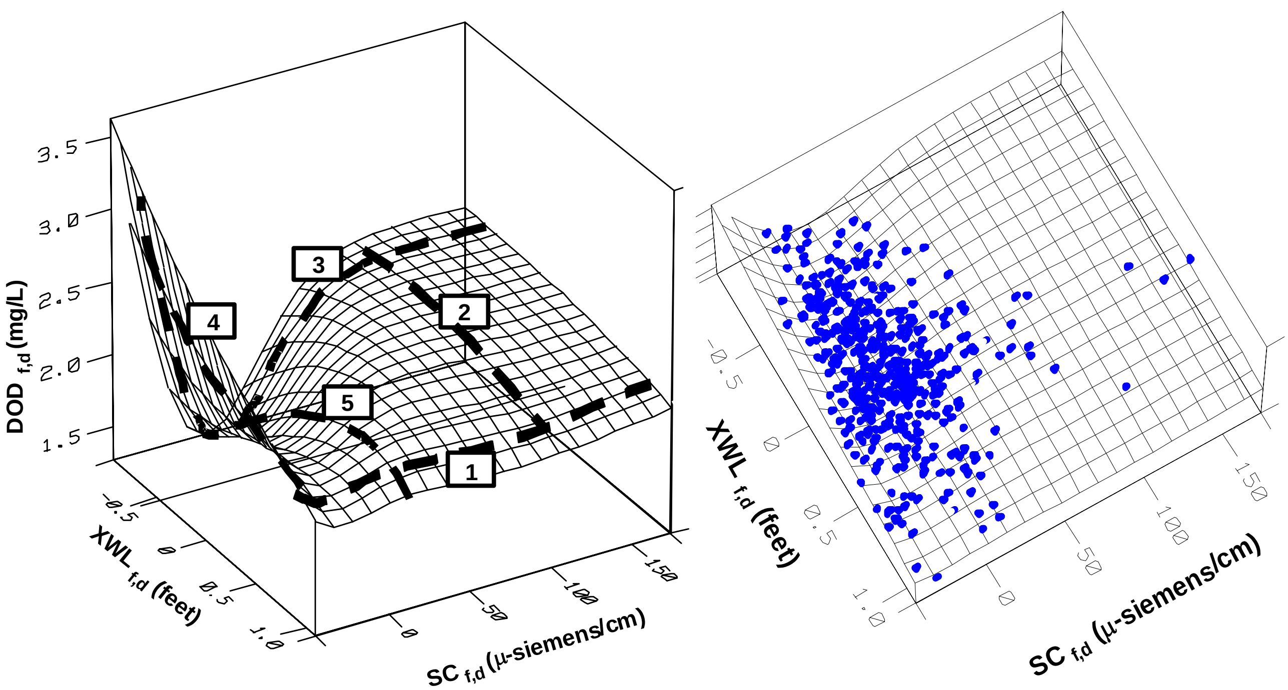

Figure 7: ANN response surface of $DOD_{f,d}$ versus $XWL_{f,d}$ and $SC_{f,d}$. Different behavioral modes are marked at left. Actual values are projected onto the same surface at right, which has been tipped to show the distribution of the data.

that the data are densest in the region of greatest surface complexity. This provides confirmation that the ANN has indeed captured the very complicated behaviors of the natural system surrounding the gage. It should also be noted that the total computed range of $DOD_{f,d} \approx 2$ mg/L, indicating that non-point organic loading caused by tidal flooding has a dramatic impact on water quality. It was found that this range increased when $WL_{f,d}$ was decreased, theoretically increasing the organic concentrations in flood waters. The range also increased when $WT_{f,d}$ was increased, effectively providing for an increased level of microbial activity. The maximum computed range of $DOD_{f,d} \approx 4$ mg/L when both $WL_{f,d}$ was decreased and $WT_{f,d}$ was increased to the limits of their historical ranges.

CONCLUSIONS

In combination, long term real-time gaging of hydrodynamic and water quality parameters, signal processing, and ANNs can provide an excellent means to understand highly complex and interacting behaviors in an estuary. The location selected for this study, being largely unaffected by anthropogenic oxygen-consuming constituent sources, provided an excellent case for evaluating the effects of non-anthropogenic, non-point source loading using these tools. The sensitivity of DOD, the dissolved-oxygen deficit, to a 1-inch rainfall was estimated to ≈ 0.25 mg/L, and the overall sensitivity to tidally forced organic loading was 2.0 mg/L or more. It should be noted that South Carolina's water-quality standard for the maximum impact of all point sources on the Cooper River is only 0.1 mg/L.

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