

Mapping and assessing evapotranspiration using MODIS-based SEBAL for groundwater potential in the Sita–Swarna river basins, coastal Karnataka, India

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Abstract

The study maps the spatial and seasonal distribution of actual evapotranspiration (ET) in the humid tropical Sita and Swarna river basins of coastal Karnataka, India and examines ET and land use and land cover (LULC) informing delineation of groundwater potential zones, giving water resource engineers a spatially explicit basis for recharge planning and abstraction control. The Surface Energy Balance Algorithm for Land (SEBAL) was applied to MODIS Terra/Aqua products (MOD09A1 reflectance, MOD11A1 land surface temperature, MOD13A1 vegetation indices) over eight image days in 2023 and 2024. Surface temperature was retrieved by split-window formulation, albedo by narrowband-to-broadband conversion, and net radiation, soil heat flux, and sensible heat flux resolved in a GIS raster environment. Latent heat flux was upscaled to 24 h actual ET via the reference ET fraction, checked against station-based reference ET (FAO Penman–Monteith, CROPWAT 8.0). Land surface temperature ranged from 27.72–34.97°C in the Sita Basin and 27.34–34.59°C in the Swarna Basin, with surface albedo of 0.039–0.155 and 0.038–0.142 and emissivity of 0.953–1.003 and 0.952–1.002, respectively. Daily actual ET ranged from 5.6 to 19.66 mm day⁻¹ in the Sita Basin and 4.01 to 6.01 mm day⁻¹ in the Swarna Basin, highest over the estuary (an upper bound partly attributable to a hot-pixel computational artifact) and lowest over built-up land, while reference ET varied between 2.56 and 4.09 mm day⁻¹ in 2023 and 2.71 and 4.03 mm day⁻¹ in 2024. Winter ET exceeded summer ET across most land cover classes, with dense vegetation and open water sustaining the highest rates year-round. Every hot-versus-cold anchor pixel contrast was significant at $p < 0.001$, and minimum relative humidity and sunshine duration alone reproduced reference ET ($R^2 = 0.978$). Sensible heat flux was represented by a single basin-wide value rather than solved pixel by pixel, and the coarse MODIS grid (500 m reflectance, 1 km thermal) limits resolution relative to the coastal plain's field sizes and urban patches. A closure check across all sixty-four anchor-pixel/image-day combinations showed the cold-pixel retrieval was internally consistent but the hot-pixel soil heat flux was not, so those fluxes are read as relative patterns, and the study overall as a regional screening layer; no in-situ ET measurements were available for validation. The ET surfaces show where dry-season demand concentrates, useful for siting recharge structures and setting abstraction limits. Extending SEBAL to this humid tropical coastal basin shows that high ET alone is not a reliable proxy for groundwater potential.

Keywords: MODIS; SEBAL; Evapotranspiration; Groundwater potential; Land use and land cover; Western Ghats.

1. Introduction

Evapotranspiration is the biggest single term to return water from the land surface to the atmosphere, and its size and distribution determine water balance closure, irrigation demand, and the residual water for recharge (Katul et al., 2012). ET is also the word that is most difficult to assess over an area because it incorporates radiation, moisture supply and vegetation activity. Lysimeters, eddy covariance towers and Bowen ratio devices can provide an exact measure of ET in time but only at a

point, and a network dense enough to cover a catchment of a few hundred square kilometres is rarely economical.

Satellite driven surface energy balance models fill this gap calculating ET as the residual energy balance in each pixel. The Surface Energy Balance Algorithm for Land (SEBAL) developed by Bastiaanssen et al. (1998a) and validated in a companion paper (Bastiaanssen et al., 1998b) does not require a priori knowledge of land use or crop coefficients, and self-calibrates internally against extreme wet and dry pixels in the image. Further single-source approaches, such as S-SEBI (Roerink et al., 2000), SEBS (Su, 2002), METRIC (Allen et al., 2007) and SSEBop (Senay et al., 2013), are based on the same residual logic and largely differ in the way the near-surface temperature gradient is constrained. Comparative evaluations have demonstrated that these models perform similarly when the assumptions of a clear sky and a wide range of surface wetness within the scene are met (Aryalekshmi et al., 2021; Bhattarai & Wagle, 2021; Wanniarachchi & Sarukkalgige, 2022). Since then, the implementations have evolved from research codes to operational monitoring, running constantly on medium-resolution images with minimal operator input (Pareeth & Karimi, 2023).

However, most reported SEBAL applications come from semi-arid or irrigated agricultural regions, where the dry-pixel assumption is easy to satisfy. Rahimi et al. (2015) mapped ET between 0.56 and 7.88 mm day⁻¹ across seasons in the Tajan catchment in Iran using MODIS-SEBAL. Cammalleri et al. (2012) examined the residual energy balance performance across a wide range of water availabilities. Jaafar and Ahmad (2020) automated anchor pixel selection for Landsat time series in the Bekaa Valley. This method has since been extended well beyond this setting. Shamloo et al. (2021) coupled SEBAL with field experiments in northwestern Iran; Tan et al. (2021) mapped ET across the upper Huaihe basin and found it positively correlated with elevation and negatively correlated with surface reflectance; Wei et al. (2022) reported paddy ET for the humid subtropical Ganfu plain of southern China, while Behura et al. (2026) applied the algorithm to the rice systems of coastal Odisha, on the opposite seaboard of peninsular India. However, humid tropical coastal basins present a distinct problem. The dense evergreen canopy, persistent high humidity, steep relief over short distances, and open estuarine water all compress the surface temperature range that SEBAL depends on, and the literature offers little guidance on how the resulting ET fields should be interpreted.

This is important in coastal Karnataka because the same catchments that receive more than three meters of monsoon rainfall become water-short within a few months of its withdrawal. Groundwater meets the domestic and agricultural demand during the dry season, and seawater intrusion has already been documented in the shallow coastal aquifers of the Udupi district (Deepika et al., 2020; Dhakate et al., 2020). Land use in these basins is changing rapidly, and both the rainfall regime and land cover exert measurable control on water availability in Western Ghats rivers (Mathew et al., 2021; Sharannya et al., 2021). Poojashree et al. (2023) reported a marked decline in green cover in the neighboring Kollur Basin. However, how ET responds to these changes and what that response implies for recharge has not been established for the Sita and Swarna basins.

Therefore, this study aimed to (i) estimate the spatial and seasonal distribution of actual ET in the Sita and Swarna river basins for 2023 and 2024 using MODIS products and the SEBAL model; (ii) compute reference ET independently from station data using the FAO Penman–Monteith method as a check on the satellite-derived surfaces; and (iii) examine ET against LULC classes to assess how ET should and should not be used in delineating groundwater potential zones in a humid coastal setting.

2. Study area

The Sita and Swarna river basins lie between latitudes 13°08'N and 13°35'N and longitudes 74°41'E and 75°11'E in the Udupi district of coastal Karnataka and together cover 1,228.05 km² (Figure 1). Both rivers rise on the western scarp of the Western Ghats and discharge into the Arabian Sea through a shared estuary; therefore, the basins traverse the full sequence from forested upland to coastal plain within a short horizontal distance. The climate is tropical, humid, and strongly seasonal, with rainfall concentrated in the southwest monsoon between June and September. Land cover grades from evergreen and deciduous forests in the headwaters, through arecanut and coconut plantations and paddy in the valleys, to aquaculture ponds, settlements, and built-up land near the coast.

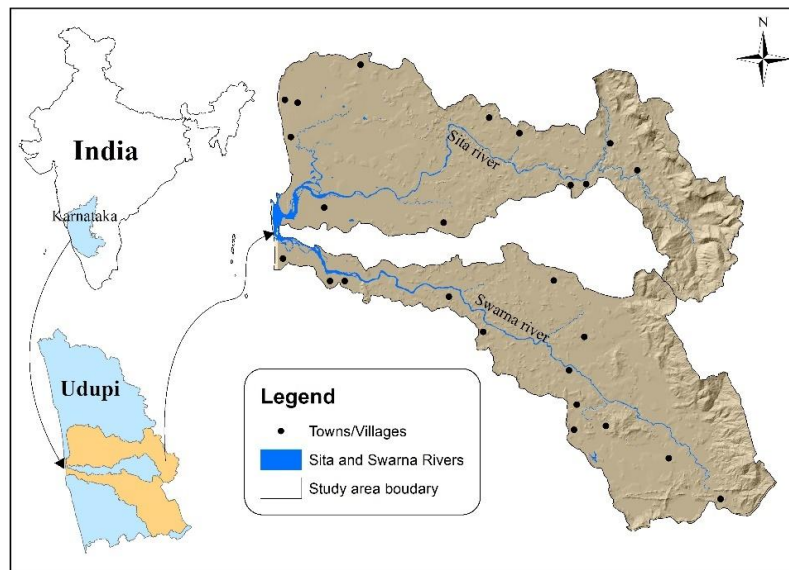


Figure 1. Location of the Sita and Swarna river basins in Udupi district, coastal Karnataka, India.

3. Data and methods

3.1 MODIS products and pre-processing

MODIS Terra and Aqua products for 2023 and 2024 were obtained from the Land Processes Distributed Active Archive Center (LP DAAC) in Hierarchical Data Format with accompanying XML metadata files. Bands 1–7 and the solar zenith angle were obtained from MOD09A1 (8-day surface reflectance, 500 m), bands 31 and 32 for land surface temperature from MOD11A1 (daily LST and emissivity, 1 km), and NDVI from MOD13A1 (16-day vegetation indices, 500 m). Files were converted from HDF-EOS to GeoTIFF and reprojected from the native sinusoidal projection to geographic WGS 84 using the HEG conversion tool. Sub-scenes covering the two basins were extracted from the processed 1,200 × 1,200 km swaths using ArcGIS shapefiles. Eight image days were processed in each year: days 1, 41, 73, 113, 129, 305, 329, and 353 in 2023, and days 1, 49, 81, 113, 129, 297, 313, and 353 in 2024, covering the winter, summer, and post-monsoon periods.

3.2 Land surface temperature

The land surface temperature was derived from the daily MOD11A1 product, which applies a split-window algorithm and regression analysis to the MODIS Terra thermal channels. Spectral radiance

values were converted to Kelvin by applying the product scaling factor of 0.02, as specified in the MOD11A1 product documentation (LP DAAC, 2015).

To cross-examine the emissivity variation, the land surface temperature was formulated following the generalized split-window algorithm of Wan and Dozier (1996), one of the retrieval approaches reviewed by Li et al. (2023):

$$T_s = A_1 + A_2(1 - \varepsilon)/\varepsilon + A_3(\Delta\varepsilon/\varepsilon^2) \cdot [(T_{31} + T_{32})/2] + B_1 + B_2(1 - \varepsilon)/\varepsilon + B_3(\Delta\varepsilon/\varepsilon^2) \cdot (T_{31} - T_{32}) + C \quad (1)$$

where T_s is the land surface temperature (K), T_{31} and T_{32} are the brightness temperatures of MODIS bands 31 (11 μm) and 32 (12 μm), respectively (K), $\varepsilon = 0.5(\varepsilon_{31} + \varepsilon_{32})$ is the mean surface emissivity, $\Delta\varepsilon = \varepsilon_{31} - \varepsilon_{32}$ is the emissivity difference between the two bands (both dimensionless), and A_1 , A_2 , A_3 , B_1 , B_2 , B_3 , and C are regression coefficients read from the MODIS look-up table.

3.3 Surface emissivity

The surface emissivity was estimated empirically from the MOD13A1 NDVI, with the raw NDVI digital numbers scaled by 0.0001 in accordance with the product specifications (LP DAAC, 2015). NDVI sub-scenes for the two basins were extracted from the processed swaths using ArcGIS shapefiles.

3.4 Surface albedo

Surface albedo is the ratio of reflected to incident shortwave radiation. It was computed from the seven MOD09A1 surface reflectance bands, scaled by 0.0001, using the narrowband-to-broadband conversion of Liang (2001), implemented in the ArcGIS raster calculator:

$$\alpha = 0.160r_1 + 0.291r_2 + 0.243r_3 + 0.116r_4 + 0.112r_5 + 0.081r_7 + 0.0015 \quad (2)$$

where α is the broadband surface albedo (dimensionless) and r_1 to r_7 are the spectral reflectance of the corresponding MODIS bands (dimensionless).

3.5 Incoming shortwave radiation

Incoming shortwave radiation was computed for each image day from solar geometry and atmospheric transmissivity:

$$R_s\downarrow = G_s C \cdot \cos\theta \cdot d_r \cdot \tau_{svv} \quad (3)$$

where $R_s\downarrow$ is the incoming shortwave radiation (W m^{-2}), $G_s C$ is the solar constant, taken as $1,367 \text{ W m}^{-2}$ (Widén & Munkhammar, 2019), θ is the solar zenith angle, obtained from the NOAA solar position calculator for the date, time, and location of each overpass, d_r is the inverse squared relative Earth–Sun distance (dimensionless), and τ_{svv} is the broadband atmospheric transmissivity (dimensionless). On 1 January 2023, the solar zenith angle was 168.96° .

3.6 Outgoing longwave radiation

Outgoing longwave radiation was computed pixel by pixel from the Stefan–Boltzmann law using the emissivity and temperature layers that had already been derived:

$$R_l\uparrow = \varepsilon_s \cdot \sigma \cdot T_s^4 \quad (4)$$

where $R_l\uparrow$ is the outgoing longwave radiation (W m^{-2}), ϵ_s is the surface emissivity (dimensionless), σ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$), and T_s is the land surface temperature (K). The computation was performed using the ArcGIS raster calculator.

3.7 Selection of hot and cold pixels

Anchor pixels were located by overlaying the basin's LULC map on the land surface temperature map. Cold pixels were placed on dense vegetation at the ridge crest of the Western Ghats, where the surface is well supplied with moisture: 299.18 K (26.03°C) in the Sita Basin and 299.08 K (25.93°C) in the Swarna Basin. Hot pixels were located on dry, cleared, and built-up surfaces. The hot pixel temperatures were used to characterize the extreme dry end of the surface energy balance and are reported for each image day in the tables that follow. However, they were not used to solve iteratively for the near-surface temperature gradient, and the consequences of this simplification are discussed in Section 5.5.

3.8 Incoming longwave radiation

Atmospheric emissivity was estimated from atmospheric transmissivity using the empirical relationship of Bastiaanssen (1995):

$$\epsilon_a = 0.85 \cdot (-\ln \tau_{svv})^{0.09} \quad (5)$$

The downward thermal radiation flux from the atmosphere was then obtained as

$$R_{l\downarrow} = \epsilon_a \cdot \sigma \cdot T_{c_{ola}}^4 \quad (6)$$

where ϵ_a is the atmospheric emissivity (dimensionless), τ_{svv} is the atmospheric transmissivity (dimensionless), and $T_{c_{ola}}$ is the cold-pixel surface temperature (K), which varies with the date and location of each image and was read from the LST layer for every image day.

3.9 Soil heat flux

Soil heat flux was obtained from the empirical model of Bastiaanssen et al. (1998a), which relates the ratio of soil heat flux to net radiation to surface temperature, albedo, and NDVI:

$$G/R_n = (T_s/\alpha)(0.0038\alpha + 0.007\alpha^2)(1 - 0.98 \cdot \text{NDVI}^4) \quad (7)$$

where G is the soil heat flux (W m^{-2}), R_n is the net radiation (W m^{-2}), T_s is the surface temperature expressed in degrees Celsius, α is the surface albedo (dimensionless), and NDVI is the normalized difference vegetation index (dimensionless). The land surface temperature raster was converted from Kelvin to degrees Celsius within the GIS, and the albedo, NDVI, and temperature layers were combined in the raster calculator to produce the G/R_n surface for each basin.

3.10 Sensible heat flux

The sensible heat flux was computed from the aerodynamic transport relation as follows:

$$H = (\rho_a \cdot c_p \cdot dT) / r_{ah} \quad (8)$$

where H is the sensible heat flux (W m^{-2}), ρ_a is the air density (kg m^{-3}), c_p is the specific heat of air at constant pressure ($\text{J kg}^{-1} \text{ K}^{-1}$), dT is the near-surface temperature difference (K), and r_{ah} is the aerodynamic resistance to heat transport (s m^{-1}). The values of air density, specific heat, temperature

difference, and aerodynamic resistance for each image acquisition day were entered into a spreadsheet.

3.11 Latent heat flux, instantaneous ET and reference ET fraction

The latent heat flux was obtained as the residual of the surface energy balance at the time of the satellite overpass:

$$\lambda ET = R_n - H - G \quad (9)$$

where λET is the latent heat flux ($W m^{-2}$). Net radiation and soil heat flux were available as raster layers and were combined with the computed sensible heat flux using the ArcGIS raster calculator. In this implementation, the sensible heat flux was represented by a single value for each basin (292.04 $W m^{-2}$ for the Sita Basin and 231.65 $W m^{-2}$ for the Swarna Basin), rather than by a spatially distributed field.

Instantaneous evapotranspiration at the time of overpass follows the latent heat flux:

$$ET_{inst} = 3600 \cdot \lambda ET / (2.26 \times 10^6) \quad (10)$$

where ET_{inst} is the instantaneous evapotranspiration ($mm h^{-1}$), and $2.26 \times 10^6 J kg^{-1}$ is the latent heat of vaporization of water.

The reference ET fraction was then obtained by dividing the instantaneous ET by the reference ET rate at the time of the image, 1.86 $mm h^{-1}$, computed by the FAO Penman–Monteith method from concurrent station data:

$$ET_rF = ET_{inst} / 1.86 \quad (11)$$

3.12 Daily evapotranspiration

The daily net radiation was obtained by integrating the instantaneous value over a solar day using a sinusoidal representation of the diurnal radiation cycle:

$$R_{n,av}^g = (2R_n/\pi) \cdot \sin(0.639) / (2.005 \cdot \pi) \quad (12)$$

The 24 h actual evapotranspiration was computed pixel by pixel as follows:

$$ET_{24} = 86400 \cdot ET_rF \cdot R_{n,av}^g / (2.26 \times 10^6) \quad (13)$$

where ET_{24} is the daily actual evapotranspiration ($mm day^{-1}$), and $R_{n,av}^g$ is the daily average net radiation ($W m^{-2}$). Equations (9)–(13) were applied identically to both basins, using the basin-specific sensible heat flux values provided in Section 3.11.

3.13 Reference evapotranspiration

Reference evapotranspiration was computed independently of the satellite retrieval for every image day using CROPWAT 8.0, which implements the FAO Penman–Monteith equation (Monteith, 1965). The maximum and minimum air temperatures, relative humidity, wind speed, and sunshine duration were obtained from the meteorological station serving the study area (Table 9). The resulting values provided a reference field against which the satellite-derived ET fractions were scaled and assessed.

3.14 Statistical and diagnostic analysis of the derived fluxes

Three further analyses were applied to the flux components already tabulated for the anchor pixels; all used only the values reported in Tables 1–10 and required no additional data. First, the closure of the surface energy balance was evaluated at every anchor pixel on every image day by computing the residual latent heat flux from Equation (9) and expressing it as the ratio G/R_n and evaporative fraction $\Lambda = \lambda ET / (R_n - G)$. Second, paired contrasts between hot and cold pixels and between the two basins were tested using the Wilcoxon signed-rank test (Wilcoxon, 1945), which assumes no particular distribution and is appropriate for a sample of 16 image days. Third, the reference ET values of Table 10 were related to the meteorological variables of Table 9 by Pearson correlation and ordinary least squares regression, and were independently recomputed from the same meteorological record by the FAO-56 Penman–Monteith procedure (Allen et al., 1998), using the basin centroid latitude of 13.35°N, an elevation of 27 m, Ångström coefficients of 0.25 and 0.50, and wind speed referenced at 2 m. The agreement between the two computations was quantified using Pearson’s correlation, root mean square error, mean absolute error, and mean bias.

3.15 Integration of ET with land use and land cover

In ArcGIS the average ET surfaces for 2023 and 2024 were overlaid on the basin LULC map and zonal statistics was used to derive the distribution of ET within each land cover class. This overlay used as a basis for assessment of groundwater potential in Section 5.3.

4. Results

4.1 Land surface temperature and emissivity

The land surface temperature of Sita Basin varied from 27.72 °C (300.87 K) to 34.97 °C (308.12 K). In the Swarna Basin, the equivalent range was 27.34 °C (300.49 K) – 34.59 °C (307.73 K). The spatial distribution seen in Fig. 2 closely follows relief and land cover, with the lowest temperatures above the forested summit of the Western Ghats and over open water, and the highest over cleared agricultural land and built-up areas on the coastal plain.

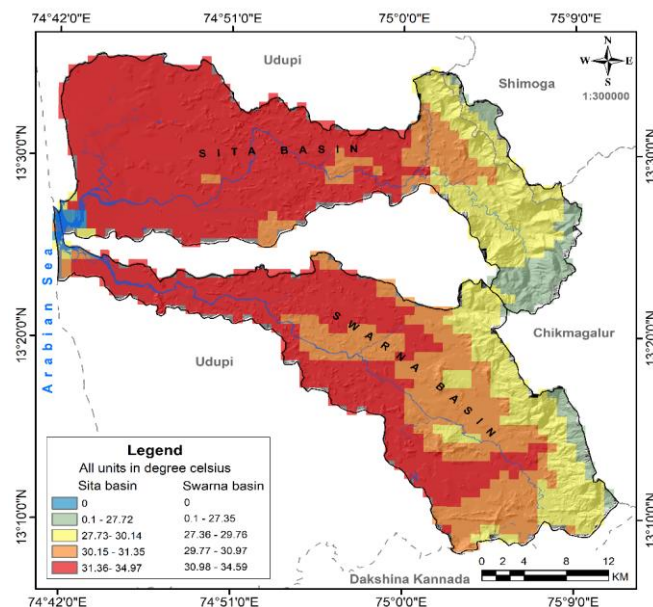


Figure 2. Land surface temperature in the study area.

The surface emissivity ranged from 0.953 to 1.003 in the Sita Basin and 0.952 to 1.002 in the Swarna Basin (Figure 3). The upper end of these ranges exceeds unity, which is physically impossible for a natural surface, and is a result of the empirical NDVI-based parameterization rather than a measured property. The excess is small (on the order of 0.003) and its effect on the derived longwave fluxes is correspondingly small. The spatial distribution was as expected, with the highest values over dense canopy and water and the lowest over bare and built-up surfaces.

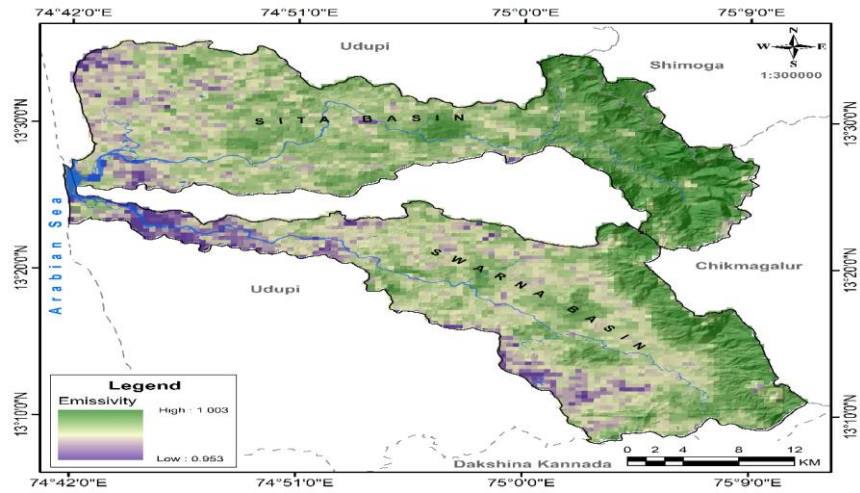


Figure 3. Surface emissivity of the study area.

4.2 Surface albedo

The surface albedo varied between 0.039 and 0.155 in the Sita Basin and between 0.038 and 0.142 in the Swarna Basin (Figure 4). The values obtained here are at the lower end of the range reported by Rahimi et al. (2015) of albedo values between 0.063 and 0.171 for the Tajan catchment in 2011, as expected for a more densely vegetated and humid basin.

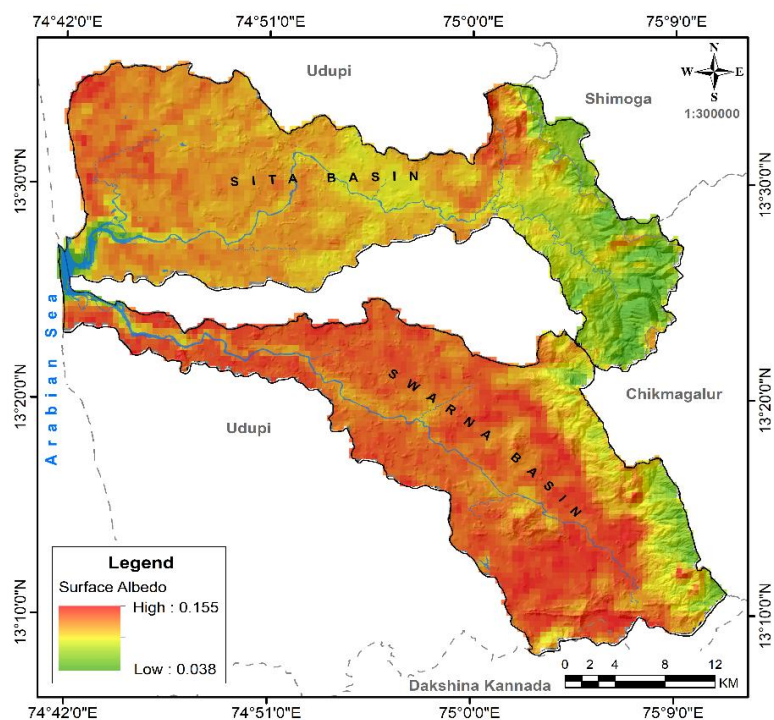


Figure 4. Surface albedo of the study area.

The albedo values of the hot and cold anchor pixels for each image day in 2023 and 2024 are shown in Tables 1 and 2, respectively. The cold-pixel albedo was low throughout the year, consistent with water and vegetation cover. The hot-pixel albedo was highest on image days 113 and 129 in both years, which fall in the pre-monsoon and early summer periods when the coastal plain carries a mixture of settlement and cleared ground with little vegetation.

Table 1. Surface albedo at hot and cold pixels in 2023.

Image day	Sita basin Hot pixel	Sita basin Cold pixel	Swarna basin Hot pixel	Swarna basin Cold pixel
1	0.15	0.04	0.14	0.04
41	0.18	0.03	0.16	0.02
73	0.18	0.01	0.18	0.01
113	0.23	0.05	0.21	0.05
129	0.27	0.06	0.26	0.06
305	0.18	0.04	0.17	0.02
329	0.15	0.04	0.16	0.02
353	0.18	0.03	0.14	0.02

Table 2. Surface albedo at hot and cold pixels in 2024.

Image day	Sita basin Hot pixel	Sita basin Cold pixel	Swarna basin Hot pixel	Swarna basin Cold pixel
1	0.17	0.04	0.15	0.03
49	0.19	0.03	0.17	0.02
81	0.23	0.05	0.20	0.03
113	0.20	0.03	0.18	0.04
129	0.21	0.05	0.20	0.05
297	0.15	0.04	0.19	0.01
313	0.18	0.03	0.17	0.01
353	0.17	0.04	0.16	0.05

4.3 Radiation and heat fluxes

The OLR ranged from 0 to 495.83 W m⁻² in the Sita Basin and from 456.72 to 502.15 W m⁻² in the Swarna Basin (Figure 5). Teixeira et al. (2015) found surface-emitted longwave radiation between 496.29 and 511.11 W m⁻² for the Brazilian semi-arid region in 2014. The higher end of the present range is comparable. The low values recorded in parts of the Sita Basin correspond to water and shadowed terrain.

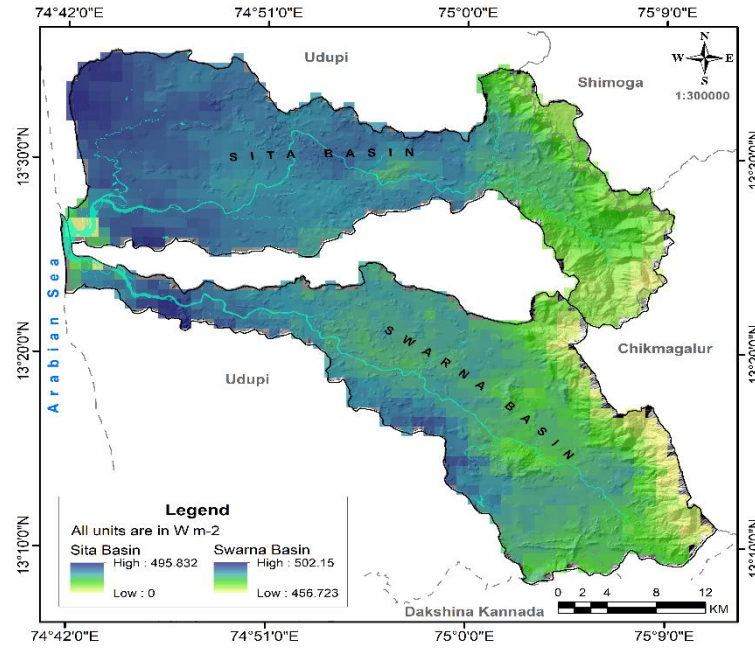


Figure 5. Outgoing longwave radiation (thermal radiation flux) in the study area.

On January 1, 2023, incoming shortwave radiation was 819.72 W m^{-2} in both basins. The value is in the range of incoming shortwave radiation measured between 250 to 980 W m^{-2} in 2003 for different climates and land cover types in Taiwan and China (Sun et al., 2013). The incoming long wave radiation was 344.88 W m^{-2} for Sita Basin and 344.42 W m^{-2} for Swarna Basin. These values are lower than the 370.48 to 403.81 W m^{-2} reported by Teixeira et al. (2015) for the Brazilian semi-arid region, which is consistent with the cooler and moister January conditions of the present study area.

The ratio of soil heat flux to net radiation ranged from -2.17 to 0.36 in the Sita Basin and from 0 to 1.33 in the Swarna Basin (Figure 6). Areas where G/R_n approaches zero correspond to dense vegetation, values near 0.1 correspond to thin vegetation, and values between 0.2 and 0.3 correspond to bare soil. The negative values in the Sita Basin and values above unity in the Swarna Basin lie outside the physically expected interval and are examined in Section 5.5.

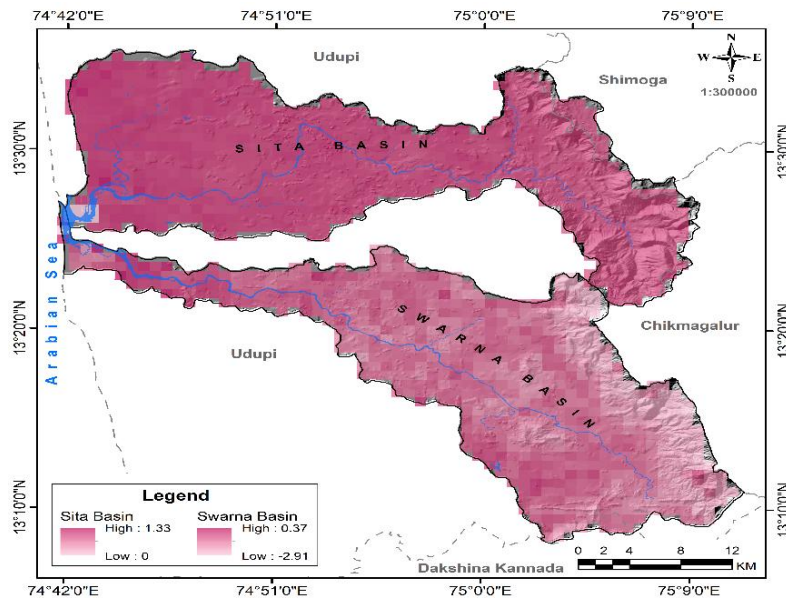


Figure 6. Ratio of soil heat flux to net radiation (G/R_n) in the study area.

The soil heat flux at the anchor pixels is reported in Tables 3 and 4. Values were consistently higher at hot pixels than at cold pixels, which follows from the shielding effect of vegetation on the radiation reaching the soil surface. Soil heat flux was lowest on the winter image days (days 1 and 41 in 2023; days 1 and 49 in 2024) and highest on the summer and post-monsoon days (days 73, 113, 129, 305, 329, and 353 in 2023; days 81, 113, 129, 297, 313, and 353 in 2024). Rahimi et al. (2015) obtained soil heat fluxes between 20.39 and 87.00 W m⁻² at cold pixels and between 22.24 and 138.25 W m⁻² at hot pixels in the Tajan catchment; the values obtained here are an order of magnitude larger, a discrepancy addressed in Section 5.5.

Table 3. Soil heat flux at hot and cold pixels, 2023 (W m⁻²).

Image day	Sita basin Hot pixel	Sita basin Cold pixel	Swarna basin Hot pixel	Swarna basin Cold pixel
1	196.18	80.93	169.58	58.71
41	808.14	280.83	549.70	286.01
73	903.87	375.73	524.08	261.01
113	756.42	350.12	650.21	254.85
129	520.54	342.18	422.13	311.22
305	771.08	362.86	633.39	402.39
329	890.13	432.85	658.70	431.38
353	722.08	161.40	705.14	392.66

Table 4. Soil heat flux at hot and cold pixels, 2024 (W m⁻²).

Image day	Sita basin Hot pixel	Sita basin Cold pixel	Swarna basin Hot pixel	Swarna basin Cold pixel
1	432.38	231.64	410.73	129.22
49	358.95	249.56	503.97	283.70
81	679.52	400.84	567.89	449.03
113	807.93	449.90	653.99	443.69
129	976.26	192.17	703.38	413.75
297	971.82	373.48	691.92	393.38
313	994.25	417.19	693.77	376.93
353	988.46	329.48	697.60	403.73

The sensible heat flux at the anchor pixels is presented in Tables 5 and 6. The lowest values occurred on the post-monsoon image days (days 305, 329, and 353 in 2023; days 297, 313, and 353 in 2024), when the near-surface temperature difference and wind speed were both small, and the highest values occurred on winter and summer days.

Table 5. Sensible heat flux at hot and cold pixels, 2023 (W m^{-2}).

Image day	Sita basin Hot pixel	Sita basin Cold pixel	Swarna basin Hot pixel	Swarna basin Cold pixel
1	284.49	293.18	225.94	231.39
41	276.64	285.69	233.02	239.42
73	298.40	306.83	215.40	223.51
113	395.59	411.73	277.34	285.19
129	269.56	279.03	359.03	376.79
305	119.61	121.46	179.23	183.54
329	180.15	182.59	224.25	228.73
353	149.68	152.69	119.68	121.58

Table 6. Sensible heat flux at hot and cold pixels, 2024 (W m^{-2}).

Image day	Sita basin Hot pixel	Sita basin Cold pixel	Swarna basin Hot pixel	Swarna basin Cold pixel
1	208.92	213.09	250.85	256.90
49	334.48	345.42	273.73	289.52
81	340.83	351.87	297.21	306.11
113	324.28	335.04	316.91	327.18
129	344.18	354.40	366.68	378.97
297	89.55	90.62	119.79	121.07
313	195.98	200.71	131.29	133.39
353	114.04	122.90	114.09	122.87

The net radiation for each image day is presented in Tables 7 and 8. Net radiation at cold pixels exceeded that at hot pixels on every image day in both basins, reflecting the capacity of vegetation and water to retain absorbed energy rather than reradiating it.

Table 7. Net radiation at hot and cold pixels, 2023 (W m^{-2}).

Image day	Sita basin Hot pixel	Sita basin Cold pixel	Swarna basin Hot pixel	Swarna basin Cold pixel
1	209.76	762.97	552.03	640.66
41	490.23	1018.36	378.19	469.48
73	369.55	939.68	340.99	838.39
113	713.44	902.49	764.25	886.61
129	216.24	808.19	224.70	845.75
305	447.80	966.96	443.33	984.88
329	472.19	964.03	481.87	975.52
353	355.84	873.94	493.20	980.19

Table 8. Net radiation at hot and cold pixels, 2024 (W m^{-2}).

Image day	Sita basin Hot pixel	Sita basin Cold pixel	Swarna basin Hot pixel	Swarna basin Cold pixel
1	466.42	967.65	480.32	986.44
49	34.92	445.27	361.73	927.10
81	377.72	956.16	397.12	969.04
113	369.45	936.70	389.23	953.37
129	375.08	932.37	384.33	933.88
297	481.93	961.31	549.82	973.73
313	435.95	968.17	448.41	986.81
353	454.91	964.71	471.90	973.59

4.4 Reference evapotranspiration

Meteorological data used to fuel the FAO Penman-Monteith computation are presented in Table 9 and the resulting reference ET for each image day are listed in Table 10. The reference ET was 2.56–4.09 mm day^{-1} in 2023 and 2.71–4.03 mm day^{-1} in 2024. In both years, the minimum was observed in the image of January 1 and the maximum in the pre-monsoon period, in agreement with the yearly cycle of temperature and atmospheric demand.

Table 9. Meteorological data for image acquisition days, 2023–2024.

Image date	Temperature (°C) Min	Temperature (°C) Max	Humidity (%) Min	Humidity (%) Max	Wind (km h^{-1})	Sunrise (h)	Sunset (h)	Sunshine (h)
01-01-2023	13.80	37.30	19.40	100.00	1.80	06:40	18:06	11:26
10-02-2023	21.20	36.10	47.40	100.00	2.00	06:46	18:25	11:39
13-03-2023	24.30	34.50	55.60	100.00	1.90	06:30	18:32	12:02
22-04-2023	25.10	38.40	51.00	93.20	2.10	06:05	18:35	12:30
08-05-2023	22.70	38.00	37.40	100.00	5.00	05:58	18:38	12:40
31-10-2023	21.40	35.20	49.30	100.00	1.00	06:15	17:55	11:40
24-11-2023	17.70	36.80	33.10	100.00	1.60	06:24	17:52	11:28
18-12-2023	19.10	34.00	57.10	100.00	1.60	06:37	17:59	11:22
01-01-2024	16.10	35.90	29.30	100.00	1.60	06:44	18:06	11:22
18-02-2024	18.00	37.70	16.70	91.40	1.90	06:43	18:28	11:45
22-03-2024	23.80	34.30	57.30	100.00	2.30	06:25	18:32	12:07
23-04-2024	22.20	36.30	55.40	100.00	2.00	06:05	18:35	12:30
09-05-2024	25.20	35.20	47.90	100.00	2.00	05:58	18:38	12:40
24-10-2024	20.50	34.20	45.80	100.00	1.20	06:13	17:58	11:45
09-11-2024	21.90	36.00	47.60	100.00	1.00	06:18	17:53	11:35
19-12-2024	16.50	32.90	35.00	100.00	1.30	06:38	17:59	11:21

Table 10. Reference evapotranspiration by image day, 2023 and 2024 (mm day^{-1}). A single meteorological station serves both basins; therefore, the reference ET is common to the Sita and Swarna basins for a given date.

Image day 2023	Reference ET Sita basin	Reference ET Swarna basin	Image day 2024	Reference ET Sita basin	Reference ET Swarna basin
1	2.56	2.56	1	2.93	2.93
41	3.50	3.50	49	2.71	2.71
73	3.96	3.96	81	4.03	4.03
113	4.09	4.09	113	4.03	4.03
129	3.74	3.74	129	3.91	3.91
305	3.53	3.53	297	3.46	3.46
329	3.09	3.09	313	3.66	3.66
353	3.59	3.59	353	3.05	3.05

4.5 Latent heat flux and instantaneous evapotranspiration

The spatial distribution of the latent heat flux for the 1 January 2023 overpass is shown in Figure 7. The average latent heat flux ranged from 352.69 to 739.32 W m^{-2} in the Sita Basin and from 387.59 to 449.83 W m^{-2} in the Swarna Basin.

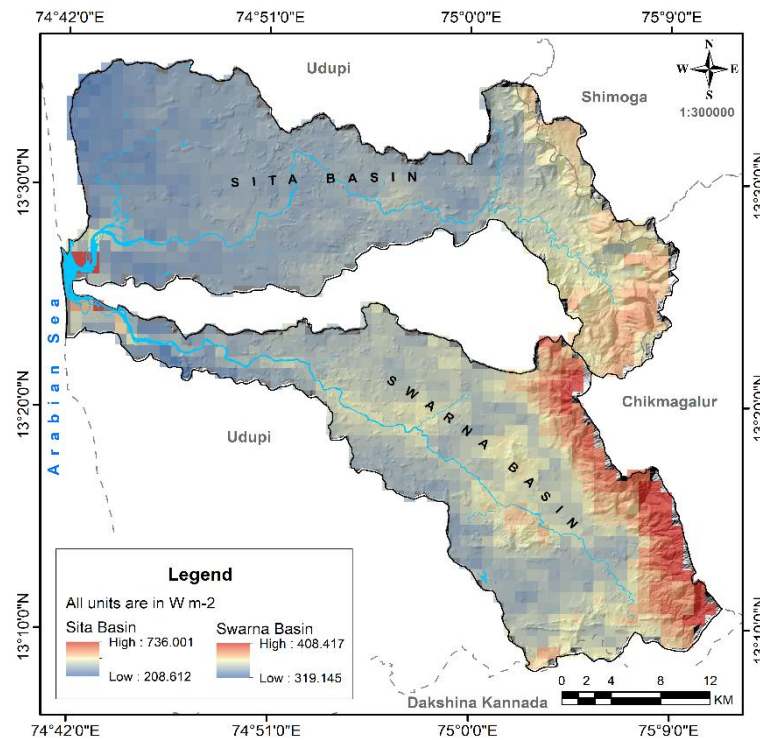


Figure 7. Latent heat flux in the study area.

The instantaneous evapotranspiration ranged from 0.33 to 1.17 mm h^{-1} in the Sita Basin and from 0.51 to 0.65 mm h^{-1} in the Swarna Basin (Figure 8); the upper end of the Sita Basin range coincides with the hot-pixel soil heat flux anomaly examined in Section 5.5 and should be read with that caveat in mind. The corresponding reference ET fraction surface is presented in Figure 9.

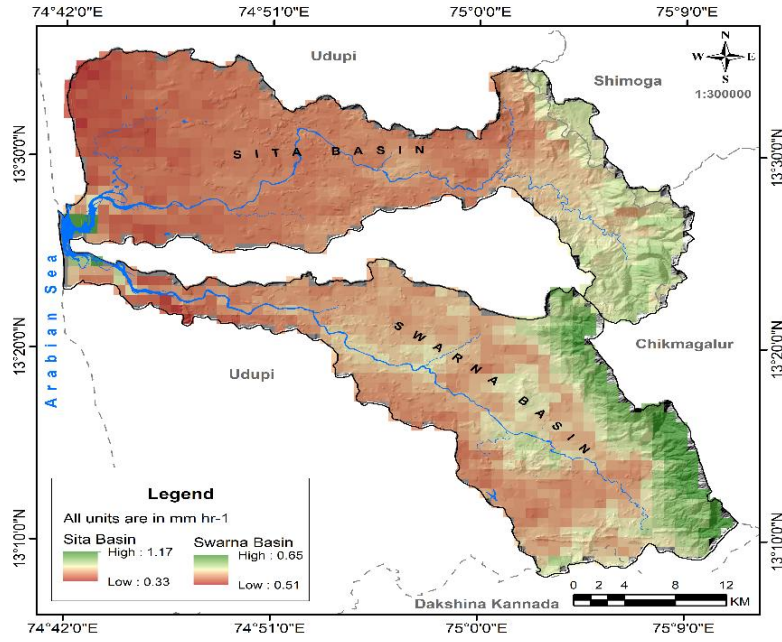


Figure 8. Instantaneous evapotranspiration in the study area.

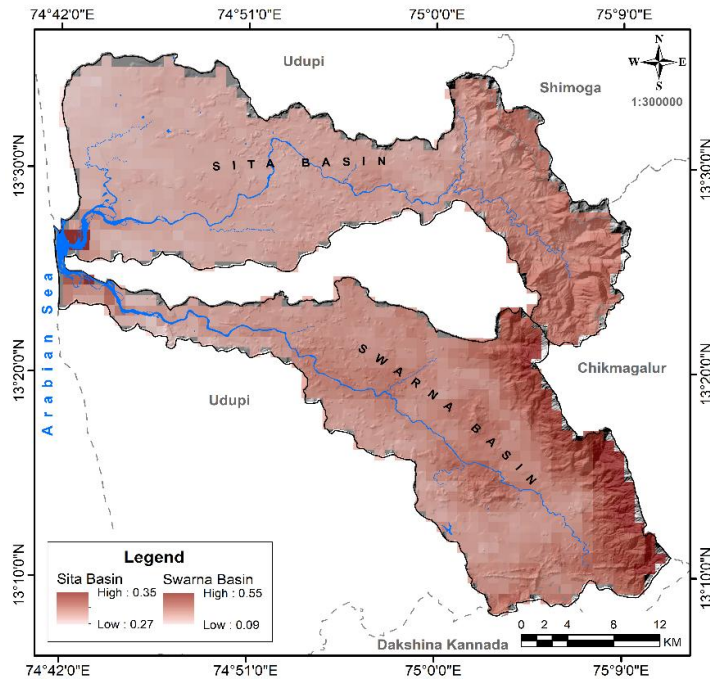


Figure 9. Reference evapotranspiration fraction of the study area.

4.6 Daily and seasonal evapotranspiration

The daily actual evapotranspiration for 1 January 2023 is shown in Figure 10. The maximum occurred over a small area at the mouth of the Sita River, where ET ranged from 8.6 to 19.66 mm day⁻¹; this estuarine maximum coincides with the hot-pixel soil heat flux anomaly examined in Section 5.5 and is best read as an upper bound on evaporative demand rather than a confirmed water-loss figure. Over the hilly terrain of the Western Ghats, ET falls to between 7.6 and 8.5 mm day⁻¹, declines further across the coastal plain to between 6.5 and 7.5 mm day⁻¹, and is lowest over settlement, at 5.6 to 6.4 mm day⁻¹. Across the full set of image days, daily ET ranged from 5.6 to 19.66 mm day⁻¹ in the Sita Basin

(see the preceding caveat on the upper bound) and from 4.01 to 6.01 mm day⁻¹ in the Swarna Basin, with values of 4.1 to 5.0 mm day⁻¹ over the Swarna coastal plain.

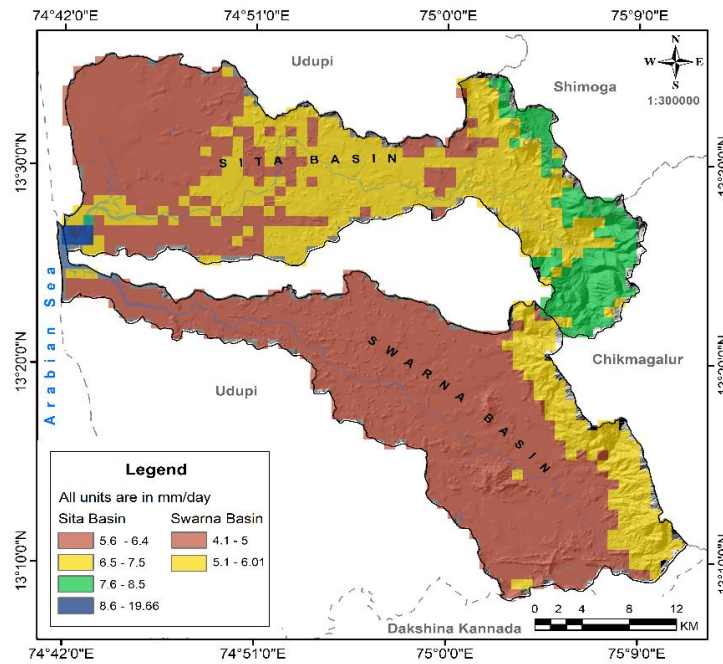


Figure 10. Daily (24 h) evapotranspiration in the study area on January 1, 2023.

The winter ET surfaces for January 2023 and January 2024 are shown in Figures 11 and 12, respectively. Cold pixels in these images fall on vegetation and water and, as expected, have a lower albedo than the hot pixels located on bare surfaces. The January 2023 surface recorded a maximum of 18.5 mm day⁻¹ and the January 2024 surface recorded 17.8 mm day⁻¹. In both years, the maximum was located at the confluence of the river and sea, where the combination of open water, low albedo, unrestricted moisture supply, and estuarine wind conditions sustains the highest evaporation rates in the basin; part of this maximum reflects genuine advection and part reflects the modelling artifact discussed in Sections 5.1 and 5.5.

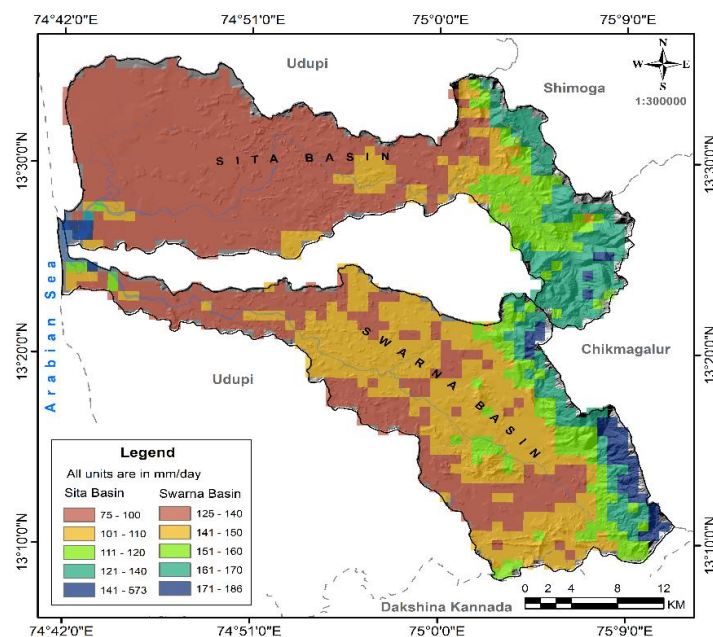


Figure 11. Evapotranspiration in the study area, January 2023 (winter season).

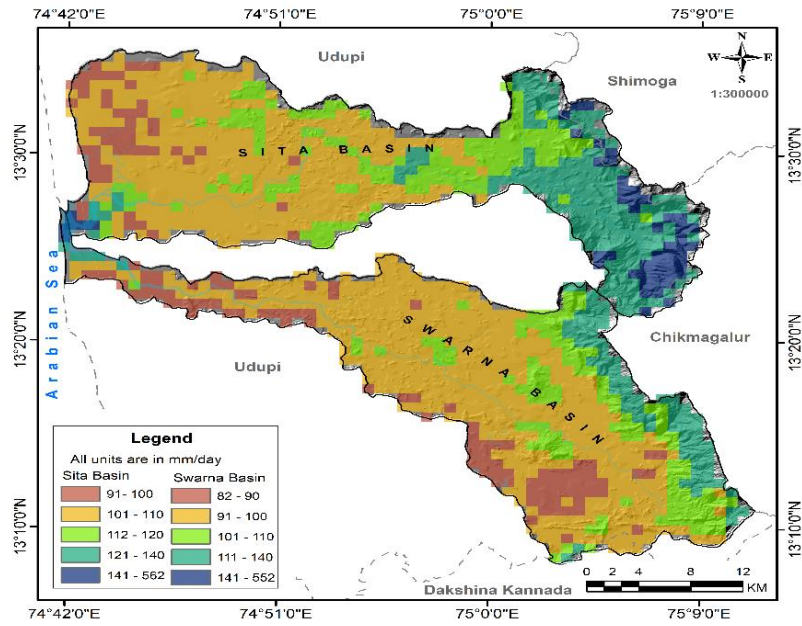


Figure 12. Evapotranspiration in the study area, January 2024 (winter season).

The corresponding summer surfaces for May 2023 and May 2024 are shown in Figures 13 and 14, respectively. ET was markedly lower than that in January across most of the basin. Hot pixels dominate the coastal plain and settlement areas, where soil moisture has been depleted and post-monsoon paddy crops have been harvested. Dense vegetation on the hills and foothills, and the water bodies, continue to transpire and evaporate at appreciable rates, although they are still below their January values. Therefore, across all seasons, the highest ET was sustained by dense vegetation and open water.

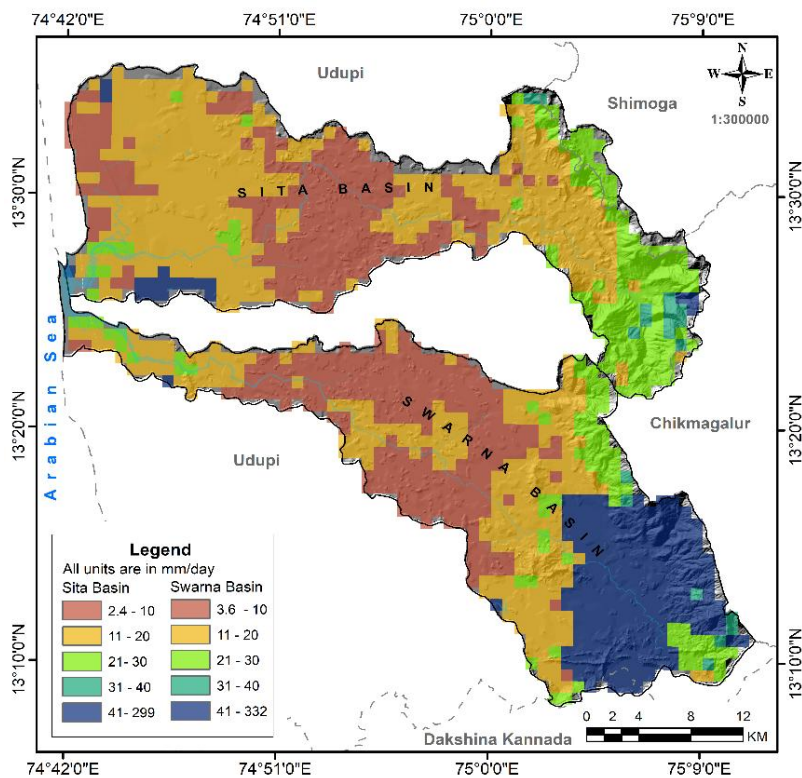


Figure 13. Evapotranspiration in the study area, May 2023 (summer season).

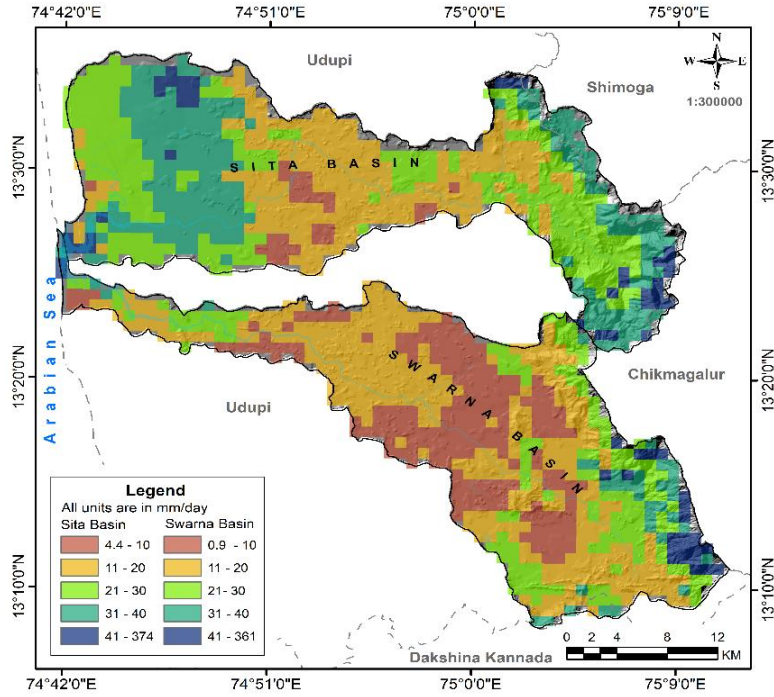


Figure 14. Evapotranspiration in the study area, May 2024 (summer season).

The two-year average ET surfaces for the Sita and Swarna basins are shown in Figure 15. These surfaces were used in the LULC overlay described in Section 3.14.

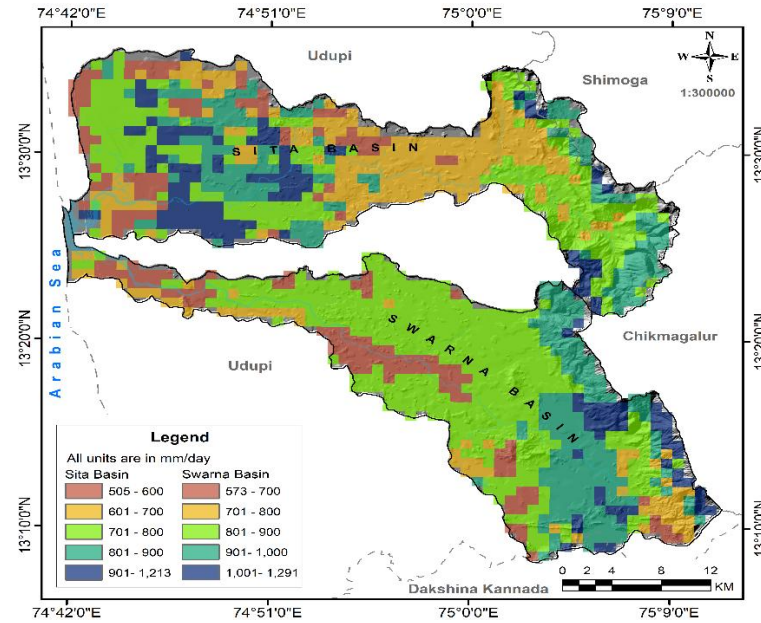


Figure 15. Average evapotranspiration in the study area in 2023 and 2024.

4.7 Statistical characterisation of anchor-pixel energy partitioning

The qualitative contrasts described in Section 4.3 were formally tested (Table 11). Every hot-versus-cold contrast was significant at $p < 0.001$ in both basins: hot pixels carried higher albedo (median difference 0.150) and higher soil heat flux (432.8 W m^{-2} in the Sita Basin and 263.4 W m^{-2} in the Swarna Basin), while cold pixels carried substantially higher net radiation (523.6 and 503.9 W m^{-2} , respectively). The two basins also differed from one another, though far less strongly: the hot-pixel

albedo was marginally higher in the Sita Basin (median difference 0.010, $p = 0.027$), and the hot-pixel net radiation was marginally lower (-15.4 W m^{-2} , $p = 0.023$). The consistency of these contrasts across 16 independent image days indicates that the anchor pixel selection captures a real and stable surface contrast rather than day-to-day noise.

One result contradicts expectations. Sensible heat flux was significantly higher at the cold pixel than at the hot pixel in both basins and on every image day (median difference: -8.8 W m^{-2} in the Sita Basin, $p < 0.001$). Physically the reverse should be the case as the sensible heat transport is highest over the driest and warmest surface. The magnitude of the reversal is small relative to the fluxes themselves, but its perfect consistency indicates a systematic rather than a random origin, and this point is discussed in Section 5.5.

Table 11. Wilcoxon signed-rank tests for paired anchor-pixel contrasts ($n = 16$ image days). Significance: *** $p < 0.001$, * $p < 0.05$.

Contrast	Median difference	z	p	Sig.
Albedo, hot vs cold (Sita)	0.150	-3.52	0.0004	***
Albedo, hot vs cold (Swarna)	0.150	-3.52	0.0004	***
Soil heat flux, hot vs cold (Sita)	432.8 W m^{-2}	-3.52	0.0004	***
Soil heat flux, hot vs cold (Swarna)	263.4 W m^{-2}	-3.52	0.0004	***
Sensible heat flux, hot vs cold (Sita)	-8.8 W m^{-2}	-3.52	0.0004	***
Net radiation, cold vs hot (Sita)	523.6 W m^{-2}	-3.52	0.0004	***
Net radiation, cold vs hot (Swarna)	503.9 W m^{-2}	-3.52	0.0004	***
Albedo, Sita vs Swarna (hot pixel)	0.010	-2.22	0.0268	*
Net radiation, Sita vs Swarna (hot pixel)	-15.4 W m^{-2}	-2.28	0.0229	*

Grouping the image days by season (Table 12 and Figure 16) resolves a seasonal cycle in surface energy partitioning that the individual image days do not make apparent. The hot-pixel albedo increased from 0.164 ± 0.017 in winter to 0.213 ± 0.030 in summer, an increase of approximately 30 per cent, before returning to 0.167 ± 0.015 after the monsoon. This tracks the exposure of dry soil following the harvest of post-monsoon paddy crops and their subsequent revegetation. Sensible heat flux followed a different trajectory, peaking in summer at $317.1 \pm 49.2 \text{ W m}^{-2}$ and falling to less than half that value, $144.8 \pm 40.9 \text{ W m}^{-2}$, in the post-monsoon period, when air temperature gradients and wind speeds were both weakest.

Dispersion is as informative as the mean. Post-monsoon net radiation had a standard deviation of only 45.1 W m^{-2} , compared to 172.0 W m^{-2} in winter and 165.4 W m^{-2} in summer. Therefore, the post-monsoon radiation regime in these basins is markedly more stable than that of the other two seasons, which has practical value: satellite-derived ET retrieved in this window is less sensitive to the choice of image day than retrievals made in winter or summer.

Table 12. Seasonal energy partitioning at hot pixels (mean $\pm$ standard deviation, both basins and years pooled).

Season	n	Albedo	G (W m^{-2})	H (W m^{-2})	R _n (W m^{-2})
Winter	8	0.164 ± 0.017	428.7 ± 203.8	261.0 ± 40.0	371.7 ± 172.0
Summer	12	0.213 ± 0.030	680.5 ± 162.7	317.1 ± 49.2	410.2 ± 165.4
Post-monsoon	12	0.167 ± 0.015	784.9 ± 136.6	144.8 ± 40.9	461.4 ± 45.1

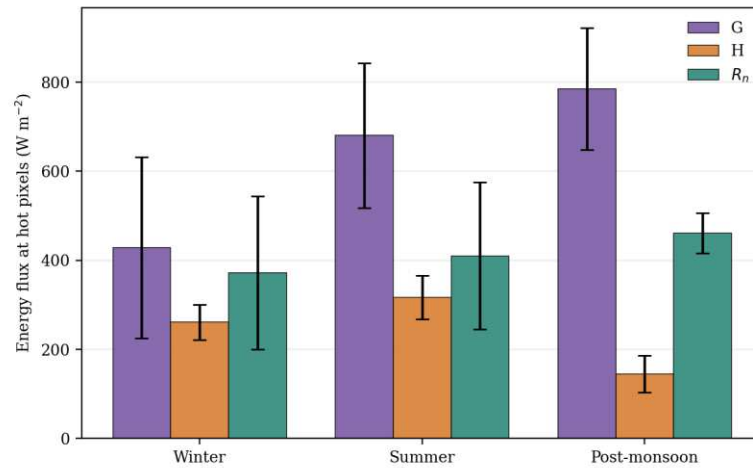


Figure 16. Seasonal energy partitioning at the hot anchor pixels (mean $\pm$ standard deviation, both basins and years pooled).

4.8 Meteorological controls on reference evapotranspiration

Relating the reference ET of Table 10 to the meteorological record of Table 9 identifies the atmospheric variables that govern evaporative demand in these basins (Table 13 and Figure 17a). The minimum air temperature was the strongest single control ($r = +0.934$, $p < 0.0001$), followed by the diurnal temperature range ($r = -0.904$) and minimum relative humidity ($r = +0.903$). Sunshine duration was also significant ($r = +0.716$, $p = 0.0018$), whereas wind speed, maximum relative humidity, and maximum air temperature showed no significant relationships.

A two-variable ordinary least squares model built on minimum relative humidity and sunshine duration accounted for almost all of the observed variation:

$$ET_o = -2.962 + 0.0278 \cdot RH_{\min} + 0.4433 \cdot n \quad (14)$$

where ET_o is the reference evapotranspiration (mm day^{-1}), $RH_{\min}$ is the minimum relative humidity (percent), and n is the solar duration (h). The model produced a R^2 of 0.978 and root mean square error of $0.069 \text{ mm day}^{-1}$ throughout the 16 imaging days. The two routinely measured variables thereby replicate the whole Penman-Monteith computation to within around 2 per cent for this station. This provides a practical short-cut in situations when the full meteorological record required by the FAO-56 approach is not available.

Table 13. Pearson correlation between reference evapotranspiration (Table 10) and the meteorological variables listed in Table 9 ($n = 16$). Significance: *** $p < 0.001$, ** $p < 0.01$, ns, not significant.

Variable	r	p	Sig.
Minimum air temperature	+0.934	<0.0001	***
Diurnal temperature range	-0.904	<0.0001	***
Minimum relative humidity	+0.903	<0.0001	***
Mean air temperature	+0.791	0.0003	***
Sunshine duration	+0.716	0.0018	**
Wind speed	+0.246	0.3577	ns
Maximum relative humidity	+0.135	0.6176	ns
Maximum air temperature	-0.126	0.6411	ns

Recomputing the reference ET directly from Table 9 using the FAO-56 Penman–Monteith procedure provides an independent check on the CROPWAT output (Figure 17b). The two computations were well correlated ($r = 0.762$) and ranked the image days consistently, but the independent estimate was systematically higher, with a mean bias of $+1.47 \text{ mm day}^{-1}$ and a root mean square error of 1.61 mm day^{-1} ; the regression of one on the other had a slope of 1.505. Because CROPWAT 8.0 implements the same FAO-56 formulation, an offset of this size indicates a difference in how the meteorological inputs are handled rather than a difference in method, most plausibly the reference height assumed for wind speed or the treatment of the humidity term, since maximum relative humidity is recorded as 100 per cent on 14 of the 16 image days. The reference ET values used throughout this study are listed in Table 10; the comparison is reported here because it bounds the uncertainty attaching to the reference ET fraction, and hence to the daily ET surfaces scaled through Equation (11).

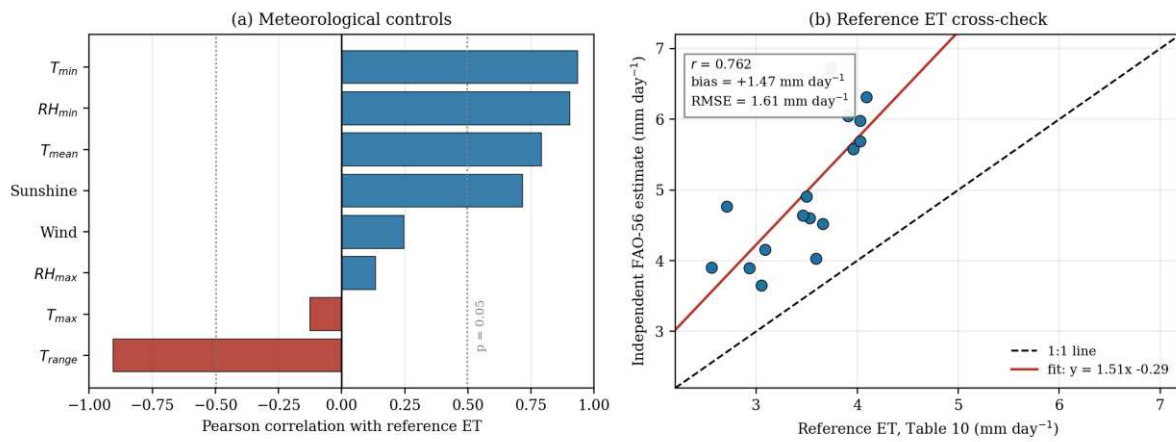


Figure 17. Reference evapotranspiration analysis: (a) Pearson correlation between reference ET and the meteorological variables in Table 9, with dotted lines marking significance at $p = 0.05$; (b) independent FAO-56 Penman–Monteith recomputation against the reported values in Table 10.

5. Discussion

5.1 Comparison with reported SEBAL applications

The daily ET values obtained for the Swarna basin (4.01 to 6.01 mm day^{-1}) were within the range reported from comparable residual energy balance studies. Rahimi et al. (2015) obtained 0.56 to 7.88 mm day^{-1} across the seasonal cycle in the Tajan catchment, and Cammalleri et al. (2012) reported 2.02 to 2.99 mm day^{-1} under the conditions they examined. Two more recent applications bracket the present results. Wei et al. (2022) obtained paddy ET of comparable magnitude in the humid subtropical Ganfu plain, and Behura et al. (2026) reported values of the same order for the coastal rice belt of Odisha, a setting climatically similar to the present study area. The figures of the Sita Basin are different in character. The bulk of the basin fell between 5.6 and 8.5 mm day^{-1} , which remained within the published envelope, but the upper bound of $19.66 \text{ mm day}^{-1}$ over the estuary was well above any value reported from the studies cited above and above the reference ET computed for the same days by a factor of four to five.

Two features of the estuarine pixels account for this. Open water has an albedo of 0.01 to 0.06 at the cold anchor pixels (Tables 1 and 2); therefore, it absorbs almost all incident shortwave radiation, and

there is no moisture limitation; therefore, essentially all of that energy is available to the latent heat term. Advection of dry air across a small water surface can raise evaporation above the equilibrium rate, and an estuary at the coast is precisely that. The remainder is more likely to be an artifact of the model configuration and is discussed in Section 5.5. Therefore, the estuarine maximum should be treated as an upper bound indicating where evaporative demand is concentrated, not as a quantitative water loss figure.

5.2 Controls on evapotranspiration variability

Across both basins and years, the spatial pattern of ET was governed by moisture availability rather than by available energy. This is the expected signature of a humid basin: energy is rarely the limiting factor; therefore, ET tracks where water is. The highest rates occur in every season, with open water and deep forest canopies, where moisture access is continuous. The upland-to-coast gradient seen here also agrees with the elevation dependency reported by Tan et al. (2021) for the upper Huaihe Basin, where SEBAL ET was consistently higher over mountainous terrain than over the nearby plains. Not at the bottom of the range are cleared agricultural land and built up surfaces.

The seasonal disparity is in favor of this conclusion. Reference ET, which is based only on atmospheric demand, increases from a low of 2.56 mm day^{-1} in January to a pre-monsoon maximum of 4.09 mm day^{-1} but actual ET varies inversely, decreasing throughout most land cover classes from January to May. Supply beats demand when demand increases and supply decreases. In January, the soil profile still retains monsoon moisture, and the paddy crop is standing; by May, the profile is drawn down, and the crop has been harvested, so the surface can no longer meet the higher demand. Only deep-rooted evergreen forests and water bodies maintained their rates. The divergence between reference and actual ET through the dry season is therefore a direct measure of the growing soil moisture deficit, and it is that deficit that determines when abstraction pressure on the aquifer peaks.

5.3 Evapotranspiration, land cover and groundwater potential

Groundwater potential assessments frequently treat ET as a loss term, so that high ET is read as poor prospect and low ET as favorable. The overlay of the average ET surfaces on the LULC map shows that this reading fails in the present setting, and fails at both ends of the range.

Built-up land recorded the lowest ET in the basin, between 5.6 and 6.4 mm day^{-1} in the Sita Basin. On a loss-based reading, this would be classified as favorable for recharge. It is not. ET is low over these surfaces because they are impervious; there is no soil moisture to evaporate and no vegetation to transpire, and for the same reason, there is no infiltration. A low ET indicates a sealed surface rather than a water surplus. Conversely, the forested uplands recorded among the highest ET in the basin, between 7.6 and 8.5 mm day^{-1} , which on a loss-based reading would be classified as poor. These are the parts of the catchment that receive the highest rainfall, have the most permeable soils and the deepest root networks, and generate the recharge on which the rest of the basin depends. A high ET is a symptom of abundant water, not its absence.

The common factor is that ET measures the flux leaving the surface, while recharge depends on the partition of the residual between runoff and infiltration — a partition ET says nothing about. ET is a real and quantitatively important term in the water balance of these basins and should be retained in groundwater potential assessment, but as one input among several, rather than as a proxy for the outcome. Read alongside land cover, soil, slope, geology, and drainage density in a multi-criteria

framework of the kind applied elsewhere in the Western Ghats (Arulbalaji et al., 2019; Moses & Sathiyamoorthy, 2025; Upendra & Sreenivasulu, 2024), the ET layer distinguishes surfaces that are dry because they are sealed from surfaces that are dry because water has been consumed — a distinction that land cover alone does not resolve. When used alone, it inverts the answer.

5.4 Engineering implications

For water resource engineering in this and comparable coastal catchments, three practical uses follow from the results.

The first is the location of recharging structures; The mid-basin agricultural plain ($ET = 6.5\text{--}7.5 \text{ mm day}^{-1}$) is intensively cultivated during the dry season, has a large moisture demand and soils and slopes that facilitate infiltration. It is on the second and third order streams that percolation tanks and check dams catch post monsoon runoff the most. The ET surfaces do not determine the sites but identify where the dry season shortfall that such buildings are intended to cushion is greatest.

Second, abstraction in coastal aquifers needs to be controlled. In the coastal plain, actual ET declines throughout the dry season while reference ET grows, and the expanding disparity is when groundwater is most heavily extracted for irrigation and residential use. Seawater intrusion has already been reported in the shallow aquifers of this district (Dhakate et al., 2020) due to the loss of freshwater head from excessive dry-season pumping. Spatially resolved ET offers the seasonal timing and spatial concentration of demand against which abstraction restrictions and monitoring networks need to be set.

Third, the hydrological model was calibrated. The distributed models used in these basins, including the SWAT applications published for the nearby Kollur Basin (Poojashree et al., 2023), use ET terms typically defined from lumped empirical relationships. The ET surfaces from satellite give a regionally distributed limit on these parameters that improves the reliability of streamflow and recharge projections used to evaluate land use and climate scenarios (Sharannya et al., 2021).

5.5 Internal consistency of the derived energy fluxes

Tables 3 to 8 show net radiation, soil heat flux and sensible heat flux for the same anchor pixels on the same picture days. Therefore, the residual latent heat flux is entirely dictated by Equation (9) and the internal consistency of the retrieval may be directly tested. This was repeated for all sixty-four combinations of anchor-pixels and image-days (Figure 18).

The result is somewhat different for the two classes anchor pixels. For cold pixels, the retrieval behaves as the surface energy balance needs: G/R_n mostly is between 0.09 and 0.48, the residual latent heat flux is positive on 15 of 16 image days in each basin, and the mean evaporative fraction is 0.50 in the Sita Basin and 0.53 in the Swarna Basin, values compatible with well-watered vegetation and open water. The retrieval is not finished on heated pixels. The residual latent heat flow was negative for all 16 picture days in the Sita Basin and for 15 of 16 days in the Swarna Basin and G/R_n values were substantially above unity compared to the physically permissible interval of about 0.05 to 0.40 for natural surfaces. Out of sixty-four combinations, thirty-three provide a negative residual

A negative residual latent heat flux at midday over a dry surface is not physically permissible. These figures thus indicate an error in the tabulated flux components rather than a condition of the basins. The pattern tells the story: the cold-pixel columns are self-consistent, therefore the inconsistency is

confined to the hot-pixel soil heat flux, and the inverted sensible heat flux contrast described in Section 4.7 goes in the same direction. Surface temperature is the numerator in Eq. (7) and is needed in deg C, otherwise using Kelvin would inflate G by about an order of magnitude. Scaling the hot-pixel values correspondingly brings thirty of thirty-two into the permissible G/R_n interval. This is circumstantial and not definitive, but it does identify the computations that need to be verified.

Two consequences follow from the interpretation of this study. First, the daily ET surfaces were scaled through the reference ET fraction anchored on the cold pixel (Equations 10 and 11), and the cold-pixel energy balance was internally consistent; therefore, the spatial and seasonal patterns of ET reported in Section 4.6 rest on the sound part of the retrieval. Second, the absolute flux magnitudes tabulated for the hot pixels and the extreme ET values at the upper end of the mapped range cannot be treated as quantitative. This is the principal reason for reading the estuarine maximum discussed in Section 5.1 as an indication of where evaporative demand concentrates rather than as measured water loss.

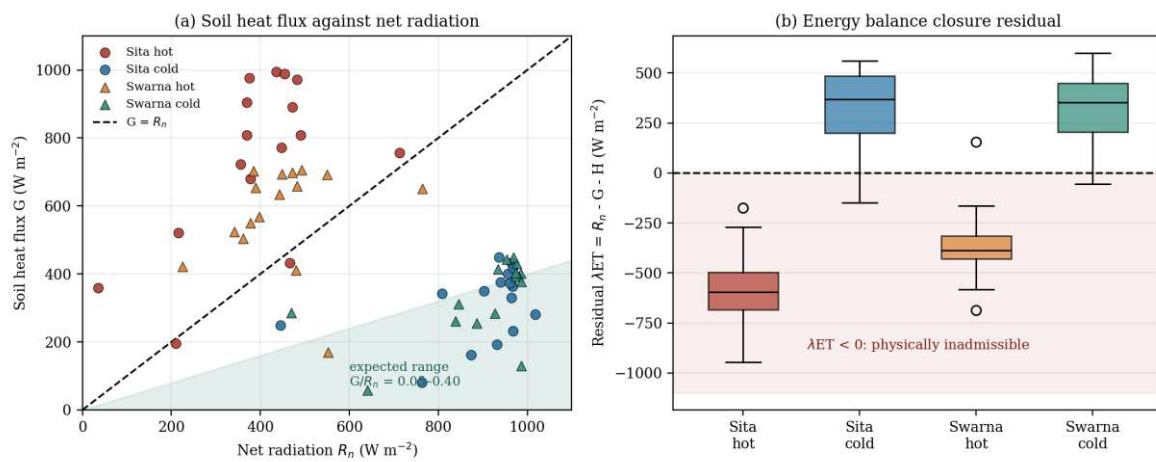


Figure 18. Internal consistency of the tabulated energy fluxes: (a) soil heat flux against net radiation at the anchor pixels, with the shaded band marking the physically expected interval $G/R_n = 0.05\text{--}0.40$ and the dashed line the limit $G = R_n$; (b) distribution of the residual latent heat flux $\lambda ET = R_n - G - H$ by the anchor pixel class.

5.6 Limitations and further work

Four limitations affect how these results should be used, and they are stated here in full because they condition the confidence attached to individual numbers.

The sensible heat flux was represented by a single value for each basin rather than resolved pixel by pixel. Standard SEBAL calibrates the near-surface temperature difference dT as a linear function of surface temperature, anchored at a cold pixel where the sensible heat flux approaches zero and a hot pixel where the latent heat flux approaches zero, and then solves for aerodynamic resistance iteratively. Using a constant instead imposes uniform sensible heat loss across surfaces that differ greatly in roughness and moisture status, and the residual latent heat flux absorbs this error. This is the most probable explanation for the estuarine ET maximum exceeding the reference ET by a factor of four to five and for actual ET exceeding the reference ET on some winter days.

Spatial resolution constrains the surfaces that can be represented. MODIS provides 500 m reflectance and 1 km thermal data, whereas the agricultural parcels, settlement patches, and riparian corridors of the coastal plain are considerably smaller. Mixed pixels are therefore common near the coast and

along the estuary, and the estuarine maximum, in particular, is derived from a small number of pixels that contain both water and land.

Finally, no in-situ ET measurements were available within the basins for direct validation. Agreement with independently computed reference ET and consistency with published SEBAL applications provide indirect support but not the point-scale verification that lysimeter or eddy covariance data would provide. Addressing these limitations through a fully iterative solution for sensible heat flux, fusion of MODIS temporal coverage with Landsat or Sentinel-2 spatial detail, and ground instrumentation across the main land cover classes is the natural next stage of this work. Operational energy balance frameworks currently running on medium-resolution imagery (Pareeth & Karimi, 2023) offer a practical route to the first two of these.

6. Conclusions

The MODIS-based SEBAL model was applied to the humid tropical Sita and Swarna river basins for 2023 and 2024 to map actual evapotranspiration and assess the contribution of mapping to groundwater potential evaluation.

The daily actual ET ranged from 5.6 to 19.66 mm day⁻¹ in the Sita Basin and from 4.01 to 6.01 mm day⁻¹ in the Swarna Basin, with the spatial pattern controlled by topography, vegetation density, and estuarine conditions. The highest values occurred over dense vegetation and the estuary, and the lowest occurred over the coastal plain and built-up land; the estuarine upper bound is affected by the hot-pixel computational artifact discussed below and should be read accordingly. Reference ET computed independently by the FAO Penman–Monteith method ranged from 2.56 to 4.09 mm day⁻¹ in 2023 and from 2.71 to 4.03 mm day⁻¹ in 2024, respectively. Actual ET was greater in winter than in summer for most land cover classes, while reference ET was greater in summer than in winter, confirming that the ET of these basins is limited by the supply of moisture and not by the available energy.

Superimposition of ET surfaces on LULC map demonstrated that ET alone is not a good indicator of groundwater potential in this situation. The lowest ET in the basin is associated with built-up land, which also has the poorest recharge prospects as both depend on the same impermeable cover. The forested uplands have high ET and the highest prospects for recharging, both a function of a plentiful water source and permeable soils. ET is a real and quantitatively important term in the basin water balance and is included in groundwater potential evaluation, but as one criterion in a multi-criteria framework also including soil, slope, geology and drainage density, and not as a substitute for them.

The statistical analysis of the tabulated energy fluxes confirms and strengthens these findings. The differences in albedo, soil heat flux and net radiation between all hot and cold anchor pixels were significant at $p < 0.001$ for 16 independent imaging days, showing that the selection of anchors captured a consistent surface contrast. Seasonal grouping solves a cycle not visible in the individual image days: hot-pixel albedo increases by 30 per cent from winter to summer, post-monsoon sensible heat flux drops to less than half its summer value, and post-monsoon net radiation is much less variable than in the other seasons. The minimum relative humidity and sunshine duration together reproduced the reference ET with $R^2 = 0.978$ and a root mean square error of 0.069 mm day⁻¹, providing a practical two-variable estimator for these basins. A closure diagnostic applied to all sixty-four anchor-pixel and image-day combinations establishes which parts of the retrieval bear

quantitative weight: the cold-pixel energy balance, on which the ET surfaces are scaled, is internally consistent, whereas the hot-pixel soil heat flux is not, and the tabulated hot-pixel magnitudes are accordingly reported as relative patterns only.

In engineering practice, the ET surfaces indicate where dry-season atmospheric demand concentrates and, therefore, where recharge structures and abstraction controls will have the most effect, and they provide a spatially distributed constraint for calibrating basin hydrological models. The flux magnitudes reported here should be read as indicative of spatial and seasonal patterns rather than as absolute values, for the reasons set out in Section 5.5; refining them through an iterative sensible heat flux solution, higher-resolution sensor fusion, and ground validation is a priority for further work in these basins.

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