An integrated electrical resistivity and geochemical approach to delineate groundwater contamination due to seawater intrusion in the southern part of Mangalore, Karnataka, India

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Abstract. In this paper, integration of electrical resistivity survey and chemical analyses of groundwater has been executed in Mangalore's southern part, Karnataka to delineate seawater intrusion phenomena. About 11 locations representing different hydrogeological and geomorphological setups were selected for the vertical electrical sounding (VES) to identify the subsurface formations and the extent of seawater intrusion. With the VES, the contaminated groundwater zones and the depth to fresh and saline water interface have been demarcated. Overall, 59 groundwater samples were subjected to various geochemical analysis viz; pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, total hardness, alkalinity, calcium (Ca\textsuperscript{2+}), magnesium (Mg\textsuperscript{2+}), chloride (Cl\textsuperscript{-}), sodium (Na\textsuperscript{+}), potassium (K\textsuperscript{+}) and sulfate (SO\textsubscript{4}\textsuperscript{2-}) to understand the nature of salinity in the aquifer. The geochemical analyses show that good groundwater conditions characterize the study area except for the southern part. The southern part is under the moderate to high salinity hazard risk, possibly due to its proximity to the sea and hydraulic connection with the seawater through the tidal creek. Two among the VES locations situated in this region show a saline water trend towards the bottom, and in the rest of the VES locations, a freshwater trend is encountered towards the depth.

1. Introduction
Mangalore's coastal stretch is one of the densely populated areas because of its rich resources and the best condition for productivity. Groundwater is one of the essential water resources for this region, and people rely on this for their daily needs. The shallow coastal aquifers are susceptible to overexploitation and contamination due to natural or anthropogenic processes [1]. These coastal aquifers are subjected to salinity hazard either due to seawater ingestion where the aquifer is in hydraulic continuity with the sea or due to seawater incursion through tidal creeks. Anthropogenic activities also aggravate this situation. The shallow coastal aquifers in hydraulic continuity with the sea are more prone to water quality deterioration. The encroachment of saltwater into the freshwater is moreover occurring through surface or subsurface pathways. To study this phenomenon, diverse approaches have been adopted by various researchers. The conventionally used approach for characterizing seawater intrusion is the geochemical method [2, 3, 4]. Isotope geochemistry is also used in coastal aquifer studies because they provide a means to differentiate among alternative sources of saline water [5, 6, 7]. Apart from major
geochemical and isotopic methods, various geophysical techniques are also applied in groundwater investigations. Commonly used geophysical techniques in coastal environments are electrical resistivity and seismic methods [8, 9, 10, 11, 12, 13, 14, 15, 16]. In this study, an integrated electrical resistivity and geochemical approach are taken up to understand the hydrogeological conditions and groundwater contamination of the coastal aquifers of Mangalore, Karnataka, India.

The study area, Kotekar Town Panchayat of Mangalore, lies between 12°46′12.528″ to 12°48′45.379″N latitudes and 74°51′18.67″ to 74°54′7.66″E longitudes under Survey of India (SOI) toposheet no. 48L/13, 1:50,000 scale (figure 1). The study area's annual rainfall is 3600 mm, and the temperature ranges from 19°C to 35°C. The major rock units include Granite Gneiss of Archean age and Laterite and coastal Alluvium of Recent age [17, 18] (figure 2a). The altitude of the area ranges from 1m to 77m (figure 2b).

![Figure 1](image_url)  
**Figure 1.** Map showing the area of study, locations of groundwater sampling points and, VES stations.
2. Materials and methods

Vertical Electrical Sounding (VES) using Schlumberger array was carried out at 11 locations to identify the vertical variation in the resistivity with an Anvic CRM Auto - C Aquameter. VES curves were initially interpreted using [19] master curves and auxiliary curves. Standard resistivity inversion program IPI2WIN (Moscow state university) was used to invert the data. Fifty-nine groundwater samples were collected during the pre-monsoon season of 2019 from various locations of the study area by following the APHA [20] standard protocol. Geographic coordinates were obtained with a Garmin GPS - eTrex-10. Physical parameters viz. pH, electrical conductivity (EC), total dissolved solids (TDS), and salinity were measured in-situ with a HANNA-HI 98195 multi-parameter water quality portable meter, and the instrument was calibrated prior to the measurements with HI 9828-0 calibration solution. Total hardness (TH), alkalinity, calcium (Ca$^{2+}$), magnesium (Mg$^{2+}$), and chloride (Cl$^{-}$) were determined by the complexometric titration method of APHA [21]. Sodium (Na$^{+}$) and potassium (K$^{+}$) were analyzed using a Systronics-130 flame photometer, and sulfate (SO$_4^{2-}$) was determined by Systronics spectrophotometer-169. The lithology of well sections was recorded, and in most of the locations, the aquifer is Laterite, and in some, it is sandy clay or clayey sand. The depth to the water level was recorded to know the variation in the groundwater level. All physico-chemical parameters were spatially plotted on an ArcGIS platform - ArcMap 10.3.

3. Result and Discussion

3.1 Physico-chemical analysis of groundwater samples

The statistical parameters of 59 groundwater samples are summarized in Table 1. All the results were compared with the standard permissible limit recommended by the Bureau of Indian Standards [22] and the World Health Organization [23] standards, as depicted in Table 2.

3.1.1 pH.

pH ranges from 4.2 to 7.8, with an average of 5.8 (figure 3a). The majority of the groundwater samples are near neutral to alkaline in nature. NE part of the study area comprises acidic water. The acidity of groundwater might be due to laterite’s presence, whose pH is always acidic [24], and the availability of more organic matter [25]. The alkaline nature of the groundwater samples might be because of the presence of dissociated anions. Most water samples are suitable for drinking purposes as the pH values are within the permissible limit prescribed by the WHO [3] and BIS [22].
Table 1. Statistical parameters of various physicochemical attributes of the groundwater samples.

| Parameters | Minimum | Maximum | Average |
|------------|---------|---------|---------|
| pH         | 4.2     | 7.8     | 5.8     |
| EC (µS/cm) | 35.0    | 17200.0 | 858.7   |
| TDS (mg/L) | 18.0    | 8606.0  | 429.4   |
| Salinity (psu) | 0.01  | 10.06   | 0.46    |
| Ca²⁺ (mg/L) | 2.0     | 164.2   | 20.3    |
| Mg²⁺ (mg/L) | 0.49    | 290.3   | 19.0    |
| Na⁺ (mg/L)  | 2.35    | 1512.6  | 57.0    |
| K⁺ (mg/L)   | 0.0     | 25.2    | 1.8     |
| Cl⁻ (mg/L)  | 0.0     | 314.9   | 14.9    |
| SO₄²⁻(mg/L) | 2.0     | 1780.0  | 59.9    |
| TH (mg/L)   | 10.0    | 1350.0  | 98.1    |
| Alkalinity (mg/L) | 2.0 | 100.0 | 24.2 |

Table 2. Drinking water standards of WHO [23] and BIS [22] showing the maximum permissible limit.

| Parameters | WHO, 2006 | BIS, 2012 |
|------------|-----------|-----------|
| pH         | 6.5-8.5   | 6.5-8.5   |
| TDS (mg/L) | 500       | 500       |
| Ca²⁺ (mg/L) | 100     | 75        |
| Mg²⁺ (mg/L) | 30       | 30        |
| Na⁺ (mg/L)  | 200       | --        |
| K⁺ (mg/L)   | 10        | --        |
| Cl⁻ (mg/L)  | 200       | 250       |
| TH (mg/L)   | 500       | 200       |
| Alkalinity (mg/L) | 120 | 200 |

Figure 3. Spatial distribution map of pH (a), EC (b), TDS (c), salinity (d), Ca²⁺ (e) and Mg²⁺ (f).
3.1.2 Electrical Conductivity (EC). EC ranges from 35 to 17200µS/cm, with an average of 858.7µS/cm (figure 3b). Higher EC values are noticed near to the coastal area. The downstream direction of the study area is marshy due to the seasonal variation of water level. These areas have high EC values due to the addition of salt from the adjacent Arabian Sea.

3.1.3 Total Dissolved Solids (TDS). TDS ranges between 18 and 8606mg/L with an average of 429.4mg/L (figure 3c). A relatively high TDS concentration is observed near the coastal plain, and this hike in the TDS values is attributed to the seawater intrusion. According to WHO [23] and BIS [22], water containing more than 500mg/L of TDS is not desirable for drinking purposes. Groundwater adjacent to the coast is recommended for drinking purposes, and the rest are suitable for human and animal consumption.

3.1.4 Salinity. Salinity ranges from 0.01 to 10.06psu (1psu = 1,000 mg/L) with an average of 0.46psu. The salinity range of most of the water samples is between 0.01-0.83psu (figure 3d). The southern stretch has more saline groundwater, and this increase might be because of the seawater intrusion occurring through the river. EC, TDS, and salinity show a perfect correlation with an $r = 1$ (Table 3).

| pH       | EC  | TDS | Salinity | Ca$^{2+}$ | Mg$^{2+}$ | Na$^+$ | K$^+$ | Cl$^-$ | SO$_4^{2-}$ | TH  | Alkalinity |
|----------|-----|-----|----------|-----------|-----------|--------|-------|--------|------------|-----|------------|
| pH       | 1.00| 0.09| 0.09     | 0.08      | 0.24      | 0.14   | 0.06  | 0.25   | 0.08       | 0.07| 0.15       | 0.68  |
| EC       | 1.00| 1.00| 1.00     | 1.00      | 0.96      | 0.96   | 0.99  | 0.92   | 0.98       | 0.97| 0.99       | -0.03 |
| TDS      | 1.00| 1.00| 1.00     | 1.00      | 0.96      | 0.96   | 0.99  | 0.92   | 0.98       | 0.97| 0.99       | -0.03 |
| Salinity | 1.00| 1.00| 1.00     | 1.00      | 0.95      | 0.95   | 0.99  | 0.92   | 0.98       | 0.97| 0.99       | -0.04 |
| Ca$^{2+}$| 1.00| 1.00| 1.00     | 1.00      | 0.93      | 0.93   | 0.91  | 0.92   | 0.91       | 0.95| 0.95       | 0.14  |
| Mg$^{2+}$|     |     | 1.00     | 1.00      | 0.98      | 0.98   | 0.98  | 0.92   | 0.98       | 0.97| 0.99       | 0.06  |
| Na$^+$   |     |     | 1.00     | 1.00      | 0.88      | 0.88   | 0.91  | 0.87   | 0.91       | 0.99| 0.98       | -0.04 |
| K$^+$    |     |     | 1.00     | 1.00      | 0.87      | 0.87   | 0.91  | 0.88   | 0.91       | 0.99| 0.99       | 0.11  |
| Cl$^-$   |     |     | 1.00     | 1.00      | 0.75      | 0.75   | 0.98  | 0.75   | 0.98       | 0.98| 0.98       | 0.01  |
| SO$_4^{2-}$|     |     | 1.00     | 1.00      | 0.83      | 0.83   | 0.98  | 0.83   | 0.98       | 0.98| 0.98       | -0.12 |
| TH       |     |     |          |           |           |        |       |        |            |     | 1.00       | 0.07  |
| Alkalinity|     |     |          |           |           |        |       |        |            |     |            | 1.00  |

3.1.5 Calcium (Ca$^{2+}$). The natural source of calcium (Ca$^{2+}$) in groundwater is chiefly from the dissolution of calcium bearing minerals present in the rocks. Ca$^{2+}$ ranges between 2 and 164.2mg/L with an average of 20.3mg/L (figure 3e). The spatial distribution of calcium shows higher values towards the S and SW direction. Out of 59 groundwater samples, sample numbers 20 and 21 show Ca$^{2+}$ beyond the desirable limit (>100mg/L) prescribed by WHO [23] and BIS [22]. This enhancement might be due to seawater intrusion and domestic waste to the freshwater aquifers [26, 27].

3.1.6 Magnesium (Mg$^{2+}$). Mg$^{2+}$ is introduced in groundwater from the ferromagnetic minerals present in the rock, seawater intrusion, etc. A higher concentration of Mg$^{2+}$ attributes hardness to the water. Mg$^{2+}$ ranges from 0.49 to 290.3mg/L with an average of 19.0mg/L. Most of the water samples are within a range of 0.49-32 mg/L (figure 3f). Out of 59 groundwater samples, 6 samples (15, 16, 20, 21, 26, 30) shows Mg$^{2+}$ beyond the desirable limit (>30mg/L) prescribed by BIS [7]. A high concentration of Mg$^{2+}$ might be from the seawater intrusion, which is occurring through the river.

3.1.7 Sodium (Na$^+$). In coastal aquifers, Na$^+$ is chiefly introduced in groundwater from the seawater intrusion. Other sources are agricultural practices and sewage effluents. In the present study, Na$^+$ ranges from 2.35 to 1512.6mg/L, with an average of 57mg/L. The majority of the water samples fall within a range of 2.4-130mg/L (figure 4a). A higher concentration of Na$^+$ (1512.56 and 838.040mg/L) is noticed around the coastal area of Uchila (location 20 and 21), which is beyond the permissible limit of the BIS.
and WHO [23] standards for drinking purpose. The most common source of this elevated sodium level in groundwater is from saltwater intrusion.

**Figure 4:** Spatial distribution map of Na$^{2+}$ (a), K$^+$ (b), Cl$^-$ (c), SO$_4^{2-}$ (d), TH (e) and alkalinity (f).

3.1.8 Potassium (K$^+$). K$^+$ is introduced in groundwater from the K$^+$ rich granites, oceanic basalts, seawater intrusion, etc. This study’s K$^+$ values ranged between 0 and 25.2mg/L, with an average of 1.8mg/L (figure4b). The spatial distribution map shows elevated K$^+$ value towards S and SW directions and fewer K$^+$ towards NE and N direction. Out of 59 groundwater samples, three samples (20, 21, and 46) shows K$^+$ beyond the desirable limit (>10mg/L) prescribed by WHO [7]. Other locations comprise good quality groundwater, which is suitable for human and animal consumption.

3.1.9 Chloride (Cl$^-$). Cl$^-$ in groundwater is derived from Cl$^-$ bearing minerals, seawater, etc. and excess of this imparts a salty taste to the water. Cl$^-$ ranges from 0 to 314.9mg/L with an average of 14.9mg/L. Most of the water samples fall within a range of 0-10mg/L (figure4c). Normal potable groundwater contains less than 30mg/L of Cl$^-$ and higher values indicate the admixture of mineralized water and anthropogenic pollution [28, 29]. Except for one sample (location 20), all water samples are suitable for drinking purposes as the chloride values are within the permissible limit prescribed by the WHO [23] and BIS [22]. The higher concentration of Cl$^-$ in the study area is attributed to seawater intrusion. Na$^+$, K$^+$, Cl$^-$ shows good correlation with EC, TDS, and salinity (r >0.88), corroborating the seawater intrusion.

3.1.10 Sulphate (SO$_4^{2-}$). SO$_4^{2-}$is introduced in groundwater from numerous minerals and through atmospheric deposition. SO$_4^{2-}$ranges from 2 to 1780mg/L with an average of 59.9mg/L (figure4d). According to the U.S public health services standards [30], the sulfate concentration should not exceed 250mg/L in drinking water. A Higher concentration of SO$_4^{2-}$ is noticed in location 20 and 21 (792 and 1780mg/L).

3.1.11 Total Hardness (TH). The total hardness of water is the total concentration of dissolved calcium (Ca$^{2+}$) and magnesium ions (Mg$^{2+}$) derived from soil and rock formation. This study’s values ranged between 10 and 1350mg/L, with an average of 98.3mg/L (figure4e). According to Sawyer and McCarty [31] and the U.S. Environmental Protection Agency’s[32] classification of natural water, most of the
groundwater samples are soft (0-75mg/L) to moderately hard (75-150mg/L). Hard and very hard water (>300mg/L) is observed in and around Uchila and nearby regions. According to Bean [33], ideal water should not exceed 80mg/L of TH. Salinity might be a significant contributing factor to the hardness of the water.

3.1.12 Alkalinity. Alkalinity is primarily due to the presence of dissolved carbon species present in the natural water, particularly the bicarbonate (HCO₃⁻), carbonate (CO₃²⁻), and hydroxyl (OH⁻) ions [34]. In the present study, alkalinity ranges from 2 to 100 mg/L, with an average of 24.2 mg/L (figure 4f). The spatial distribution of alkalinity shows the majority of water samples are more alkaline. As the alkalinity values are within the permissible limit prescribed by the WHO [23] and BIS [22], most of the water samples are suitable for drinking purposes.

3.2 Electrical resistivity survey

Vertical Electrical Sounding (VES) was carried out at 11 locations to identify the vertical distribution of ground electrical resistivity (all the VES data are given in Table 4). The true resistivity and true thickness of geoelectrical layers were obtained (Table 5) and were used to explain different zones of groundwater quality as fresh (ρ = 10 -100Ωm), brackish (ρ = 5-10Ωm), and saline water (ρ<5Ωm).

Table 4. Vertical Electrical Sounding (VES) data.

| VES No/- | VES1 | VES2 | VES3 | VES4 | VES5 | VES6 | VES7 | VES8 | VES9 | VES10 | VES11 |
|---------|------|------|------|------|------|------|------|------|------|-------|-------|
| AB/2    | App.R | App.R | App.R | App.R | App.R | App.R | App.R | App.R | App.R | App.R | App.R |
| 1.5     | 308.0 | 125.0 | 277.0 | 859.0 | 1262.0 | 473.0 | 1199.0 | 612.0 | 595.0 | 804.0 | 942.0 |
| 2       | 259.0 | 92.7 | 250.0 | 812.0 | 1154.0 | 499.0 | 1031.0 | 589.0 | 496.0 | 694.0 | 765.0 |
| 2.5     | 192.0 | 63.3 | 204.0 | 764.0 | 1017.0 | 514.0 | 791.0 | 528.0 | 399.0 | 565.0 | 659.0 |
| 3       | 143.0 | 44.0 | 173.0 | 696.0 | 962.0 | 527.0 | 632.0 | 495.0 | 318.0 | 501.0 | 550.0 |
| 4       | 107.0 | 26.1 | 148.0 | 602.0 | 742.0 | 520.0 | 421.0 | 466.0 | 260.0 | 396.0 | 420.0 |
| 6       | 71.1 | 11.3 | 126.0 | 442.0 | 561.0 | 467.0 | 200.0 | 397.0 | 215.0 | 251.0 | 198.0 |
| 8       | 56.5 | 7.1 | 94.2 | 336.0 | 471.0 | 388.0 | 114.0 | 350.0 | 177.0 | 192.0 | 123.0 |
| 10      | 45.4 | 5.5 | 72.2 | 270.0 | 377.0 | 289.0 | 87.7 | 332.0 | 157.0 | 167.0 | 98.0 |
| 15      | 28.9 | 3.5 | 40.8 | 176.0 | 261.0 | 178.0 | 84.1 | 293.0 | 129.0 | 139.0 | 69.4 |
| 20      | 20.6 | 2.8 | 29.4 | 124.0 | 191.0 | 106.0 | 77.7 | 236.0 | 108.0 | 118.0 | 70.7 |
| 25      | 14.8 | 2.2 | 18.8 | 95.5 | 154.0 | 70.4 | 91.3 | 188.0 | 89.3 | 94.2 | 83.7 |
| 30      | 12.8 | 1.9 | 13.7 | 68.3 | 133.0 | 62.1 | 101.0 | 148.0 | 72.3 | 82.4 | 96.1 |
| 40      | 12.4 | 1.6 | 8.5 | 43.0 | 102.0 | 61.4 | 119.0 | 98.9 | 52.1 | 49.5 | 117.0 |
| 50      | 12.6 | 1.6 | 6.4 | 32.3 | 83.8 | - | 136.0 | 63.8 | 26.8 | 41.5 | 148.0 |
| 60      | 13.1 | 1.5 | 5.0 | 28.5 | 72.2 | - | 152.0 | 39.3 | 18.4 | 38.7 | 180.0 |
| 80      | - | 1.5 | 4.5 | 24.3 | - | 70.7 | 172.0 | 23.0 | 10.5 | 35.0 | 246.0 |
| 100     | - | 1.5 | - | 24.2 | - | 75.4 | 188.0 | 17.0 | 9.0 | 33.6 | 311.0 |

Table 5. The calculated geophysical parameters obtained from Vertical Electrical Sounding curves.

| VES | NL | p₁ | p₂ | p₃ | p₄ | T₁ | T₂ | T₃ |
|-----|----|----|----|----|----|----|----|----|
| 1   | 3  | 395| 65 | 12.5| -  | 1.1| 5.2| -  |
| 2   | 3  | 165| 8.5| 1.6| 4.2| 1.2| 8.5| 3.4|
| 3   | 4  | 300| 120| 43  | 85 | 1.5| 14.3|    |
| 4   | 3  | 865| 224| 23  | -  | 2.3| 9.5| -  |
| 5   | 3  | 1410| 430| 80  | -  | 1.5| 7.5| -  |
| 6   | 4  | 480| 630| 43  | 85 | 1.5| 3.5| 14.3|
| 7   | 4  | 1440| 480| 65  | 285| 1.2| 2.4| 8.5|
| 8   | 3  | 620| 315| 15  | -  | 1.7| 14.8|    |
| 9   | 3  | 600| 150| 8   | -  | 1.4| 14.8|    |
| 10  | 3  | 855| 175| 32  | -  | 1.5| 11.1|    |
| 11  | 4  | 1050| 150| 38.5| 850| 1.5| 3.7| 10.5|

Notes: NL - number of geoelectrical layers, p₁ - true resistivity (Ωm) of geoelectrical layer 1, T₁ - the true thickness (m) of geoelectrical layer 1, *brackishwater and ,*saline water.
The interpreted results reveal that most sounding curves are Q type (VES 1, 2, 4, 5, 8, 9, 10). A very high resistivity value indicates the presence of laterite at the topmost layer. At VES 1, 4, 5, 8, 9, 10, the results indicating the presence of low resistivity zones towards the bottom, which might be due to the availability of brackish water (figure 5a, 5d, 5e, 6b, 6c, 6d) and at VES 2 there is a clear-cut indication of saline water in the bottom (figure 5b). VES 3 is a QQ type curve that indicates Brackish and Saline water at the bottom (figure 5c). VES 6 is a KH type curve showing fresh water at the bottom (figure 5f). VES 7 and 11 are QH type curves suggesting fresh water at the bottom (figure 6a and 6e). VES 7 and 11 also indicates the presence of semi-weathered gneiss followed by gneiss towards the bottom.

![Figure 5](image.png)

*Figure 5.* VES curves for station number 1 to 6.
Apparent resistivity contour maps at various depths (2, 10, 20, and 80m) were prepared to know the lateral resistivity variation with respect to depth and thus to identify different zones of fresh, brackish, and saline water quality. The apparent resistivity contour map at 2m depth (figure 7a) portrays the surface layer is characterized by low resistivity values indicating topsoil in the central portion and high resistivity values in the remaining portions showing the top lateritic layer.

Figure 7b (10m depth) shows a decrease in electrical resistivity towards the southern direction due to water's brackish nature. At 20m depth (figure 7c), saltwater's presence is observed towards the southern direction, and it is fresh towards the center. 80m contour map (figure 7d) shows saline water in the southern portion towards the deeper depths.

From the calculated geophysical parameters for the obtained vertical electrode sounding curves, VES curves, and apparent resistivity contour maps, it is understood that VES 2 has brackish water below a depth of 1.1m and saline water below a depth of 6.4m. In VES 3, freshwater is observed below 4.6m, and it is brackish below a depth of 13.1m. In other VES stations, freshwater is observed below a depth of 6.3m in VES1, 11.8m in VES4, 9m in VES5, 5m in VES6, 3.6m in VES7, 16.5m in VES8, 16.2m in VES9, 12.6m in VES10, and 5.2m in VES11 respectively. The previously discussed water quality analysis also corroborates the resistivity data of all these regions.
4. Conclusions

This study aimed to understand the groundwater quality of the southern part of Mangalore using an integrated resistivity sounding and geochemical approach. The groundwater quality studies reveal that the seawater contaminates the south part of the study area, and the seawater intrusion is chiefly occurring through the river. The geochemical analysis suggests that the groundwater adjacent to the river is unsuitable for drinking purposes. The topographically elevated regions and regions away from the river have good groundwater quality and are suitable for drinking.

The resistivity sounding data also support these geochemical data. The areas with resistivity values <10Ωm show that saline water intrusion and groundwater developmental activities should not be encouraged in these areas. The depth to saline and freshwater interface in the southern direction is around 13m. Suitable suggestions can be given to the public of that region to keep the freshwater and saltwater interface stationary by feasible management of the groundwater pumping pattern.

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