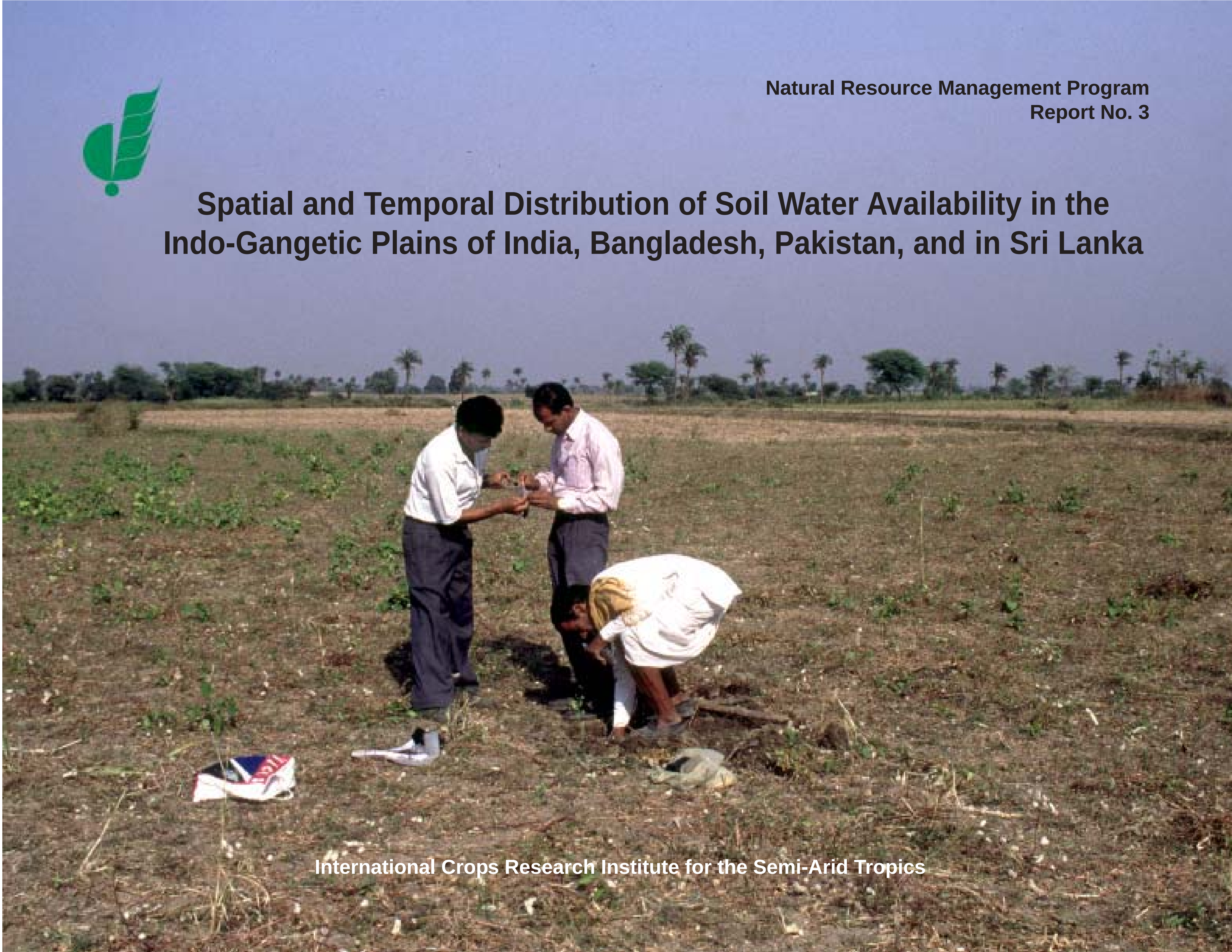
Natural Resource Management Program
Report No. 3

Spatial and Temporal Distribution of Soil Water Availability in the Indo-Gangetic Plains of India, Bangladesh, Pakistan, and in Sri Lanka



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Abstract

Cultivation of legumes, which used to be an important component of the cropping systems in South Asia, has been ignored by farmers growing rice and/or wheat crops, or relegated to marginal lands in recent years. This bulletin contends that greater cultivation of legumes for grain, forage or as green manure in rice and wheat systems can help maintain sustainability of these systems and achieve a required level of crop diversification. As legumes are normally grown rainfed, soil water availability will be a major determinant of their success or otherwise. This bulletin presents temporal and spatial soil water availability scenarios in order to assess the scope for greater inclusion of legumes in the predominantly rice or wheat-based cropping systems of the Indo-Gangetic Plains of India, Bangladesh, and Pakistan and for rice-based cropping systems in Sri Lanka. This has been achieved through the application of a water balance model 'WATBAL' and making use of geographic information systems (GIS) to display and analyze month-wise maps of various indices of soil water availability, and determine length of growing season. The scenarios indicate considerable spatial and temporal variability with respect to rainfall and moisture indices varying from more favorable to less favorable. The water availability scenarios presented in this bulletin are generic in nature and can also be used to assess other rainfed crops besides legumes and refine irrigation scheduling for irrigated crops. These scenarios are based on monthly input of climatic data and therefore could be improved further using daily or weekly climatic data for the target regions.

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Executive Summary

South Asia is one of the most densely populated and poverty stricken regions of the world. The introduction of high yielding rice and wheat varieties with increased inputs of irrigation, fertilizer and chemical pesticides since the 1960s has allowed self-sufficiency of cereal grains in the region. However, a number of soil degradation processes and build-up of pests and diseases are slowing down the increases in crop productivity that have been witnessed in the past. Continuous cereal cropping, at the expense of a diversified cropping system, is considered to be a major reason for this. Cultivation of legumes, which used to be an important component of the cropping systems in the region, has in recent years been ignored by farmers or relegated to marginal lands. The sustainability of rice and wheat systems and the availability of food crops additional to cereals are of crucial concern for food security of the region. This bulletin contends that greater inclusion of legumes for grain, forage or as green manure in rice and wheat cropping systems can help maintain sustainability of these systems and achieve a required level of crop diversification. As legumes are normally grown rainfed, soil water availability will be a major determinant of their success or otherwise. Therefore, temporal and spatial soil water availability scenarios were developed in order to assess the scope for greater inclusion of legumes in the predominantly rice or wheat-based cropping systems of the Indo-Gangetic Plains of India, Bangladesh, and Pakistan and for rice-based cropping systems in Sri Lanka. This was achieved through a linked application of geographic information systems and a water balance model 'WATBAL' to produce month-wise maps of various estimates of soil water availability, and hence potential length of growing season as determined by soil water availability for the target regions. The scenarios indicate considerable spatial and temporal variability with respect to rainfall and moisture indices varying from more favorable to less favorable. In general, outside the main rainy and postrainy seasons, water availability for legumes is very limited. There are, however, opportunities for introducing legumes on regular basis in large areas in Bangladesh and Sri Lanka (2^{nd} rainy season) where fallowing, either during the rainy season or postrainy season, is common and moisture indices are adequate for growing them. In the Indo-Gangetic Plains (IGP) of Pakistan and India, legumes could be introduced either as a rotation crop replacing either rice or wheat at regular intervals; as a catch crop or a summer crop (with irrigation). For assessing the prospects of legumes under rainfed conditions in the IGP countries, the calculation of length of growing season for rainy season crops should be restricted to only for rainy period and should not include moisture storage, which should contribute to postrainy season growing period. The water availability scenarios presented in this bulletin are generic in nature and can also be used to assess other rainfed crops besides legumes and refine irrigation scheduling for irrigated crops. These scenarios are based on monthly input of climatic data and therefore could be improved further using daily or weekly climatic data for the target regions.

1. Introduction

South Asia is one of the most densely populated regions of the world and its population still growing at an alarming rate. It is also one of the poorest regions in the world in spite of rich natural resources in terms of productive soils, good quality surface and ground water, and climatic features permitting multiple cropping. The region suffered perennial food shortages and a very high incidence of poverty prior to 1970s. The development of irrigation potential, and concomitant introduction of high yielding varieties of wheat and rice in the Indo-Gangetic Plain countries (Pingali and Shah 1999) turned the perennial shortages into surpluses. Similar advances in increasing irrigation potential and grain yield of rice were made in rice productivity in Sri Lanka. This made rice and wheat systems in South Asia a major source of income for farmers which eventually increased area under these cereals generally at the expense of other crops, especially of legumes. For example, about three million ha area originally under grain legumes in the Indian IGP went largely to rice and wheat (Kumar et al. 1999). Legumes traditionally used to be a regular feature of the rice and wheat-based cropping systems due to their ameliorative effects. Low yields of legumes, inappropriate crop duration, coupled with high risks of their cultivation due to their susceptibility to pests and diseases vis-à-vis rice and wheat have greatly contributed to reduced cultivated area under legumes (Kumar et al. 1998).

Continuous cultivation of cereals is, however, beginning to have its effect on the fragile agro-ecosystems of these countries and a slow down in their productivity growth is beginning to occur (Pingali and Shah 1999, Kumar et al. 2000). Build-up of salinity and waterlogging, depletion and pollution of ground water resources, formation of a hard pan due to repeated puddling, depletion of ground water in tube-well irrigated areas, decreased nitrogen supplying capacity of soil resulting in declined factor productivity of fertilizer nitrogen (N), and build-up of pests and diseases are some of the major environmental consequences of intensification with these cereals (Hobbs and Morris 1996; Pingali and Shah 1999). Cassman and Pingali (1993) estimated that decline in soil N supply alone can reduce rice yield by about 30% over a 20-year period irrespective of soil N levels. The decline in N supplying capacity occurs due to decline in N from mineralization of organic matter, which meets considerable proportion of N requirement of cereals (De Datta 1981). Continuous cereal mono-cropping and decline in use of organic sources of nutrients such as legumes and organic manure have been suggested to be the major factors responsible for this situation. The area under legumes has declined drastically in many parts reducing not only their potential to contribute to improvement in N economy, but also reduce local availability of these crops. In particular, legumes have potential to improve organic matter and N supplying capacity of the soil (Whitbread et al. 1999), improve physico-chemical properties of saline-alkaline soils (Dhawan et al. 1958), utilize insoluble and fixed phosphorus (P) and make it available for the succeeding crops. Also there is equally high concern about the reduced per capita availability of legume and other important crops.

It has been suggested that if these systems could be diversified with legumes and the related socio-economic and policy issues resolved, the sustainability of these important cereals could be enhanced and the process of land degradation reversed (Sinha 1995; Joshi et al. 1998; Ali et al. 1998, 2000). This would also ensure increased availability of legumes at affordable prices to consumers.

However, there is a need for an assessment of the situations, where these legumes can be introduced into the systems without greatly affecting the productivity of the rice and wheat cropping systems. These legumes generally would be grown under rainfed conditions or on stored soil moisture, as major irrigation input would continue to be reserved for wheat and rice. Invariably therefore, sufficiency or inadequacy of water would be an important factor in determining inclusion of legumes in the rice-and wheat based cropping systems (Khanna-Chopra and Sinha 1989). To assist in determining these situations it is necessary to know the spatial and temporal distribution of soil water availability over the areas that can assist in calculating length of growing season. The lengths of growing season have earlier been mapped for India (Sehgal et al. 1993) and Sri Lanka (Panabokke and Walagama 1974). A recent publication enlists the opportunities of introducing legumes in rice-wheat systems in the Indo-Gangetic Plain countries (Johansen et al. 2000). Sehgal and Mondal (1993) presented a concept of soil moisture regimes and described the methodology used in determining it, its applications and limitations, and presented soil moisture regimes maps for India. They considered soil moisture regimes as a partial function of climate, soil and land form and defined it in terms of number of days soil moisture control section (SMCS) and 1500 kpa. They used SMCS to classify different soils of India and the potential cropping intensity on them. These publications, however, do not provide information on spatial and temporal variability for various moisture availability indices in a GIS format. To match requirements of crop development and physiology, it would be ideal to have the temporal resolution of weekly climate data. However, if limiting, even monthly data can be useful in delineating water availability scenarios. Recent advances in modeling and geographic information systems (GIS) tools can greatly assist in visualizing scenarios. This could be complemented by availability of improved shorter duration genotypes and management techniques for fitting them into narrow cropping windows.

This bulletin describes the methodology and results of generation of soil water availability maps developed through a linked application of geographic information systems (GIS) and water balance models for the rice and wheat based cropping systems of the IGP of India, Bangladesh, Pakistan, and for rice based systems of Sri Lanka in South Asia. The "cell" approach that was used in determining the soil moisture availability required interpolated climate values, of which the available data have monthly temporal resolution. Though, initially developed for legumes, these outputs could also be applicable to rainfed non-legumes, and for irrigation scheduling.

2. Methodology and data

2.1. Methodology

The objective of this application of GIS was to map out spatially and temporally the soil water availability of the target areas – IGP of India, Bangladesh, Pakistan, and Sri Lanka. The approach used was to link GIS techniques with a simple water balance model, WATBAL (Keig and McAlpine 1974). The WATBAL model is not crop-specific and assumes complete crop cover during the season. It operates on a weekly basis and requires inputs of weekly rainfall (R or precipitation), weekly potential evapotranspiration (PE), and maximum water-holding capacity (AWHC) of the soil. The area of interest was decomposed into discrete cells and the water balance model run for each cell. Rainfall, PE, maximum available soil water holding capacity (SWHC) were the inputs for each cell. The model calculated water storage for each cell in each month (the use of one month as the time period was constrained by non-availability of daily/weekly data), as the sum of soil water storage of the previous month plus the rainfall during the month minus the soil water loss as actual evapotranspiration (AE) during the month. AE during the month was calculated as the ratio of AE/PE multiplied by PE. The ratio AE/PE was taken 1.0 as soil water storage varied from 100% to 0%; and decreased linearly from 1.0 to 0 as soil water storage varied from X to 0 %. X is calculated from a square root function, 3+3.868*(SQRT(SWHC)). This fits the three values of X supplied by Reddy (1979): 30, 50, and 70 for soil holding capacities of 50, 150, and 300 mm, respectively.

The computer program (coded in Fortran) used in running the water balance model was developed by P. Jones of CIAT (Centro Internacional Agricultura Tropical), who patterned it after the Basic-Plus example by Reddy (1979). The program was modified to suit the available data.

2.2. Datasets

The available interpolated values of rainfall and PE required for the WATBAL described above, were extracted from the World Water and Climate Atlas (1997) of International Water Management Institute (IWMI). IWMI has compiled the rainfall data from various climate stations located in different parts of the target region. These are monthly long-term means over the period 1961 to 1990, with a spatial resolution of 2.5 arc-minutes (cell size of about 4.5 km). PE values were Penman-Monteith reference evapotranspiration rates.

The values of maximum available soil water holding capacity (determined as difference between amount of water held at field capacity and permanent wilting point) were obtained from the digital soil map of the world (FAO 1995). The soil map of a country comprises different map units, which consist of soil units or associations of soil units. The soil water holding capacities are grouped into 7 classes: W (wetlands); A: > 200 mm; B: 150-200 mm; C: 100-150 mm; D: 60-100 mm; E: 20-60 mm; and F: <20 mm to a meter depth. For wetland areas, no values are given. As explained in the notes included in the FAO soil map, "Water availability to plants grown on Histosols, Gleysols, and Fluvisols was mainly a function of groundwater or surface water levels and flooding. Although, an Smax (soil water holding capacity) value can be deduced for these soils, this was largely irrelevant for practical purposes. Hence, these soils groups are considered here as "wetlands" and therefore no Smax was determined for them. For the purpose of calculating/assigning a value for the soil water holding capacity of the soil map units, the mid-value of the class was used: B – 175 mm, C – 125 mm, D – 80 mm, E – 40 mm, and F – 10 mm. There was no need to assign a value for moisture storage to class A as there were no map units in the countries considered with the A category.

In great majority of cases, a soil map unit consists of more than one component area with different storage capacity classes. The component areas with different storage classes are only indicated as percentages of the total area of the map unit. This causes some ambiguity in the assigning of a value of soil water holding capacity to a soil map unit. Therefore, the area-weighted average was used:

$$SWHC = m_{1*}P_1 + m_{2*}P_2 + m_{3*}P_3 + \dots$$

where m_i is the mid-value of the storage class of the soil association in the soil map unit, P_i is the weight (area / total area) of the soil association, and the sum of P_i's is 1.0. The application of the above formula was straightforward in cases where the soil map unit does not have a wetland component. In map units with wetland, a modification of the formula was used to accommodate the fact that wetlands have no values of soil water holding capacity. Examples of specific calculations are given below.

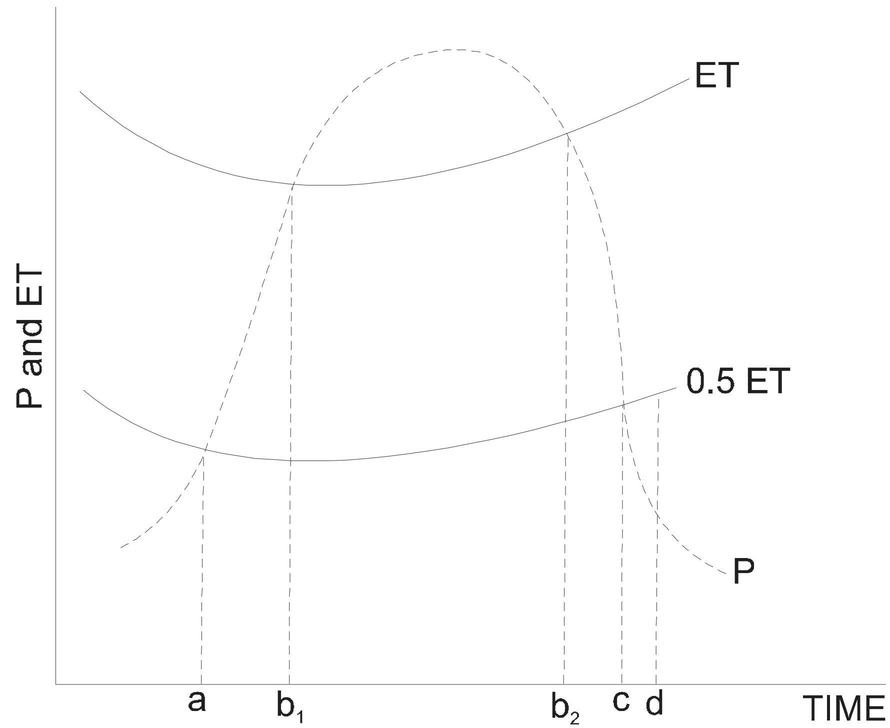
As an example, Table 1 shows the soil map units of Pakistan with the corresponding storage classes and their area percentages. The last column gives the calculated soil water-holding capacity. Of the 36 soil map units, only two are wholly wetlands and four are partially wetlands. The two wholly wetlands soil map units are just assigned the code 0 for purposes of display. The four soil map units which are partially wetlands, with percentages 20 and below, have their soil water holding capacity calculated as follows: ignore the wetland and calculate the area-weighted average for the remaining associations.

Table 1. Soil Water Holding Capacity (SWHC)—Pakistan

FAO Soil Map Unit	Area	W	A	B	C	D	E	F	SWHC
Be70-2/3a	4100	20	0	80	0	0	0	0	175
Be71-2/3a	7283	0	0	90	10	0	0	0	175
Be72-2c	560	0	0	100	0	0	0	0	175
Be72-3c	3663	0	0	100	0	0	0	0	175
Be73-2c	12268	0	0	60	0	0	10	30	125
GLACIER	3685	100	0	0	0	0	0	0	0
I-B-U	9109	0	0	33	0	0	33	34	80
I-B-U-2c	21603	0	0	25	0	0	25	50	40
I-Rc-Yk-c	266058	0	0	50	0	0	0	50	80
I-X-2c	599	0	0	33	0	0	0	67	40
I-X-c	34480	0	0	33	0	0	0	67	40
Jc42-2/3a	38336	100	0	0	0	0	0	0	0
Lo44-1b	136	0	0	100	0	0	0	0	175
Qc47-1/2b	111703	0	0	38	13	0	0	50	80
Qc47-1a	5465	0	0	50	50	0	0	0	175
Qc48-1a	402	0	0	30	70	0	0	0	125
Rc40-2b	11384	0	0	100	0	0	0	0	175
WATER	675	0	0	100	0	0	0	0	175
Xh18-bc	561	0	0	20	0	60	20	0	80
Xh42-2/3a	15685	0	0	100	0	0	0	0	175
Xh43-2/3a	424	0	0	100	0	0	0	0	175
Xk19-2a	6505	0	0	100	0	0	0	0	175
Xk35-2/3a	2302	0	0	100	0	0	0	0	175
Yh26-2/3a	76175	0	0	100	0	0	0	0	175
Yh27-2a	55017	10	0	80	10	0	0	0	175
Yk30-bc	84	0	0	70	0	0	0	30	125
Yk36-2/3a	67741	0	0	40	0	50	0	10	125
Yk39-3a	2186	0	0	70	30	0	0	0	175
Yk40-2/3a	15695	0	0	100	0	0	0	0	175
Yk42-2a	12108	0	0	100	0	0	0	0	175
Zg13-2/3a	1755	10	0	90	0	0	0	0	175
Zg3-3a	3055	0	0	100	0	0	0	0	175
Zg6-2/3a	4657	0	0	100	0	0	0	0	175
Zo27-3a	748	0	0	100	0	0	0	0	175
Zo29-3a	139	10	0	90	0	0	0	0	175

With the soil water holding capacity of the map unit determined, the soil map of the country was converted into a grid with a resolution of 2.5 arc-minutes to match the resolution of the climate data. Thus, each cell now had the values of rainfall, PE and soil water holding capacity—which are required to run the model.

With the data preparation completed, runs of the WATBAL model were performed for each cell in the country. The weekly inputs for the model were generated through interpolation. More cycles of the WATBAL were run on the same data sets to stabilize the simulated initial moisture content. The soil water



a - Beginning of rains and growing period
b_1 and b_2 - Start and end of humid period respectively
c - End of rains and rainy season
d - End of growing period with storage
p - Precipitation
ET - Potential evapotranspiration

Figure 2. Schematic presentation of a typical rainy season characterization

holding capacity for a given soil-mapping unit is an area-weighted average. All values of rainfall or precipitation, dependable precipitation, PE, AE, soil water and soil water holding capacity are in millimeters.

The water availability scenarios derived from water balance model using climatic inputs of rainfall, PE, their definitions and implications are given below:

2.2.1. Rainfall

Information about rainfall (R) for a given environment/region provides a general indication of water availability for crops and helps in development of suitable strategies for agricultural planning and implementation. This is an important input for any water balance model. Rainfall at 75% level of probability level is dependable precipitation (DP) which has been used as an indication of dependable rainfall amount that is amenable to management practices to maximize or optimize benefits (Hargreaves and Samani 1985). Though not attempted in this bulletin, further statistical treatment of rainfall data can provide more accurate information on the amount and distribution of rainfall and reveals valuable information to exploit rainfall data for agricultural planning.

2.2.2. Moisture availability indices

Potential evpotranspiration: Potential evpotranspiration (PE) is defined as the amount of water transpired from an active growing, short, green plant cover (usually grass) with a full cover and a continuous adequate moisture supply (Penman 1948). It indicates potential demand of water at a given location. It is an agroclimatic index and not an evaluation of evapotranspiration taking place at a given time. The amount of water required by a crop could be different at two locations due to differences in PE although the amount of rainfall and its distribution could be similar. PE demand is generally low during cooler months.

Relative rainfall (R/PE): The ratio of R and PE, also known as relative rainfall, can be used to define beginning and end of the rainy season and quality of moisture supply (Fig. 2). The beginning of growing period is taken as when moisture supply from rainfall and storage is equal to half of the PE (Higgins and Kassam 1981). Within the rainy season, a humid period is when R/PE is >1. During this period, R in addition to meeting crops' PE demand, replenishes soil moisture and a part may also be lost as runoff. The time when the R/PE ratio becomes £0.5, is considered end of rainy season. The rainy season crops can draw up to 100-mm soil moisture stored during the humid period. The length of growing period could constitute the length of rainy season plus the period required to evpotranspire 100-mm water, but for multiple cropping situations, it should ideally contribute to the length of postrainy season growing season.

In locations with more than one rainy season, the pattern described above is repeated again.

The minimum water needs of rainfed crops are met if R/PE ratio is ≥0.33 during the establishment phase, ≥0.67 during the vegetative and harvest stages and ≥1.0 during the reproductive stage (Reddy 1993). An R/PE ratio of ≥1.5 indicate waterlogging hazard for rainfed crops, but may be favorable for rice. The difference between PE and R (PE – R) gives and an indication of the extent of deficit in quantitative terms.

Hargreaves (1974) proposed the ratio of dependable presentation (DP) and PE (DP/PE) as moisture availability index (MAI), which is a relative measure of the precipitation available for meeting moisture requirement of crops. It provides an indication of probable effective length of the growing season for rainfed agriculture. Usually, an MAI value > 0.33 for three month is suitable for growing rainfed crops. This has also been used for classifying agro-climatic environments (Hargreaves 1977). An MAI of ≥1.34 is considered a period with waterlogging situation.

Relative evapotranspiration (AE/PE): This is an important water balance parameter calculated by dividing actual evapotranspiration (AE) by PE. Actual evapotranspiration relates to the amount of water evaporated by the soil and transpired by the plants under existing meteorological and soil moisture conditions and crop growth stage. The threshold limits of relative evapotranspiration for the rainfed crops are ≥0.25 for the seeding stage (1 month); ≥0.5 for the vegetative stage (1 to 1.5 months); ≥0.70 for the reproductive stage (1 to 1.5 months); ≥0.5 for the physiological maturity (0.5 to 1 month); and ≥0.25 for harvest maturity (1 month) depending upon the phenology of the cultivar (Reddy 1993). For successful crop production under rainfed conditions cropping pattern (duration and sowing dates) should be adjusted to match these limits. An AE/PE ratio of ≥0.3 is required for establishing rainy and postrainy season crops. An AE/PE ratio < 0.3 for about a month during the vegetative phase and <0.5 during the reproductive phase would result in crop failure unless supplemental irrigation could be provided.

Soil moisture holding capacity and soil moisture storage: Keig and McAlpine (1974) water balance model relates soil moisture extraction to soil water holding capacity under complete ground cover. The soil moisture status of the soil is useful in determining the length of growing season and the prospects of the postrainy season crops. If soil moisture is <100 mm at the end of rainy season, then it is not suitable for postrainy season crops under rainfed conditions; whereas if soil moisture of >200 mm, the season could be considered very favorable for the postrainy season crops. For successful establishment of the postrainy season crops, moisture present in the surface layers should at least be 50 to70% of the field capacity or else there should be a rain event of ≥20 mm.

2.3. Characterization of growing seasons

Rainy season: Rainy season begins with R/PE ratio reaching ≥0.5 and ends with decline to ≥0.5.

Postrainy season: Postrainy season begins when the rainy season ends (R/PE ratio ≤0.5). Postrainy season ends when AE/PE ratio falls to ≤0.2. Rainfed crops use moisture stored during the preceding rainy season, with occasional rain being received during the postrainy season.

Length of growing season: This is a period from the beginning to the end of season. For rainy season the period is considered to be continuous till the difference between PE and R does not increase more than 50 mm.

3. Results and Discussion

The results are indicative of the overall trend in the spatial and temporal distribution of soil water availability in the four countries studied. Region-wise results are described below.

3.1. Indo-Gangetic Plain (IGP) of India

The Indian part of the IGP extends over 21°31' to 32° 20'N and 73° 16' to 89° 52' E and is spread over the states of Punjab, Haryana, Delhi, Uttar Pradesh, Bihar, West Bengal, and small parts of Uttaranchal, Jammu and Kashmir, Himachal Pradesh and Rajasthan (Fig. 3.1). The parts of Punjab, Haryana, hills and plain of western Uttar Pradesh have been referred to as western IGP; parts of eastern Uttar Pradesh as central IGP, and those of Bihar and West Bengal as eastern IGP in this bulletin. The major cereals are rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), pearl millet *(Pennisetum glaucum* (L.) R.Br.), barley (*Hordeum vulgare* L.), and sorghum *(Sorghum bicolor* (L.) Moench). The major legumes that have traditionally been grown in the IGP are pigeonpea (*Cajanus cajan* (L.) Millsp.), black gram (*Vigna mungo* (L.) Hepper), mung bean (*Vigna radiata* (L.) Wilczek) in the rainy season; and chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* Medic.), and pea (*Pisum sativum* L.) in the postrainy season. Mung bean is also cultivated in some pockets in the summer season (Ali et al. 2000). The area under cereals is around 41 million ha and has stabilized over the years. In contrast the area under legumes is <4.5 million ha and is declining.

3.1.1. Rainfall: Most of the rainfall (mm) in the IGP is received during June to September, July being the wettest month with a maximum of up to about 450 mm rain at a given location (Fig. 3.1.1). There is generally more rainfall in the eastern than in the western IGP, especially during June to October period, and it occurs over a longer period than in the western IGP. There is, however, more rainfall in January and February in its western and northern parts than in the eastern part. The periods from October to December in the Western IGP and from November to February in the Eastern IGP receive relatively much less rain.

Figure 3.1.2 gives distribution of dependable presentation (DP). The rainfall (mm) that has a 75% probability of occurrence is received from June to September in the central and eastern IGP and from July to August/September in the western. The maximum monthly DP received is in July in the eastern IGP and gradually decreases to in the western IGP.

3.1.2. Potential evapotranspiration (PE): The monthly PE (mm) depicted in Figure 3.1.3 suggests considerable variation among months and across the IGP. It is very low during January and February and increases gradually during March to June period, and then begins to decline beginning November, and from the western IGP towards the eastern IGP. PE increases from March onwards to peak in May and then gradually declines. The hill regions of the IGP comprising Himachal Pradesh and Uttaranchal generally have less PE. The PE is generally lower in the eastern IGP than in the western IGP during May to October, but are higher or similar in the remaining months of the year.

3.1.3. Relative rainfall (R/PE): A R/PE ratio of >0.5 marks the beginning of rainy period. The R/PE ratio exceeds the 0.5 thresholds for most of the eastern IGP in June and in July in the western IGP (Fig. 3.1.4). These are the months indicating the beginning of rainy season in the respective regions. The R/PE ratio is >0.5 until September in the western IGP and until October in the central and eastern IGP. Thus, in most of the IGP, the R>PE is for about three to four months categorizing it as a dry semi-arid climate. The threshold ratio again increases to >0.5 in December and January to April in Uttaranchal indicating an existence of a second rainy season.

The rainfall exceeds the PE demand for only from July to September in the eastern IGP and from July to August in the western IGP (Figure 3.1.5). As the excess of monthly rainfall over the PE is >200 mm for over two consecutive months in the eastern most IGP, it generally creates a waterlogging situation. There is about >200 mm excess rainfall in the central IGP. In the western IGP excess rainfall is <100 mm and is confined mainly to August; hence there is a net deficit in rainfall in June, July and September. There could be water deficit for well-developed crop canopies in September in the western IGP.

The months when the DP/PE (i.e., MAI) is >0.33 are from June to September in the eastern of the IGP and from July to August in the western IGP (Fig 3.1.6). These are the months when rainfed crops can be established. The MAI is > 1.33 in most of the central and eastern IGP for over two months suggesting that upland crops would need natural or artificial drainage.

3.1.4. Relative evapotranspiration (AE/PE): The ratio of AE/PE is maintained ≥0.3 until November, except in a few districts in the western IGP (Fig. 3.1.7). The AE/PE ratio falls to >0.2 in December, but rises again for most of the western and central IGP from January onwards. In most of the IGP, except in the hills of Uttaranchal, the AE/PE ratio again declines <0.2 in April. These months constitute the postrainy season in the IGP. The AE/PE ratio was <0.2 in May throughout the IGP except in the eastern most IGP and in June in the western IGP and southern parts of central IGP. May and June constitute the summer season in these parts.

3.1.5. Soil water availability: The maximum water storage capacity was about 200 mm in most of the IGP (Fig. 3.1.8). The water storage capacity is less than 50 mm in the hills of Uttar Pradesh. Soil water holding capacity in soils of the IGP are more than a meter deep and, except for the soils of Uttaranchal Hills, can hold an appreciable amount of plant available water (Fig. 3.1.9). Soil water availability generally begins to increase from June onwards and most soils, except in Uttaranchal, store up to about 200 mm water by July. The soil water availability reaches up to 175 mm from July to September in the western IGP and about 150 mm in most areas of the eastern and central IGP. Soil water availability recedes from western to eastern IGP from October onwards, but in the western and northern IGP increases slightly again during January and February when winter rains are received.

3.1.6. Growing seasons:

Rainy season: The beginning of the rainy period is from May in the eastern IGP, June in central IGP and July in the western IGP (Fig. 3.1.10). The rainy period ends in September in the western and central IGP and October in the eastern IGP. The length of growing period (LGP) during the rainy season is about three months for most of the western IGP, four months in the central IGP, and five to six months in the eastern IGP. Four districts in the western IGP adjoining Rajasthan desert had LGP of about two months only.

Postrainy season: The postrainy season commences when the rainy season ends in October in the western IGP, November in the central and eastern IGP. The postrainy season ends with the decline of AE/PE ratio to <0.2. This is in February in the eastern IGP and April in the western IGP. The LGP in this season is determined by the amount of water stored in the soil at the beginning of the postrainy season, the amount of winter rainfall, and PE during the season. Thus, postrainy season LGP is up to 5 months in the western IGP and about 3 months in the eastern IGP. For maximizing yields, the crops being grown should roughly match this duration in the respective zones. The crops would suffer from the terminal stress if their duration is longer than the LGP of the postrainy season.

Summer season: The summer season commences at the end of postrainy season, and AE/PE ratio is <0.2. The duration of summer period is correlated with PE and AE, than the rainfall amount during the summer season. Also, longer the postrainy season, shorter the summer season. The PE demand is very high during this period, and with little or no rainfall soil moisture declines. The cropping during this period cannot be sustained without the supplemental water, as there are little or no rains.

3.1.7. General discussion

The opportunities for greater inclusion of legumes need to be examined in concert with assessment of climatic resources of rainfall, soil moisture storage and PE demand, thermal requirements of the crop and sensitivity to waterlogging. The length of growing season in the rainy season has been considered to include rainy period (R/PE $\geq$0.5) plus additional period required for using about 100 mm stored in the profile (Higgins and Kassam 1981). It appears to apply largely for a single cropping season per year. For more than one season per year, cropping period for rainy season crops should be so adjusted that crops mature soon after the rainy period to enable greater proportion of the stored moisture becoming available for the postrainy season crops. Huda and Virmani (1987) reported that for Patancheru (17^{o}N) environment simulated yield of chickpeas were lower after rainy season sorghum than after a rainy season fallow especially in a low rainfall year. For the postrainy season crops following irrigated rice, the profile may have more moisture even after the harvest rice crop.

Most tropical legumes grown under rainfed conditions have a PE requirement of about 500-700 mm (Muchow 1985). They complete their growth in the rainy season itself, except long-duration pigeonpea varieties, which extend into the postrainy season. Any opportunity where legumes could be included should have at least 500 mm of rainfall, or provision of supplemental irrigation in case of a shortfall. Most of the IGP, however, seems suitable for cultivation of legumes under rainfed conditions during the rainy season.

In the western IGP, the rainfall received is generally sufficient for a raising rainy or postrainy season crops under rainfed conditions by replacing rice or wheat. The inclusion of additional legume crop in rice-wheat sequence as catch crop after rice or after wheat would only be possible with supplementary irrigation. In the western and central IGP, the PE demand at the beginning and end of rainy season is in excess of rainfall. In the western IGP, there was no month when R was greater than PE. This would reduce the possibility of excess water and runoff substantially. There is up to about 60 mm deficit in rainfall in June and up to about 60 mm in September in the western IGP.

Chickpea requires about 110 to 240 mm water to produce 900 to 3000 kg ha^{-1} yields in the postrainy season (Singh and Bhushan 1979). In the western IGP, PE for chickpea ranged from 204 to 280 mm (Sharma et al. 1974). Chickpea crop begins to show stress when extractable moisture falls to <40%. Most soils in IGP would hold <200 mm if a rainy season crop has been grown on them and hence chickpea would suffer some stress towards the end of the rainy season. In some places in the western IGP, a postrainy season crop cannot be established without a supplementary irrigation.

There are several opportunities in the IGP when legumes can be included in both rainfed and irrigated conditions. In the western IGP, the rainy season is of less than three months duration. Traditionally legumes such as mung bean and black gram in the rainy season; and chickpea, pea, and lentil in the postrainy season have been grown in the region. But, most of legumes are unable to provide similar economic returns as rice in rainy season and wheat in the postrainy season (Joshi et al. 2000). Large-scale subsidies on fertilizers and electricity for irrigation contribute to the advantage of the rice and wheat over legumes, but even without subsidies, cultivation of legumes is less profitable than cereal crops (Joshi et al. 2000). There is a possibility of rotating the rainy season rice crop with extra-short- or short-duration pigeonpea in the western IGP. Yadav et al. (1998) indicated that for a legume such as pigeonpea to be economically as remunerative as rice, its yield should be about 2.5 t ha^{-1}. In the last three decades, availability of short-duration cultivars such as UPAS 120, AL 15, AL 201, Manak, Pusa 84, and ICPL 151 pigeonpea has opened up the possibility of cultivating pigeonpea in the western IGP in rotation with wheat. However, the area under short-duration pigeonpea has become stagnant at about 200,000 ha as the existing short-duration cultivars tend to delay sowing of wheat and are less profitable (Ali et al. 2000). Developments of extra-short-duration pigeonpea (ESDP) genotypes such as ICPL 85010 and ICPL 88039, which mature by October end, has opened up fresh opportunity for inclusion of pigeonpea in rotation with wheat (Laxman Singh et al. 1996). In some cases a crop can be established in May with irrigation. ESDP can replace rice or other coarse grain cereals in the western IGP, where rainfall matches its PE and does not require irrigation nor suffers much from waterlogging. The yield potential of ESDP cultivars is about 3.0 t ha^{-1}, but due to faulty production techniques and a number of biotic and abiotic constraints, the realized yields are generally half of the potential. Recent efforts to include high yielding extra-short-duration pigeonpea genotypes in rotation with wheat have been successful in Haryana (Dahiya et al. 2001). There is about 1 million ha area in the northwest IGP that can be brought under extra-short- and short-duration pigeonpea-wheat rotation. There is a need to develop technologies ensuring realization of high yields of legumes to make as remunerative them as the rice crop.

Groundnut-wheat sequential cropping is also an attractive proposition on sandy loam soils and is more profitable than cultivation of maize, pearl millet or sorghum (Jadhav 1990). There is another opportunity of cultivating short season legumes such as mung bean and black gram as catch crops after rice and wheat harvest. However, for this system to succeed, both rice/wheat and mung bean crop will need to be of shorter duration.

Short-season legumes can be grown during the summer season with irrigation after the harvest of the postrainy season crops such as mustard, potato, pea and even after wheat (Ali et al. 2000). Under rainfed conditions, this opportunity cropping is feasible in areas with a second season such as in hills of Uttaranchal or in years with high winter rainfall. Elsewhere, supplementary irrigation is necessary as there is little rainfall and PE is very high. In fact, the cultivation of these crops is already increasing with the availability of mung bean and black gram cultivars resistant to yellow mosaic disease. Already, about 100,000 ha has been covered under summer crops of mung bean and black gram in the states of Punjab, Haryana, and western Uttar Pradesh. As the AE/PE becomes very low crops towards the end of the cropping season, there would be need for supplementary irrigation to raise relative transpiration >0.5 for this system to succeed.

In the eastern IGP, length of the rainy season is 5 to 6 months and waterlogging during the season is very common in lowland areas. Cultivation of extra-short-duration pigeonpea in rotation with wheat has been recommended in this region (Singh 1995; Ali et al. 2000). However, on the basis of scenarios in Figures 3.1.1 to 3.1.10, cultivation of short-duration pigeonpea would be a very risky proposition even on uplands, both due to high chances of waterlogging as well as due to severity of insect pest attack, especially *Maruca* pod borer, due to rains during the reproductive phase in October/November to which pigeonpea is highly susceptible. Extra-short-duration pigeonpea would be even less certain.

In areas where winter rains are received and winters are mild, a postrainy season crop of pigeonpea using *Alternaria* blight resistant cultivars, such as Sharad and Pusa 9, can also be established after the harvest of rice crop, or other upland cereals (Ali et al. 2000). This situation applies in the eastern Uttar Pradesh, northern Bihar and West Bengal. Pigeonpea in this season is safer than in the rainy season, when it sometimes fails due to waterlogging and pest attack. However, for currently available cultivars to produce reasonable yield, sowing within September is necessary. Development of cultivars that are less sensitive to low temperature and can give economic returns in October sowing are needed for wider acceptance of postrainy season pigeonpea system. The other possibility is to include common beans (*Phaselous vulgaris* L.), which can be sown in October.

3.2. Bangladesh

Bangladesh is located within 20°34’ to 26°38’N and 88°01’ to 92°41’E (Fig. 3.2). Of the total 14.85 million ha arable area, legumes are grown in about 0.715 million ha (Sarwar 1995).

Rice (*Oryza sativa* L.) is the major crop grown in the country in about 10.4 million ha. The major pulse crops grown are grasspea (*Lathyrus sativus,* L.), lentil (*Lens culinaris* Medik), field pea (*Pisum sativum* spp.) chickpea (*Cicer arietinum* L.), black gram (*Vigna mungo* (L.) Hepper), mung bean (*Vigna radiata* (L.) Wilczek), and cowpea (*Vigna unguiculata* (L.) Walp.) and they contribute to more than 95% of total pulse production (Gowda and Kaul 1982). Of this, grasspea, lentil, field pea, chickpea, and cowpea are grown in dry winter months (November to March) and contribute to 83% of the legume production. Groundnut (*Arachis hypogaea* L.) is the second most important oilseed crop after rapeseed and mustard. These legumes are largely grown under rainfed conditions, usually without any monetary inputs and their yields are generally low. To meet grain requirements of the country, more area is being brought under rice-rice and rice-wheat (Rahman et al. 2000). As a result, the cultivation of food legumes is being relegated to increasingly marginal conditions and production of some legumes is in fact declining. Any fresh impetus for legume production in better endowed lands in rotation with rice and wheat should ensure that it should not be at the cost of principal cereal crops, otherwise it will be difficult to popularize it. There is an urgent need to have a renewed look at the opportunities in concert with natural resources where these legumes can be incorporated into systems without affecting major production systems. The soil water availability scenarios for Bangladesh are therefore reviewed below.

3.2.1. Rainfall: Major rains (>100 mm per month) in most parts of Bangladesh are generally received from March to October period (Fig. 3.2.1). The amount of rainfall increases up to July and then decreases thereafter. The period from November to March receives less than 100 mm monthly rainfall. Monthly rainfall is highest in the northeastern Sylhet region (>1500 mm in June and July) and lowest in the northwestern parts (100 to 200 mm). The total annual rainfall varies from 1500 in the northwestern parts to 6800 mm in the northeastern part of the country.

Figure 3.2.2 depicts the distribution dependable rainfall. Significant rains are received in eastern Bangladesh from March to October with a peak in July. The maximum monthly DP occurs in the northeastern region, in Sylhet. The country does not receive appreciable DP during November to March.

3.2.2. Potential evapotranspiration (PE): The monthly PE depicted in Figure 3.2.3 suggests considerably high PE demand from March to May. PE is lowest in December followed by January and November. The maximum monthly PE of 160-175 mm is in the mid-western Rajshahi, Pabna, and Jessore districts in April and May.

3.2.3. Relative rainfall (R/PE): The precipitation in much of Bangladesh is generally more than >1.5 times PE from July to September (Fig. 3.2.4). The ratio is between 1.0 and 1.5 in

October in the western Bangladesh. The ratio declines to <0.5 from November to April. From May onwards the R/PE ratio is more than >1.0.

Rainfall generally meets the PE demand or is in excess from May to October (Fig. 3.2.5). Rainfall is less than PE from November to April, except in northeastern Sylhet region where R is more than PE from April onwards. The difference in PE-R is largest in the western region in the dry months.

The moisture availability index is >0.33 for the eastern part of the country from April and throughout the country from May (Fig. 3.2.6). The MAI is >1.34 for the entire country from May to September indicating a high probability of waterlogging for legumes in areas with poor drainage. MAI becomes <0.33 from November to March indicating that rainfed crops during this period have to largely rely on stored moisture.

3.2.4. Relative evapotranspiration (AE/PE): Except for February and March the AE/PE is conducive for crop growth (Fig. 3.2.7). The AE/PE ratio declines to ≤ 0.2 in February and March for most of Bangladesh.

3.2.5. Soil water availability: Soils of Bangladesh hold about 200 mm water in up to 1 m deep profile (Fig. 3.2.8). The water storage capacity of soils is up to 175 mm in the Chittagong region and in Sylhet.

The soil water availability in the wettest months (June to October) is up to 200 mm and declines thereafter (Fig. 3.2.9). The country's eastern part covering Sylhet and Chittagong has up to 200 mm water from April to October. The soil water availability recedes earlier in the western Bangladesh from November onwards. However, in January and February there is still some water in the soil profile.

3.2.6. Growing seasons:

The beginning of rainy period is from March in the Sylhet region, April in the mid-country region, and May in the western parts comprising Rajshahi and Dinajpur area (Fig. 3.2.10).

Rainy season: The length of rainy season is nearly six months in the northwestern parts, seven months in the central parts of Bangladesh and eight months in the eastern Sylhet and Chittagong region. The season is therefore long enough to take two crops either after *aus* rice or before *aman* rice.

Postrainy season: The postrainy season begins with the end of rainy season in October in most of the country. The postrainy season continues up to February when AE/PE ratio drops down to ≤0.2.

Summer season: The summer season commenced at the end of postrainy season for a period AE/PE ratio is ≤0.2. The PE demand is very high during this period, and with little or no precipitation soil moisture declines. Generally, AE/PE ratio is ≤ 0.2 from February onward in most of the Bangladesh.

3.2.7. Discussion

According to a conservative estimate, Bangladesh need to produce about 1.8 million ton of legumes, whereas only 30% of its requirement is currently produced within the country (Sarwar 1995). It is difficult to increase legume production by increasing area at the cost of principal cereals, but can be achieved by introducing legumes during the fallow periods wherever soil moisture availability is sufficient or by increasing productivity.

The amount and the distribution of rainfall in Bangladesh not only meet the PE demand for a greater part of the year but also create some runoff. There is a single rainy season followed by a postrainy season. However, “pre-monsoon” rains occur during March to May, enough to allow some rainfed cropping. Rice is principal crop in both the seasons wherever water is available, but rice-wheat cropping system is also gaining popularity (Rahman et al. 2000). The opportunities where legumes can be included are largely in areas where no crop is generally taken after the rainy season ‘*aman*’ rice crop. Such areas mainly lie in northwestern (e.g., Barind) and coastal areas (Raisuddin and Nur-E-Elahi 1984). Nearly 0.8 million ha of land in the high Barind remains fallow during winter, and if only 10% of the area is brought under chickpea cultivation, it may double chickpea production (Kumar et al. 1994). These areas receive <100 mm monthly rainfall during postrainy season and thus suitable for raising cool season food legumes such as chickpea. Similarly, in Faridpur, Rajbari, Kustia, Meherpur, Chuadanga, Jessore, Rajshahi, and Pabna districts, lands are fallowed after cultivation of broadcast aus/jute in high lands. There is plenty of moisture in the soil and AE/PE ratio is favorable for growth. However, chances of waterlogging and diseases are also high. A waterlogging- and disease-resistant short-duration crop, particularly mung bean and black gram could be cultivated. There is also a possibility of growing legumes in Bogra, Rangpur and Dinajpur districts with addition of micronutrients such as boron, and molybdenum.

Although, the present calculations indicate minimum soil moisture availability in the north-west of the country in Jan-Feb, recent studies have shown that considerable soil moisture can be retained below 20 cm, in soils of the High Barind Tract at least, during this time (Ali 2000). This can be utilized by deep rooted crops and as chickpea, provided the crop establishes well and other potential constraints are managed (Musa et al. 2001). Therefore, deeper rooting cool season food legumes and other deep rooting rainfed crops have potential in the north-western region. Mung bean, sown in Jan-Feb, is being increasingly grown in southern coastal areas, where rains in

March and April can support its growth (Rahman et al. 2000). Groundnut is increasingly being grown, and has further potential, in lands emerging from the receding river waters (char lands) during the winter period. Black gram has been traditionally grown on receding soil moisture of the silty flood plain soils of Chapai Nawabganj district in the northwest and other parts of the country. The crop is sown as river water recedes in Sep-Oct. It has been proposed that 'Rabi' (postrainy) pigeonpea could be intercropped with black gram by sowing it at the same time (Rahman et al. 2000). As initial pigeonpea growth is slow, and it would reach maturity after harvest of black gram, the two crops would be complementary with each other to better exploit the abundant soil moisture.

3.3. Pakistan

Pakistan is located within 24^o 37' to 36^o 95' N and 60^o 75' to 75^o 44'E (Fig. 3.3). Of the total geographical area of 79.6 million ha about 20 million ha is presently under cultivation. Approximately 80% of the country's arable area is irrigated, and the remaining is rainfed (Haqqani et al. 2000). Most of the food requirement of the country is met mainly from rice and wheat. Grain legumes are also cultivated in about 1.5 million ha area to meet the protein needs of the population. Legumes are mostly grown in Punjab, and to some extent in Sind, Northwest Frontier Province (NWFP), and to a very little extent in Baluchistan province. Due to over-dependence on irrigation to grow rice and wheat crops, some areas are getting degraded due to the build up of salinity, and the negative balances of major mineral nutrients, even when recommended doses of N and P are being applied. Wheat yields are particularly low after a rice crop (Byerlee et al. 1986). The declining yields from this cereal-cereal cropping system are a major concern for maintaining food self-sufficiency in Pakistan. There are currently 0.85 million ha under rice-wheat cropping system in Punjab and 0.56 million ha in Sind (Zia et al. 1992). A need for greater inclusion of legumes in the Pakistan agriculture is therefore being increasingly recognized both to meet increasing demand of legumes as well to arrest the process of soil degradation, (Haqqani et al. 2000). As legumes are likely to be grown under rainfed conditions, it is imperative to characterize water availability scenarios for the country to identify niches where legumes could be included into the existing cropping systems without jeopardizing the production of principal crops that provide food security to the country. The water availability scenarios for the country are described below.

3.3.1. Rainfall: Pakistan receives up to 800 mm of annual rainfall. The northeastern parts of the country receives more rain than the southwestern part (Fig. 3.3.1). Rainfall is mainly received during July to September followed by relatively dry October to December. During the subsequent months, some winter rains are received in the northern regions.

The dependable rainfall is received only in July and August in the Punjab region and February and April in the northern part (Fig. 3.3.2). The southern and southwestern parts do not receive dependable rainfall in any month.

3.3.2. Potential evapotranspiration (PE): The monthly PE (mm) depicted in Figure 3.3.3 suggests considerably high PE demand from April to September. Monthly PE is highest, at 150-250 mm in May and June and lower, at 0-125 mm per month, in December, and January-March for the Punjab Province. The southern province of Sind generally has higher PE in any given month than the rest of the country.

3.3.3 Relative rainfall (R/PE): In the north-eastern province of Punjab, the R/PE ratio exceeds the threshold ≥0.5 for the commencement of rainy period from July to August and in North West Frontier Province (NWFP) and Northeastern provinces from December, and January to April (Fig. 3.3.4).

Rainfall generally meets the PE demand in the month of December, and January to April in NWFP, which is very cold, and in July and August in Punjab (Fig. 3.3.5). In rest of the country, the PE is generally more than that of R, especially during April to October. The monthly difference between the PE demand and the R is >240 mm in the May and June month in its southern Province of Sind.

The months when the MAI is >0.33 were July and August in Punjab and from January to March in the NWFP (Fig. 3.3.6). Except in March in NWFP, MAI does not increase above 1.34, and were generally less than 0.33 for rest of the country indicating existence of a generally arid climate.

3.3.4. Relative evapotranspiration (AE/PE): The ratio of AE/PE is maintained ≥0.3 in Punjab till October (Fig. 3.3.7). AE/PE ratio falls to <0.2 in May in most of the country, except the northern most part of NWFP, and remains less than this until July. These months constitute the summer months. AE/PE ratio is favorable for rainfed crop production from August to October in the Punjab Province.

3.3.5. Soil water availability: Agricultural soils in Pakistan are mainly alluvial and vary from clayey to sandy soils. The maximum water storage capacity is up to 200 mm in Punjab (Fig. 3.3.8).

Clay loam and sandy loam soils are more common. Soils in Punjab hold up to 200 mm water in July and August and to some extent in September (Fig. 3.3.9). For rest of the periods the water availability is rather low, especially in Sind.

3.3.6. Growing seasons

Rainy season: The beginning of rainy period is from July in Punjab (Fig. 3.3.10) and NWFP. In much of the Baluchistan and Sind, except in its southernmost part (beginning July), there is no pronounced rainy period. The length of rainy season in the Punjab and southernmost areas of Sind is about two to three months beginning July.

Postrainy season: The postrainy season commences when the rainy season ends in September/October in the Punjab and continues until April next year. Thus, the length of postrainy season is up to six months in the Punjab, which is much longer than the rainy season. The postrainy season ends with the AE/PE ratio declining to <0.2. This is in May in the Punjab.

Summer season: The summer season commences at the end of postrainy season for a period AE/PE ratio was ≤0.2. The PE demand was very high during this period, and with little or no precipitation soil moisture declined. Generally, AE/PE ratio was ≤0.2 from May to July in the Punjab Province, and most of the Sind, Baluchistan, and North West Frontier Province.

3.3.7. General discussion

Pakistan imports considerable amount of pulses, spending precious foreign exchange. Increasing legume production is not only required to sustain rice and wheat yields, but also to meet domestic shortfalls. The rice-wheat cropping sequence is largely practiced in Punjab and Sind, hence need for crop diversification, especially involving legumes (Woodhead et al. 1993; Haqqani et al. 2000). The water availability scenarios for Pakistan provide clear indication that the rainy season rainfall is generally minimal and falls short of the PE requirements for most of the rainfed crops. The moisture availability index is above >0.33 for only about two months in Punjab and not even for one month in Sind, suggesting it to be a generally arid climate (Khan et al. 1991). Thus, under the rainfed conditions only legumes with very short growing seasons such as mung bean, black gram, and fodder legumes can be grown. These legumes have traditionally been grown in this season, but their productivity is very low when rainfed, and they have been unable to compete with rice if irrigation is available. In many rainfed areas of Punjab and Sind, mung bean-wheat or black gram-wheat and groundnut-wheat are common.

There is longer, up to six month, and favorable growing season available during the postrainy season in most of the Punjab. The cool season food legumes such as chickpea and lentil can be grown in lieu of a wheat crop. In areas where no further cereal cropping is planned, legumes such as chickpea and lentil are planted to exploit residual moisture. Lathyrus is sometimes planted as a relay crop in the standing rice crop for fodder purposes, especially in Sind. As in the case of the western IGP of India, there is a need to explore the opportunities of using legumes as a catch crop between the rice and wheat. This should be attempted through the use of slightly shorter duration rice crop, followed by a catch crop of legume and finally wheat. Lack of major rainfall events during the rice season, especially in September, permits shorter duration rice without the serious risk of it being caught in rains. Legumes such as mung bean and black gram can be established as a relay crop. Already a rice-pea-wheat system is practiced in some parts of Sheikhupura and Gujranwala (Haqqani et al. 2000). In some parts, lathyrus is established between rice and wheat crops in a similar manner and used as a green manure.

There is awareness to grow legumes in the summer season such as mung bean after wheat harvest and before rice transplanting (Haqqani et al. 2000). This, however, requires substantial amount of water and cultivars that are photoperiod insensitive and heat tolerant. As there is little prospect of rain and soil moisture storage, a minimum of two to three irrigations are required for crops to succeed in this season. There is also scope for growing green manure crops, but high labor costs and shortage of irrigation water restrict the cultivation of green manure crops during the summer season.

The water availability scenarios in the country suggest that soil water availability remains very low throughout the year and inclusion of legumes in current cropping systems can be encouraged only if their production is remunerative (Haqqani et al. 2000).

It needs to be emphasized that much of agricultural land in Pakistan is irrigated, and this provides additional available soil water after rice or wheat (or cotton) compared to what comes from rainfall (or snow in north). There would always be stored water at the end of rainy season to raise a postrainy season crop. The low AE/PE ratio depicted in the Figure 3.3.7 would be higher, especially if there would be an input of irrigation during the postrainy season.

3.4. Sri Lanka

Sri Lanka is located between latitudes 5°54’ to 9°54’ N and longitudes 79°39’ to 81°53’ E. (Fig. 3.4). The arable area of the country has been divided into wet (0.85 m ha), intermediate (1.2 m ha) and dry (4.17 m ha) zones. Rice (*Oryza sativa* L.) followed by rice, and rice followed by a fallow are the major traditional cropping systems practiced in the country. There is a need to diversify rice-rice systems for greater cropping system sustainability and the sources of income generation. The wet and intermediate zones cover low-country (<300 m mean sea level) and mid-country (300-900 m mean sea level) and up-country (>900 m mean sea level). The vast dry zone has an altitude of <300 m mean sea level. The low country is flat or undulating, while the mid- and up-country varies from undulating, through rolling, hilly and steeply dissected to mountainous.

The important legumes grown are mung bean, cowpea, black gram, and groundnut. In recent years, efforts have been made to popularize pigeonpea to substitute imported lentil, but the expansion of the area under the crop has been rather limited because of cheaper imports of lentil. The development of shorter duration varieties of pigeonpea, mung bean, black gram and groundnut, and better production technologies have created fresh opportunities to increase legume production and therefore diversifying rice-based cropping systems in Sri Lanka. This effort requires reconsideration of moisture availability scenarios and identification of opportunities for including legumes into the cropping systems (Nayakekorala et al. 2000).

3.4.1. Rainfall (R): The monthly rainfall (mm) scenario given in Figure 3.4.1 suggests that there are rains throughout the year in one or other parts of the country. The rainfall in large parts is essentially bimodal. The first smaller peak is in May and another peak, which is characterized by more intense rainfall and is widespread, is in October. There is least rainfall in February. The intensity of monthly rainfall varies from 5 to 400 mm. Rainfall is generally more in the southwestern wet zone of the country, and relatively less in the dry and intermediate zones of the northern parts of the country.

Dependable rainfall is received from April to June (with first peak in May) and again from September to December (with a peak in October) (Fig. 3.4.2). The maximum monthly dependable rainfall (up to 300 mm) is largely confined to a small area in the wet zone in southwestern Sri Lanka. The dry zone of the country receives much less DP from January to March and June to September, whereas the wet zone receives DP almost throughout the year.

3.4.2. Potential evapo-transpiration: The PE demand depicted in Figure 3.4.3 suggests considerably high monthly demand from March to May, which gradually decreases until September. The PE is higher in its northeastern parts than the southwestern parts. The PE is lowest in November-December. The maximum monthly PE for most of the country is in March.

3.4.3. Relative rainfall (R/PE): The scenarios of R/PE given in Figure 3.4.4 suggest that large parts of the country have a R/PE ratio of ≥0.5 throughout the year. Only in April to August the northernmost districts have R/PE ratio ≤0.5. The R/PE ratio is ≥0.5 for the entire country from October to December.

Rainfall generally meets the PE demand or is in excess from October to December in whole country and from April to December in the wet zone of the country (Fig. 3.4.5). Rainfall in the southwestern part is generally more than the PE for most part of the year, but less in northeastern dry zone parts except for period from October to December, when R is much in excess of PE indicating possibility of runoff and waterlogging for the sensitive legumes.

The moisture availability index is <0.33 for most of the country from January to March (Fig. 3.4.6). During April to

August MAI is >0.33 in the southwestern and southeastern parts. From October to December, MAI of most of the country is ≥0.33 and in some areas ≥1.34 continuously for several months. The wet zone has MAI of ≥1.34 for April to June and from September to December. These areas would be unfit for legumes without adequate provision of drainage.

3.4.4. Relative evapo-transpiration (AE/PE): The scenario given in Figure 3.4.7 suggests that the ratio of AE/PE is ≥0.3 for most months except the northern and northeastern areas in April and June to September. AE/PE ratio is more >0.3 throughout the year for the southern and central parts of the country comprising wet and intermediate zones.

3.4.5. Soil water availability: The soil water holding capacity is generally less than 180 mm for most soils (Fig. 3.4.8). Small areas with soils having <100 mm water holding capacity is also present throughout the country. The maximum water storage capacity of soils in the northern and central parts is up to 175 mm.

The soil water availability (mm) scenario is quite heterogeneous varying both due to soil as well as rainfall pattern (Fig. 3.4.9). The soil water availability is about 200 mm from October to December and gradually declines thereafter until April from the mid-western side of the country. Soil water availability increases again towards the intermediate and dry zone from April onwards.

3.4.6. Growing seasons:

Long rainy season: Rainfall in Sri Lanka is essentially bimodal. The major rains (*Maha* season) begin in September to October in most of the country. The season beginning October is up to four month long in the dry northwestern zone and up to six month long in the intermediate zone (Figure 3.4.10). This is the major cropping season for growing rice in wetlands and other crops in upland areas.

Short rainy season: This season is also called '*Yala'* season in Sri Lanka. This season begins in April in most part of the dry and intermediate zone in the north-central country and lasts up to 2 to 4 months. The amount of rainfall received in this season is less, and generally low and PE is high. Rice crop requires frequent irrigation in this season, and only drought resistant legumes can be grown in this season under rainfed conditions.

3.4.7. General discussion

The cultivation of crops in rainfed conditions depends upon the choice of crops, optimizing use of current rainfall and moisture stored in the soil profile. In Sri Lanka, where agriculture has been historically associated with development of irrigation systems and irrigated rice culture, the quest for using every drop of rain that falls on land for the production of crops is no less strong. In an excellent analysis of rainfall pattern in Sri

Lanka, Panabokke and Walgama (1974) outlined the strategy on the selection of sowing dates and match the rainfall resources by choosing crops whose moisture requirements match the periods of probable moisture supply. The analysis is largely based on rainfall data records of a few stations. In the present scenario analysis a countrywide picture is presented.

About two third of the total rainfall is received during *Maha* Season. The intermediate zone receives about 2000 to 2700 mm rainfall and dry zone 1000-2000 mm rainfall. Presently, cultivation of legumes is widespread on uplands in *Maha* Season, although the area under them is much smaller than under rice. The areas closer to the Colombo in the southwestern parts are wet areas where rainfall is received almost throughout the year and always exceeds PE. The rainfall from October to December in many areas is not only sufficient to meet PE demand but also creates considerable runoff. Therefore, these areas are ideal for growing rice. In other areas with hilly, undulating slopes especially in the dry zone, however, there would be insufficient water for rice either because of low rainfall or limited ability of rice to exploit soil moisture stored in the profiles. In such areas, deep-rooted crops such as legumes and coarse cereals such as maize can be grown under rainfed conditions. In recent years, there have been attempts to introduce pigeonpea (*Cajanus cajan*) in these upland areas (Saxena 1999) to provide a substitute for the imported lentil (*Lens culinaris*) for local consumption. Pigeonpea develops a deep root system, and thus is capable of effectively using moisture stored in the soil profile (Chauhan 1993). However, due to very humid conditions for 3 to 5 months beginning October, pod borers such as *Maruca vitrata* and *Helicoverpa armigera* populations increase considerably and are difficult to control. Hence, the efforts to introduce pigeonpea in the *Maha* season have not succeeded.

Other legumes such as cowpea and mung bean are grown in this season on a limited scale due to their low yields. More than 20% of the groundnut crop is grown in *Maha* season due to more assured rainfall. Some areas with minor irrigation schemes are also being brought under groundnut cultivation. However, lack of substantial domestic consumption hampers further expansion of the area under this crop.

Rice is the first choice as a crop for Sri Lankan farmers, there is sufficient water available. The development of irrigation command areas since 1930 have created opportunities for taking a rice crop even in the second rainy (*Yala*) season beginning April/May when rainfall is less than PE in the dry and wet zones. However, with more areas being brought in under irrigation, often there is insufficient water to ensure irrigation in all the areas beyond the *Maha* season (Nayakekorala et al. 2000). This presents an opportunity to grow legumes in the *Yala* season in rotation with rice. Cultivation of short-season legumes has been advocated in such areas

(Panabokke and Walgama 1974; Nayakekorala et al. 2000). Presently, there are about 280,000 ha of rice fallows in the *Yala* season compared to cultivation of legumes in about 15,000 ha (Nayakekorala et al. 2000). Cultivation of legumes in rice fallows is generally increasing, except in some districts due to the incidence of insect pests and diseases and introduction of more remunerative crops such as chili and onion (Nayakekorala et al. 2000). Chauhan et al. (1999) found extra-short-duration pigeonpea yields better than Chili and onion, and other short-season crops such as mung bean, black gram, cowpea, and sesamum under rainfed conditions in the *Yala* season. There exists a similar potential for groundnut in rice fallows especially on sandy soils in the coastal areas in the southern parts of the country. Thus, the real scope to diversify rice based cropping systems exists only in the *Yala* season.

4. Summary and conclusions

The spatial and temporal presentation of major climatic parameters along with soil water availability and crops, evaporative demand using water balance model is the unique feature of this bulletin attempted for the first time for major rice and wheat growing areas of the Indo-Gangetic Plain countries and of Sri Lanka. This takes stock of water deficits, adequate and normal water supply situations, and characterization of growing season and their length. The relative transpiration ratio provides indication of quality of moisture supply, whether adequate or insufficient. We believe that the monthly resolutions of these parameters, though may appear insufficient for detailed assessment, would be easier to comprehend than weekly data. A more accurate assessment would require higher resolution datasets, spatially and temporally, and a more accurate water balance model than that used in this study. A primary limitation of this is that it assumes complete ground cover, which may bring error in estimation of soil moisture storage in the early stages of crop growth and has no crop specificity. Monthly input of weather data available has been interpolated to run the model. A suggestion has been made in the bulletin for not including period required for depletion of 100 mm moisture storage in the length of rainy season (as proposed by Higgins and Kassam (1981)) as it generally applies to single crop cycle and may not apply to irrigated rice fallow situations. However, in multiple cropping situations, it is important that stored moisture should be made available for the postrainy season crops. The length of rainy season crops should be so selected that they mature as the rainy season ends so that moisture stored in the profile is used for postrainy season crops. There are a number of situations in Bangladesh (Barind area) and Sri Lanka (rice fallows in the 2nd rainy season) where fallowing is common. Moisture availability during the fallow period permits cultivation of other crops. However, for IGP of India and Pakistan, options of catch cropping between rice and wheat crop either before wheat or after wheat with supplementary irrigation and crop rotation seem more practical. The maps given here are generic for all crops (WATBAL is not crop and stage specific) and although the focus of this bulletin is on legumes, the maps may be applied on any rainfed crops, and even to irrigation scheduling of irrigated crops.

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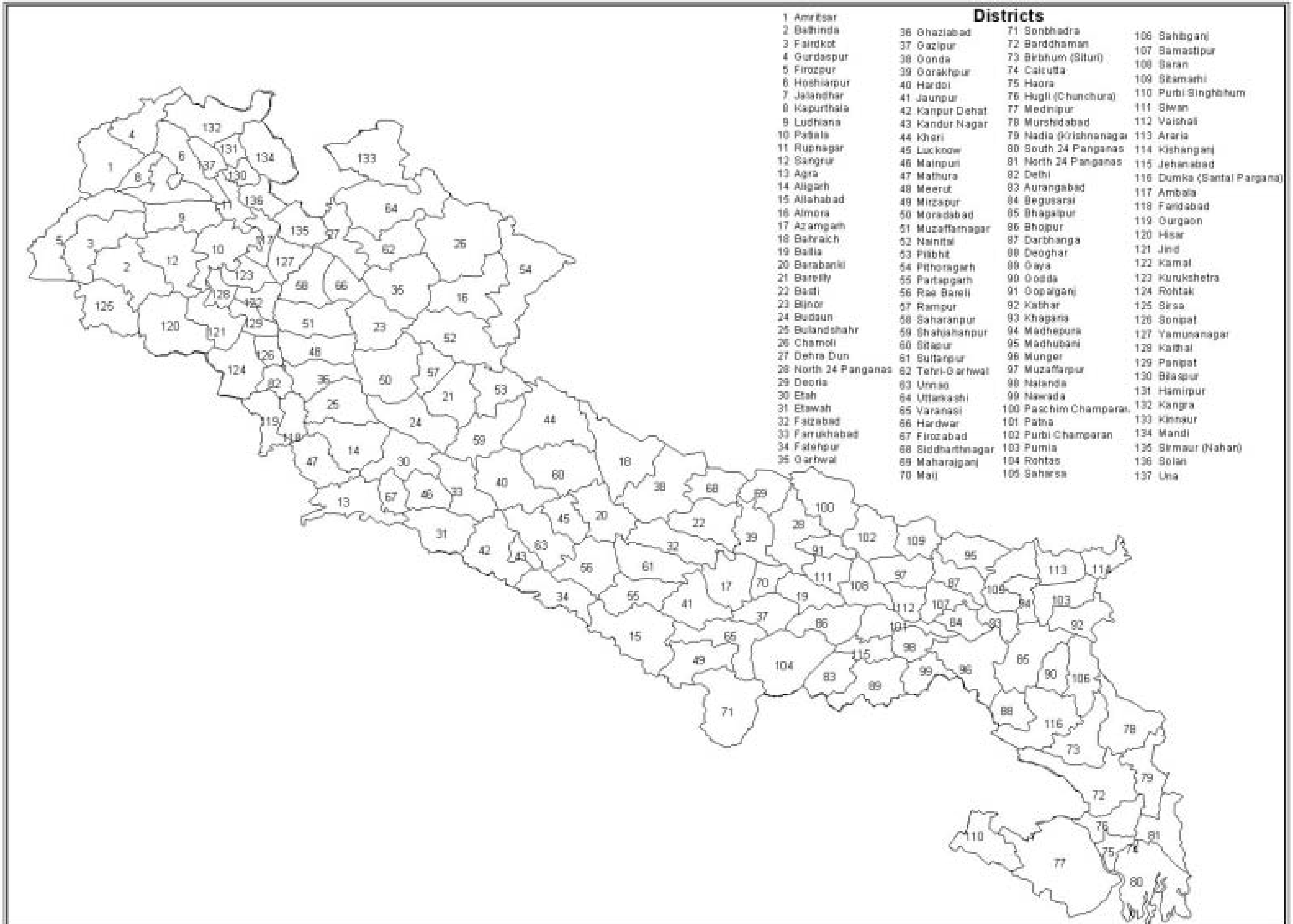


Figure 3.1. Administrative map of Indo-Gangetic plain.

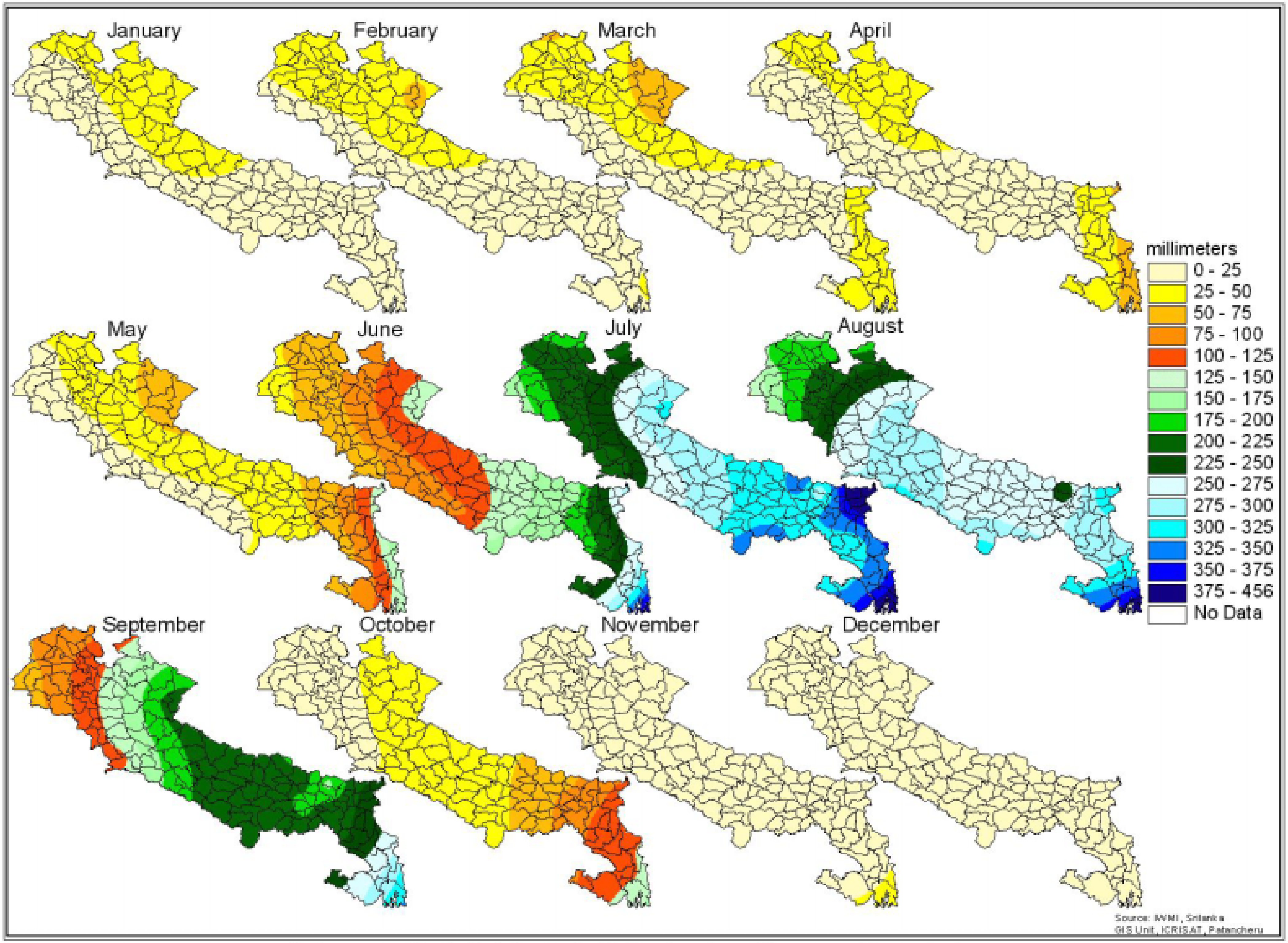


Figure 3.1.1 Rainfall in Indo-Gangetic plain

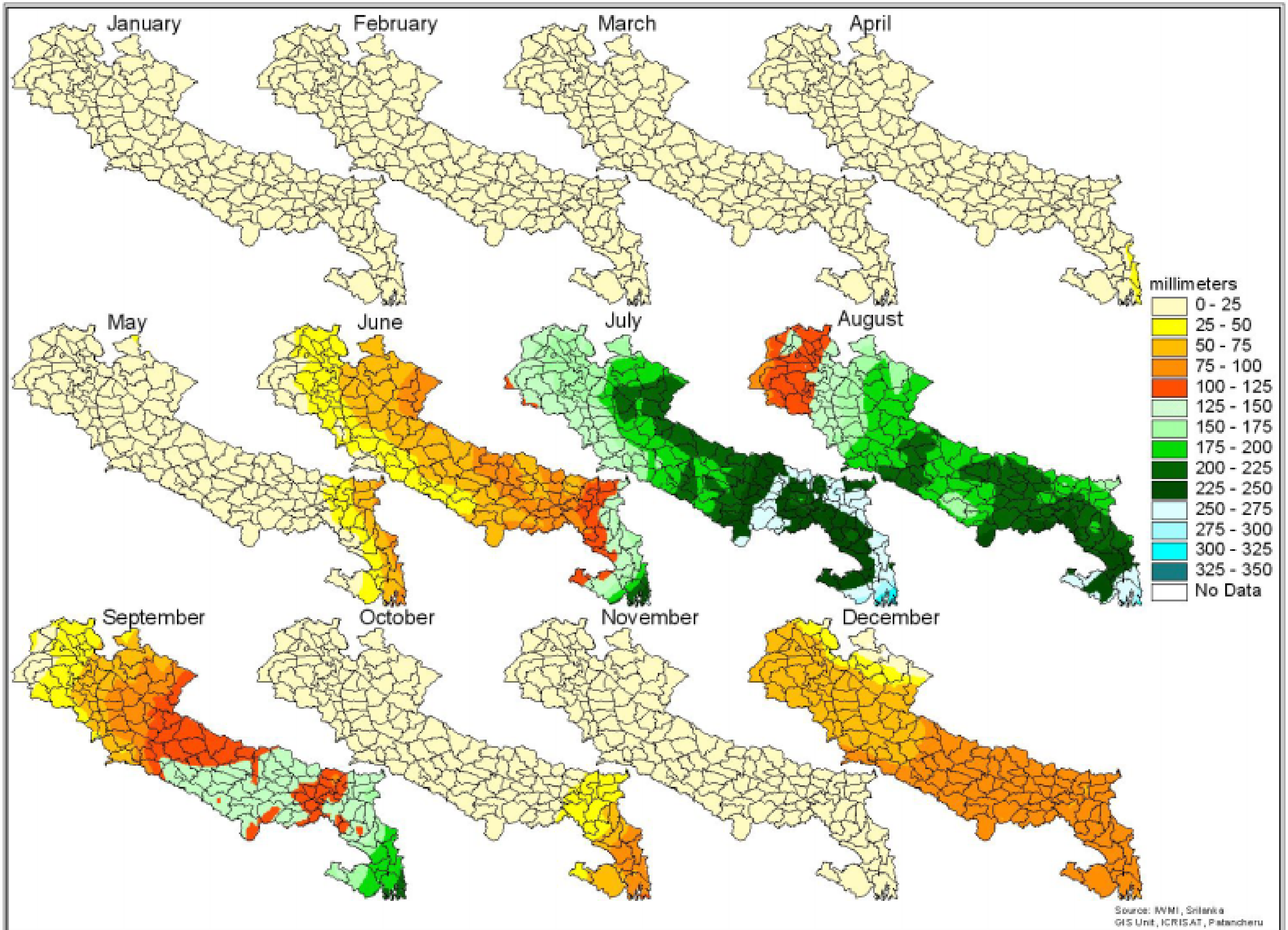


Figure 3.1.2 Dependable precipitation in Indo-Gangetic plain

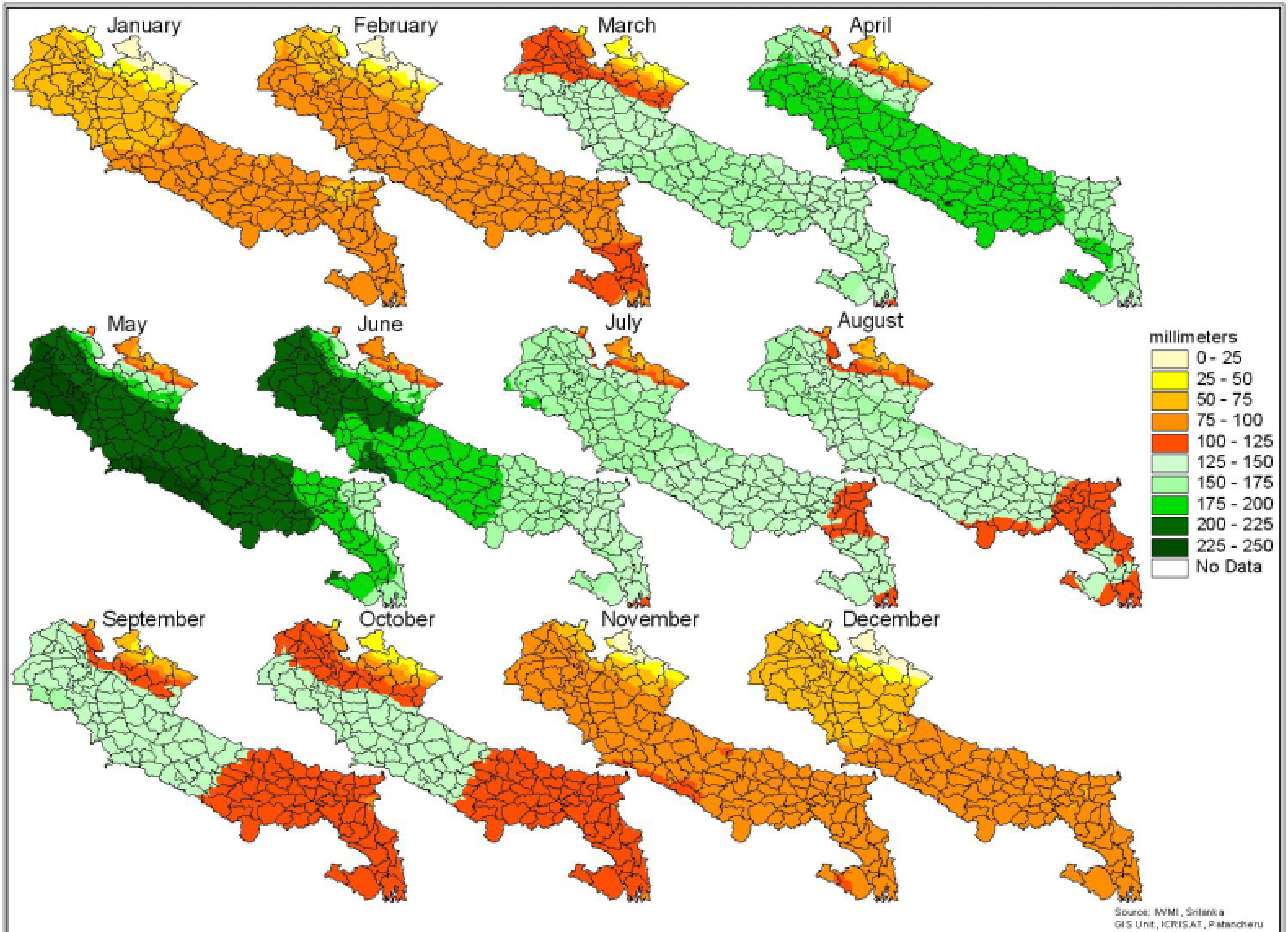


figure 3.1.3 Evapotranspiration in Indo-Gangetic plain

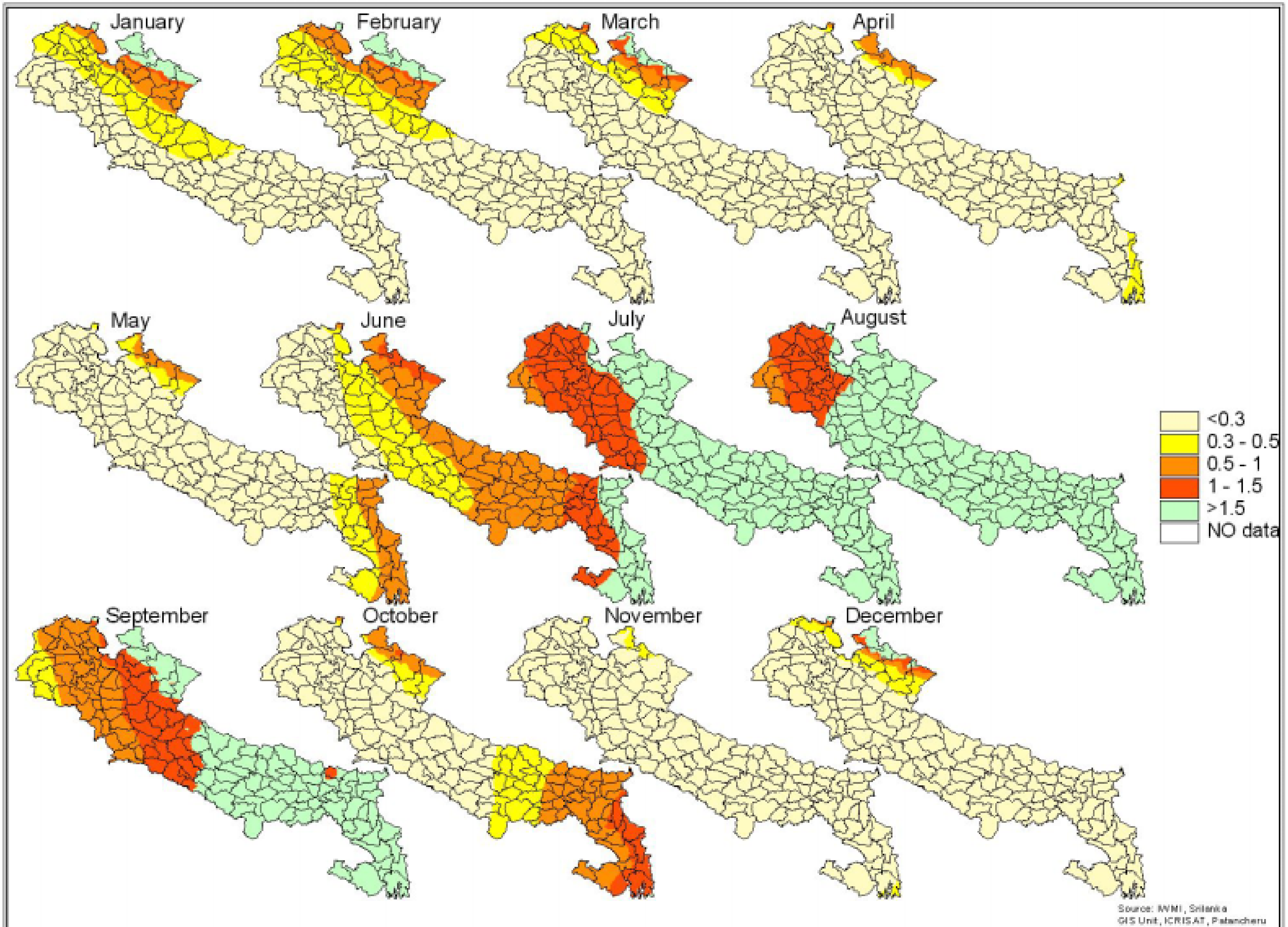


Figure 3.1.4 Precipitation / Potential evapotranspiration in Indo-Gangetic plain

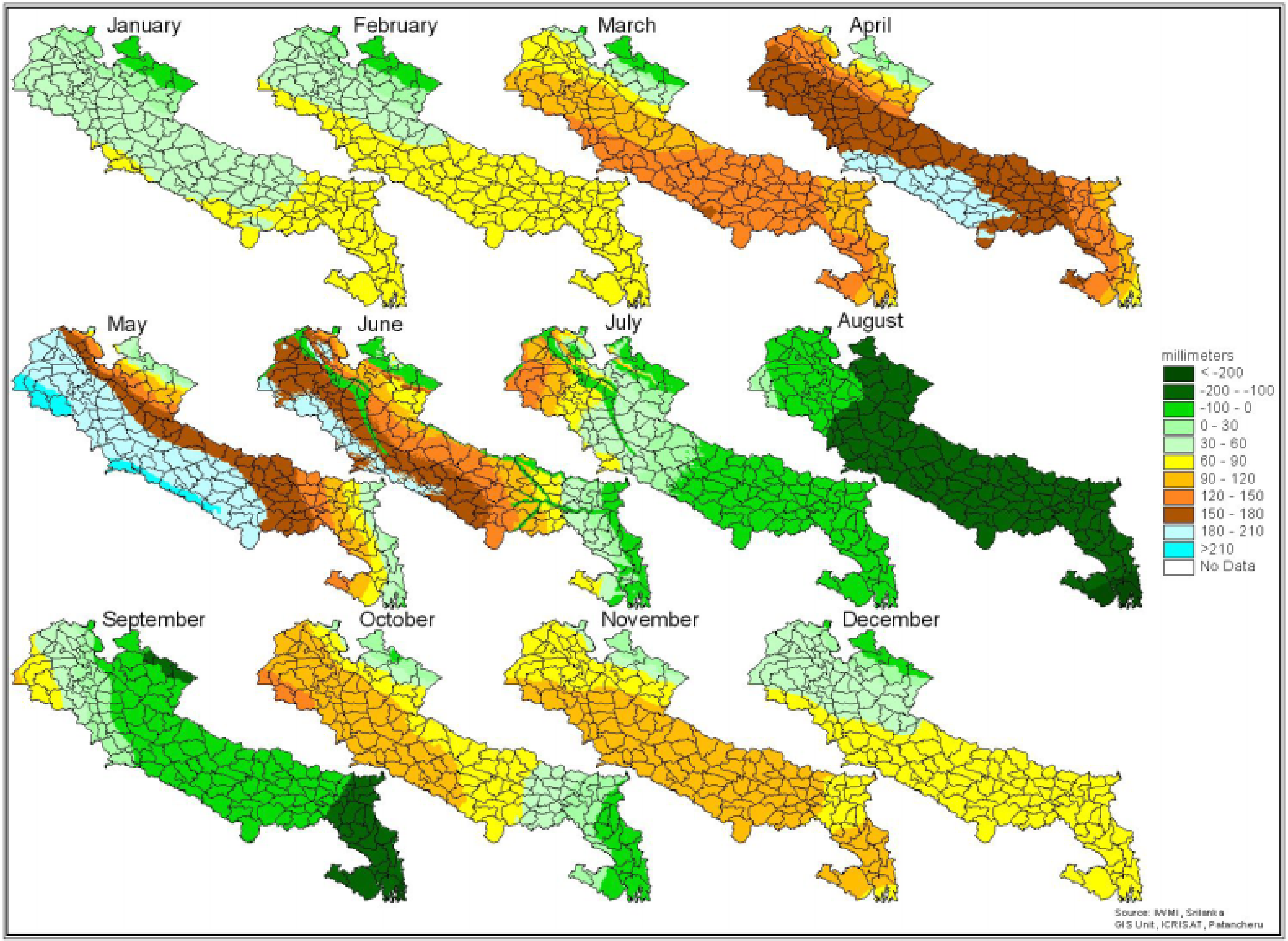


Figure 3.1.5 Potential evapotranspiration - Precipitation in Indo-Gangetic plain.

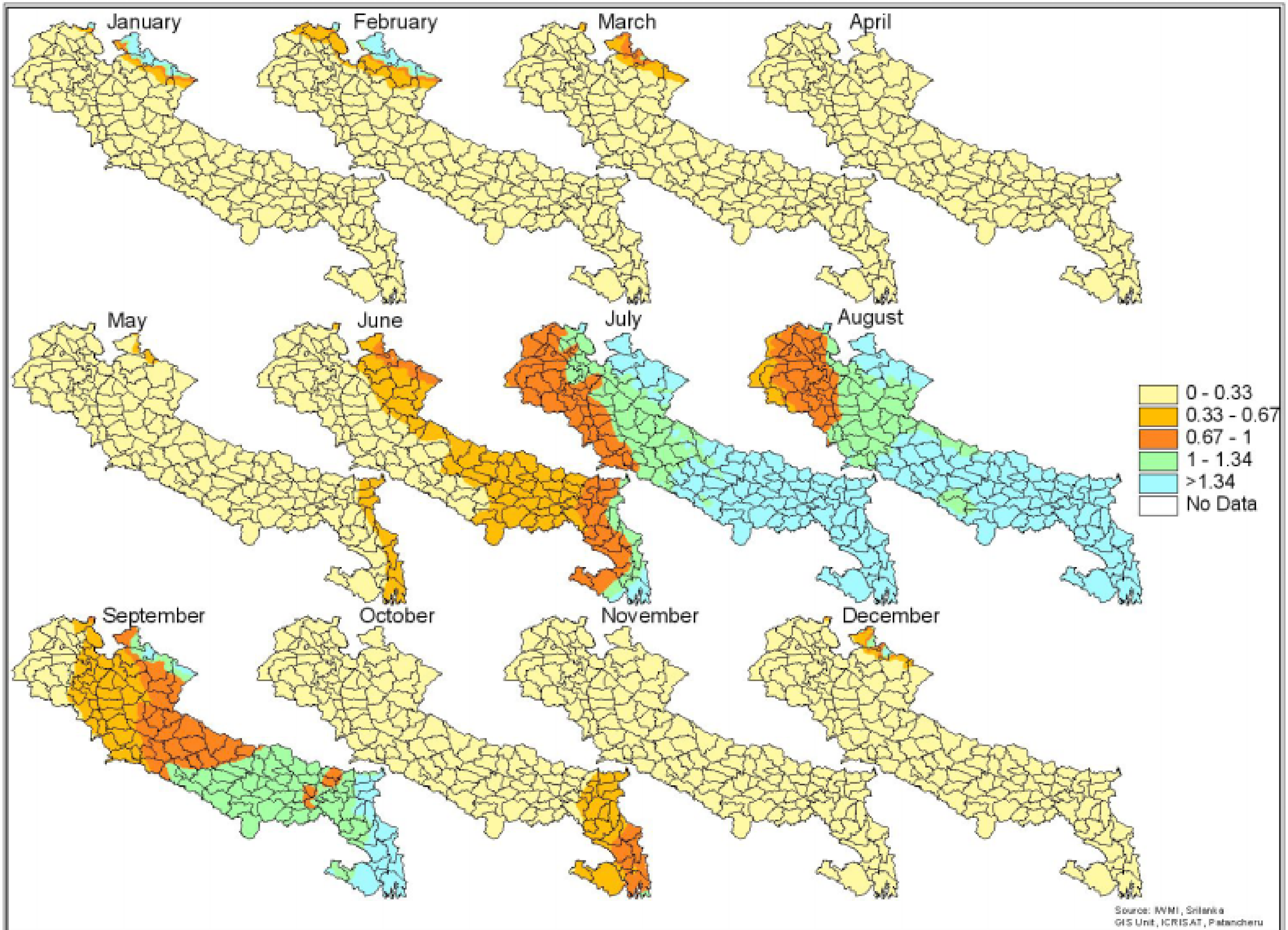


Figure 3.1.6 Moisture availability index in Indo-Gangetic plain.

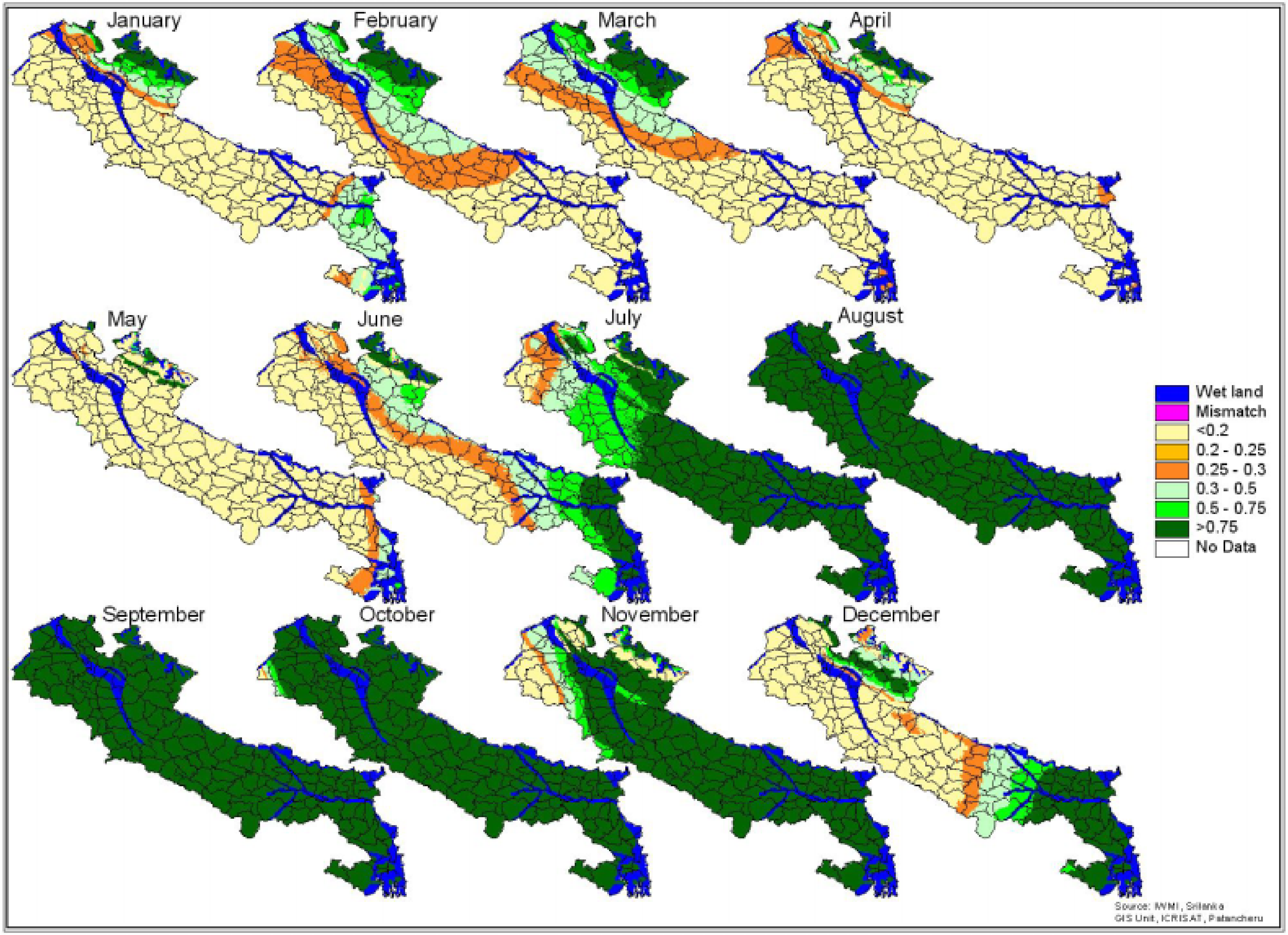


Figure 3.1.7 Actual evapotranspiration / Potential evapotranspiration in Indo-Gangetic plain.

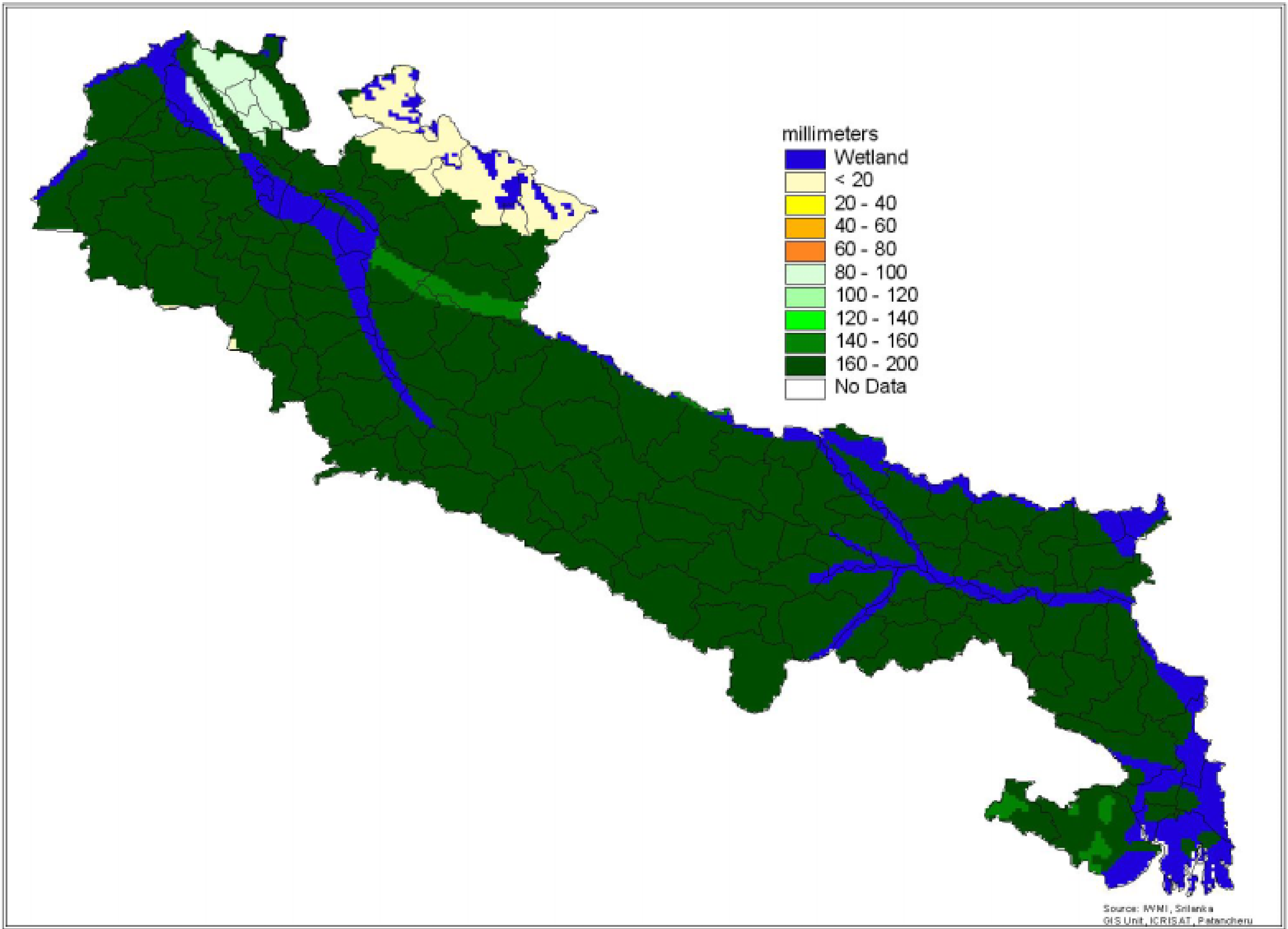


Figure 3.1.8 Soil water holding capacity in Indo-Gangetic plain.

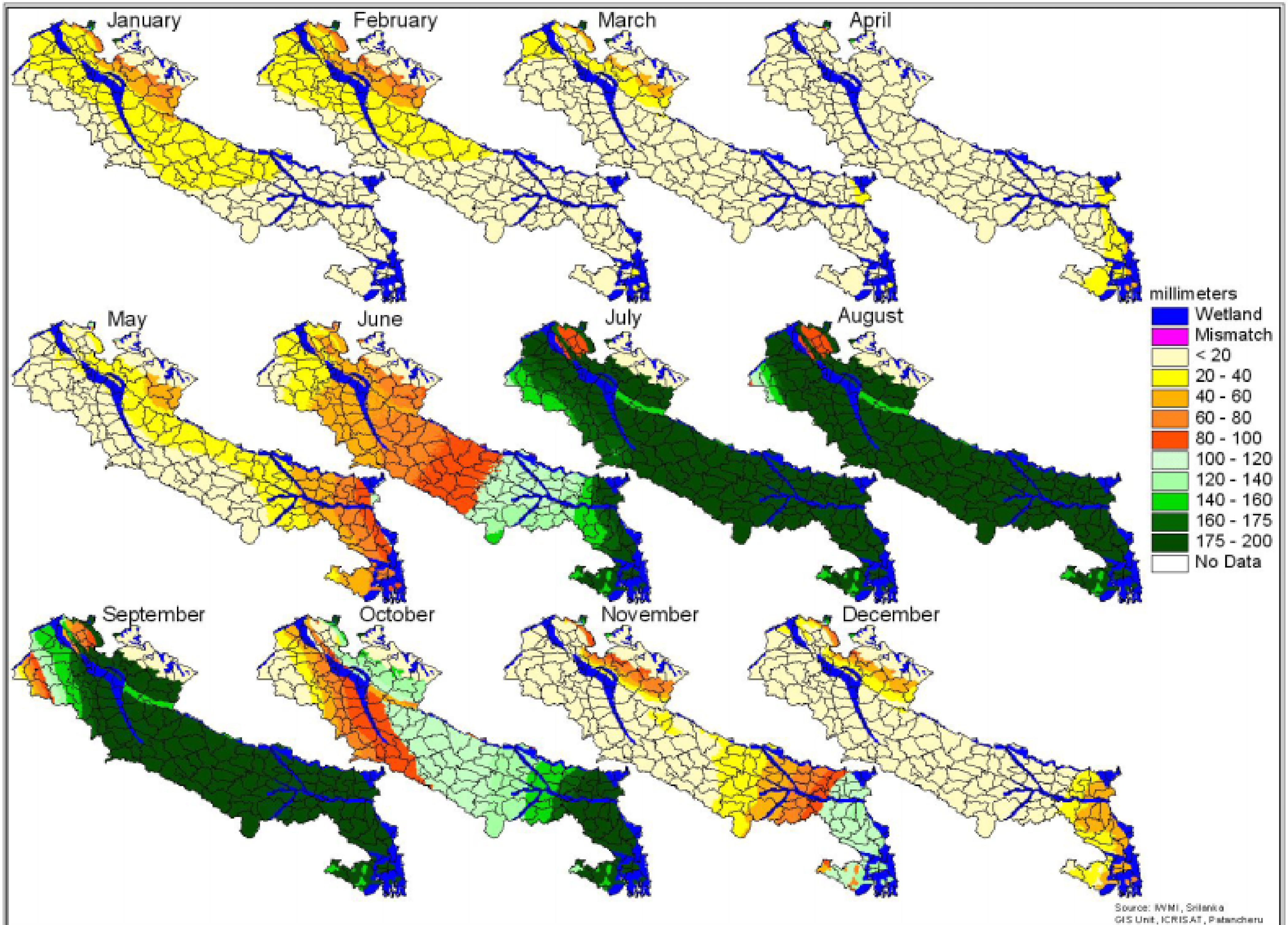


Figure 3.1.9 Soil water availability in Indo-Gangetic plain.

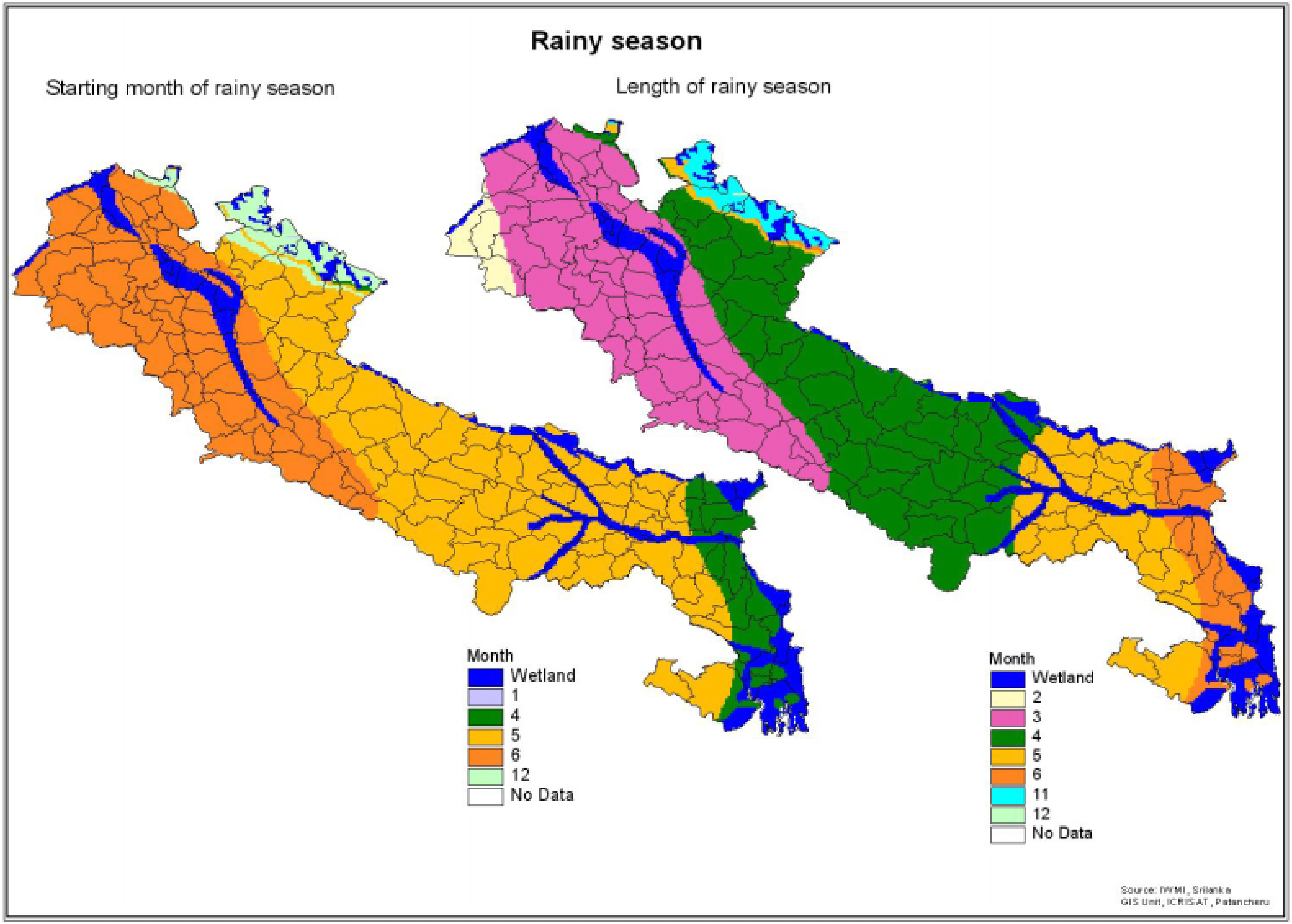
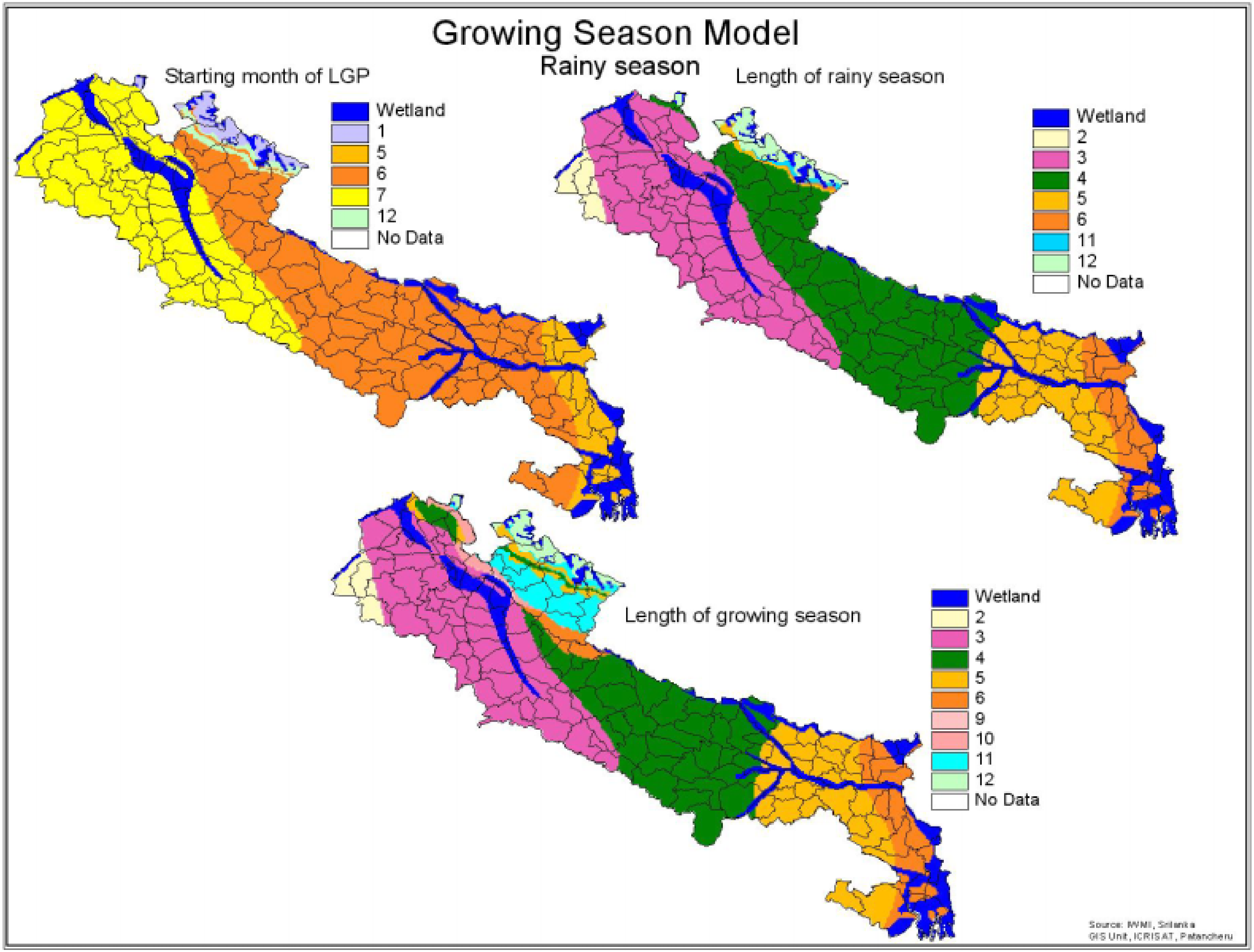


Figure 3.1.10 Precipitation / Evapotranspiration model, Indo-Gangetic plain.


Growing Season Model
Rainy season
Starting month of LGP
Wetland
1
5
6
7
12
No Data
Length of rainy season
Wetland
2
3
4
5
6
11
12
No Data
Length of growing season
Wetland
2
3
4
5
6
9
10
11
12
No Data
Source: IWMI, Srilanka
GIS Unit, ICRISAT, Patancheru

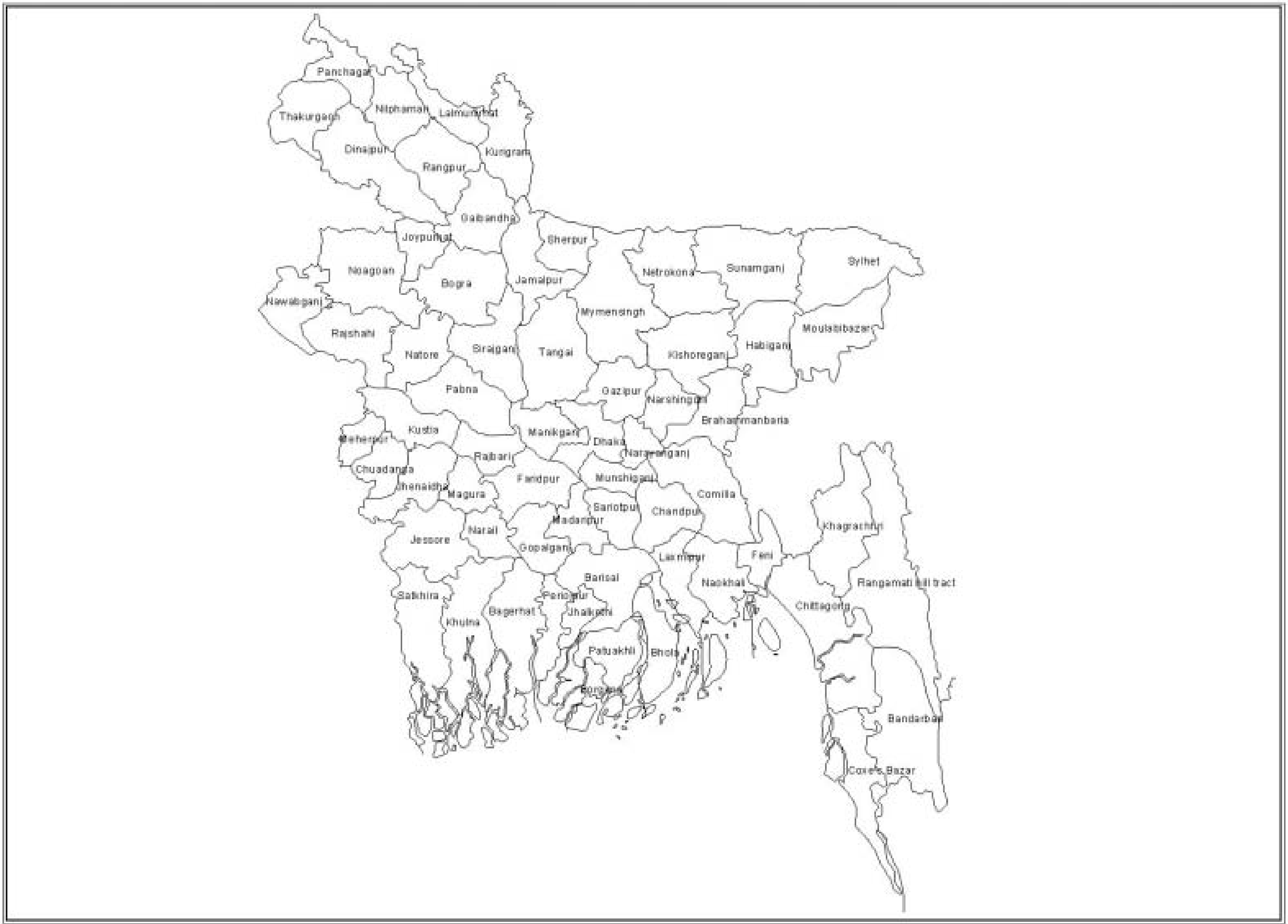


Figure 3.2 Administrative map of Bangladesh.

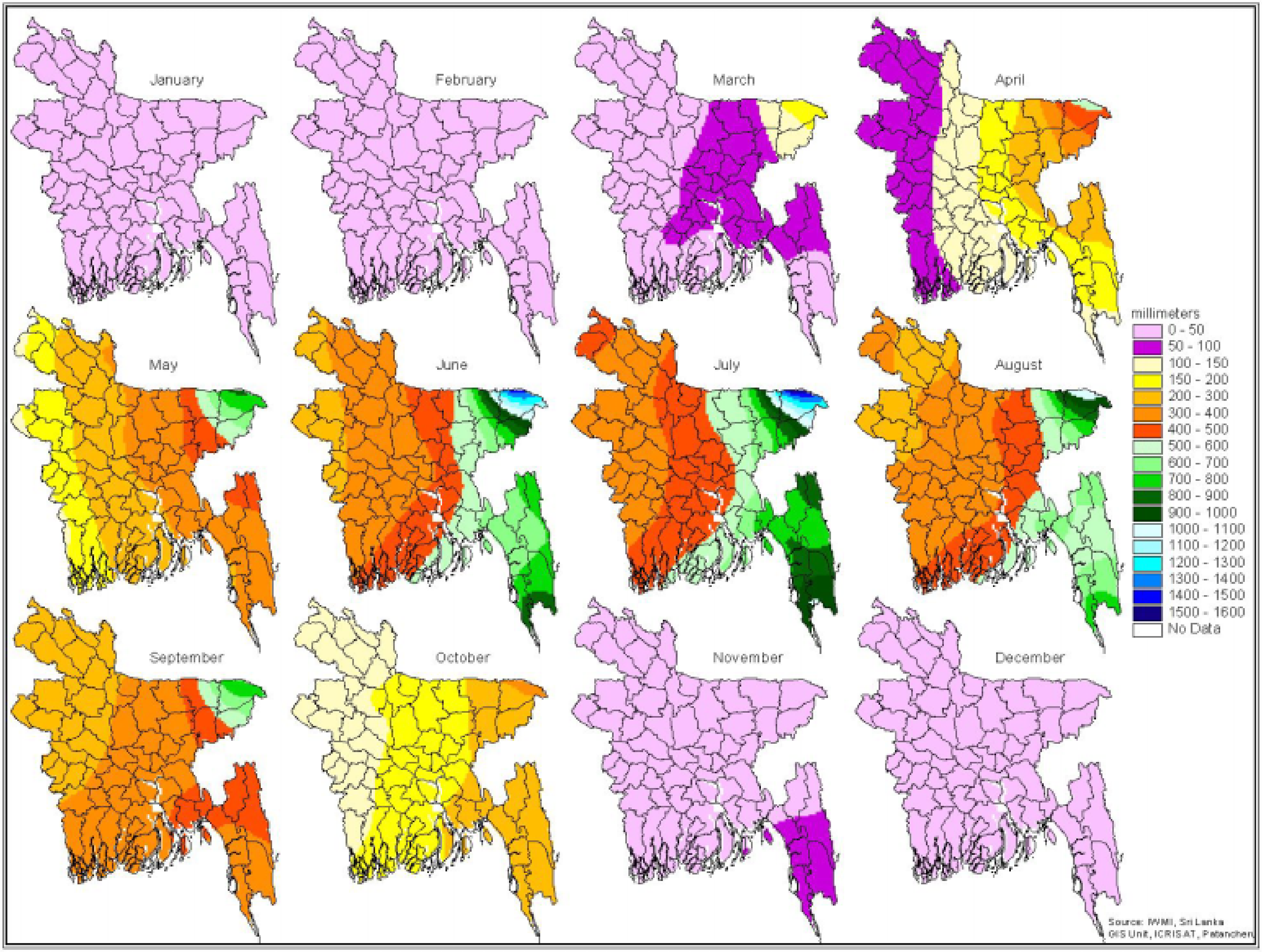


Figure 3.2.1 Rainfall in Bangladesh.

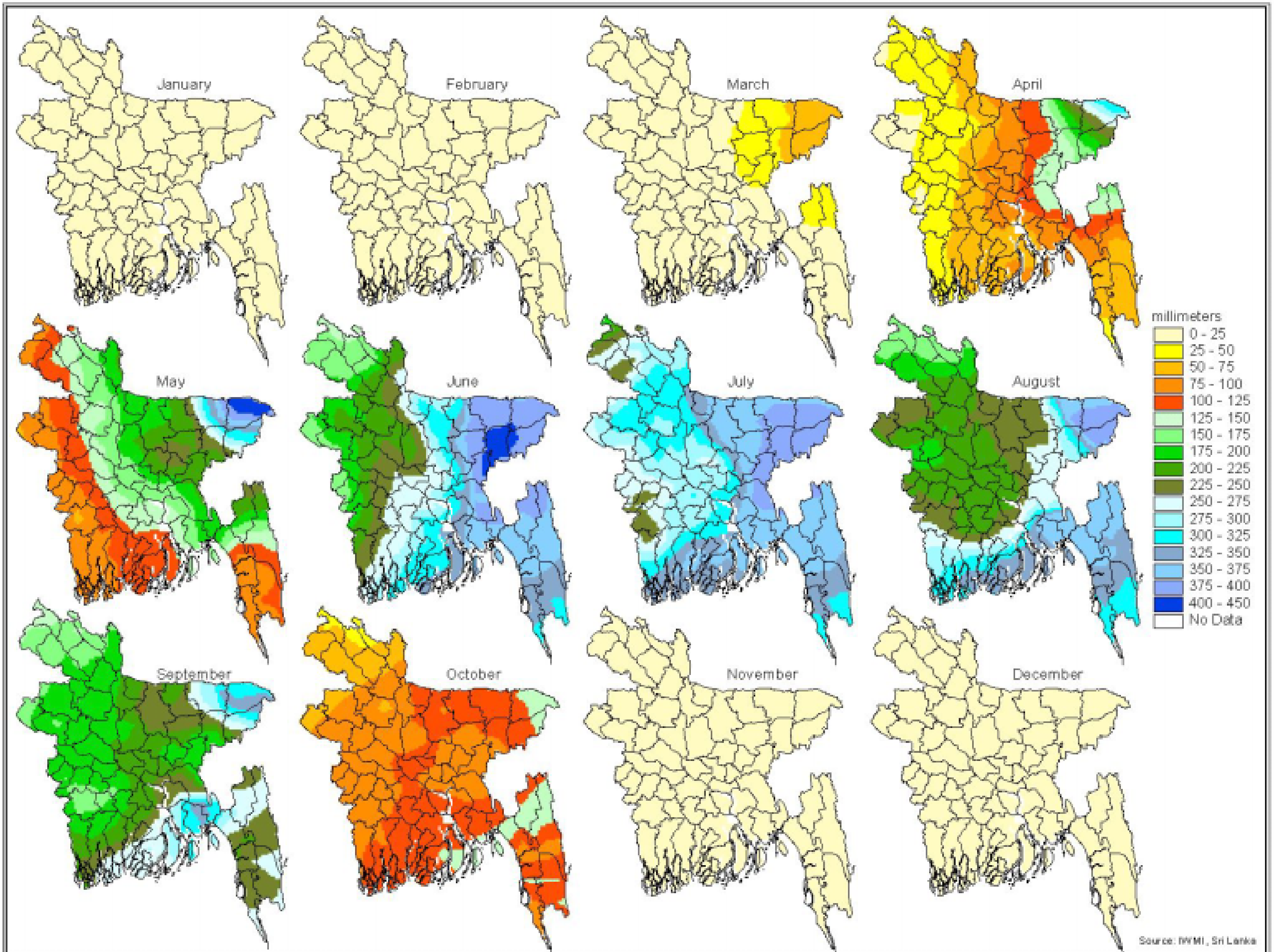


Figure 3.2.2 Dependable precipitation in Bangladesh.

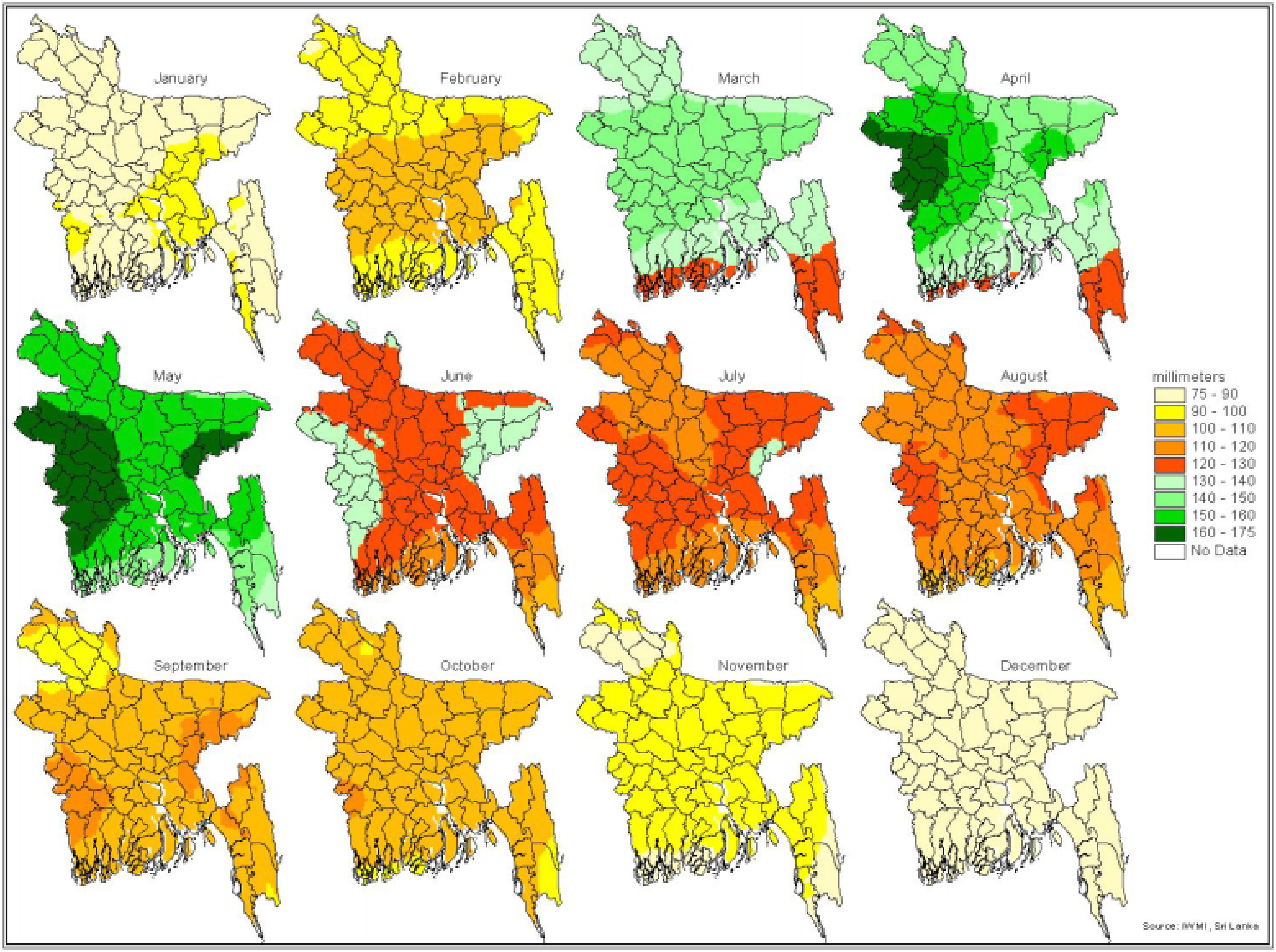


Figure 3.2.3 Evapotranspiration in Bangladesh.

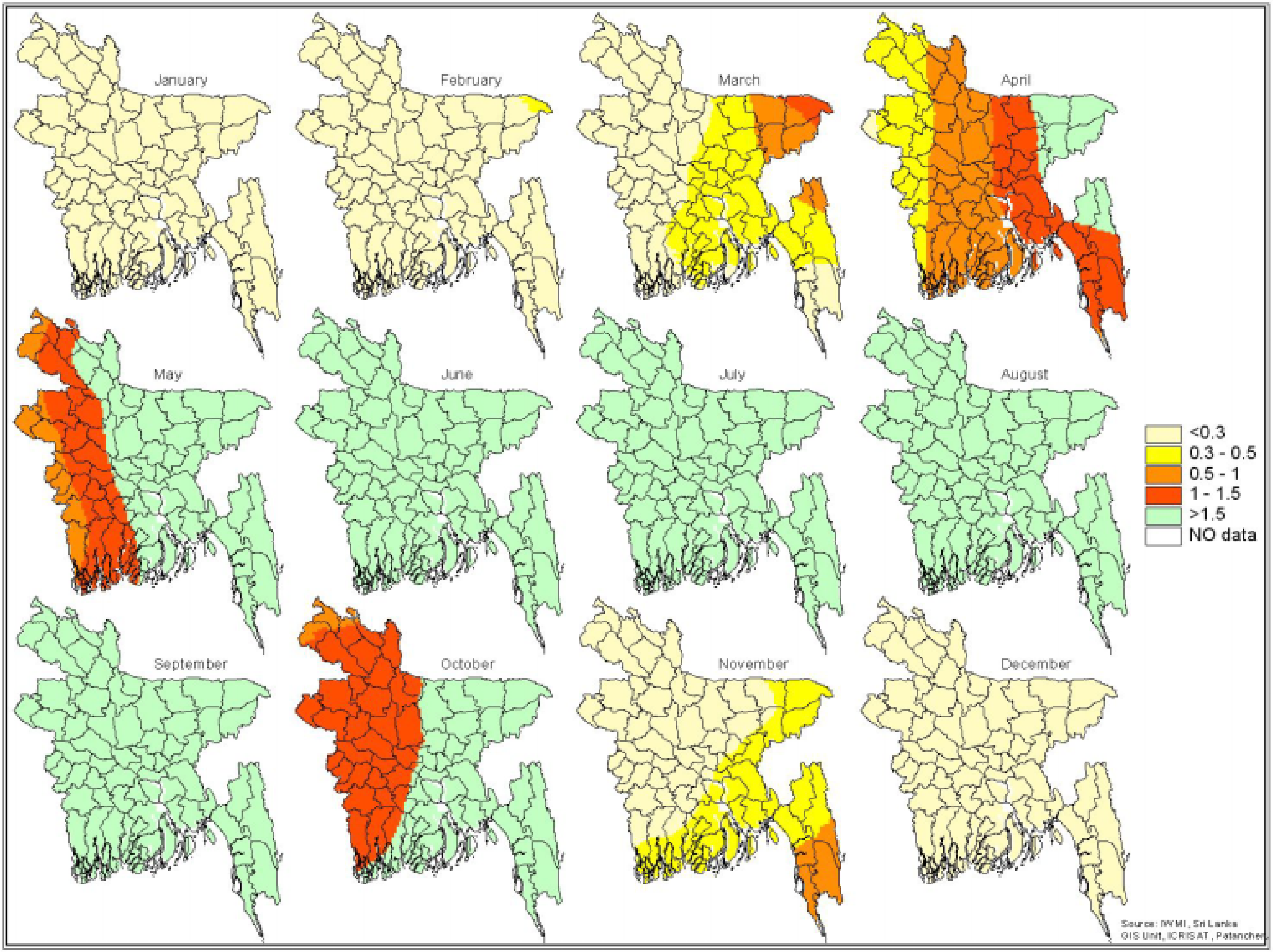


Figure 3.2.4 Precipitation / Potential evapotranspiration in Bangladesh.

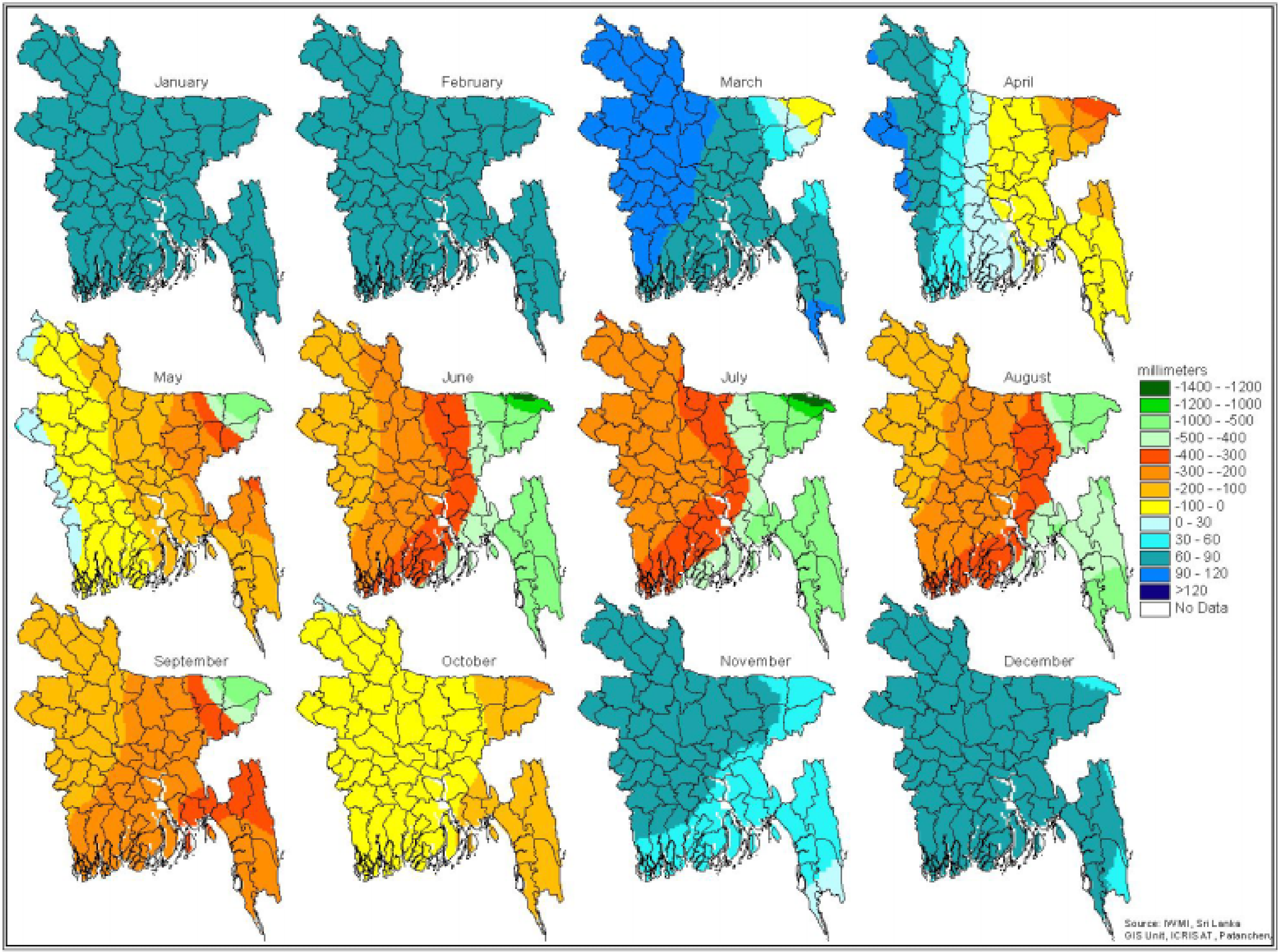


Figure 3.2.5 Potential evapotranspiration - Precipitation in Bangladesh

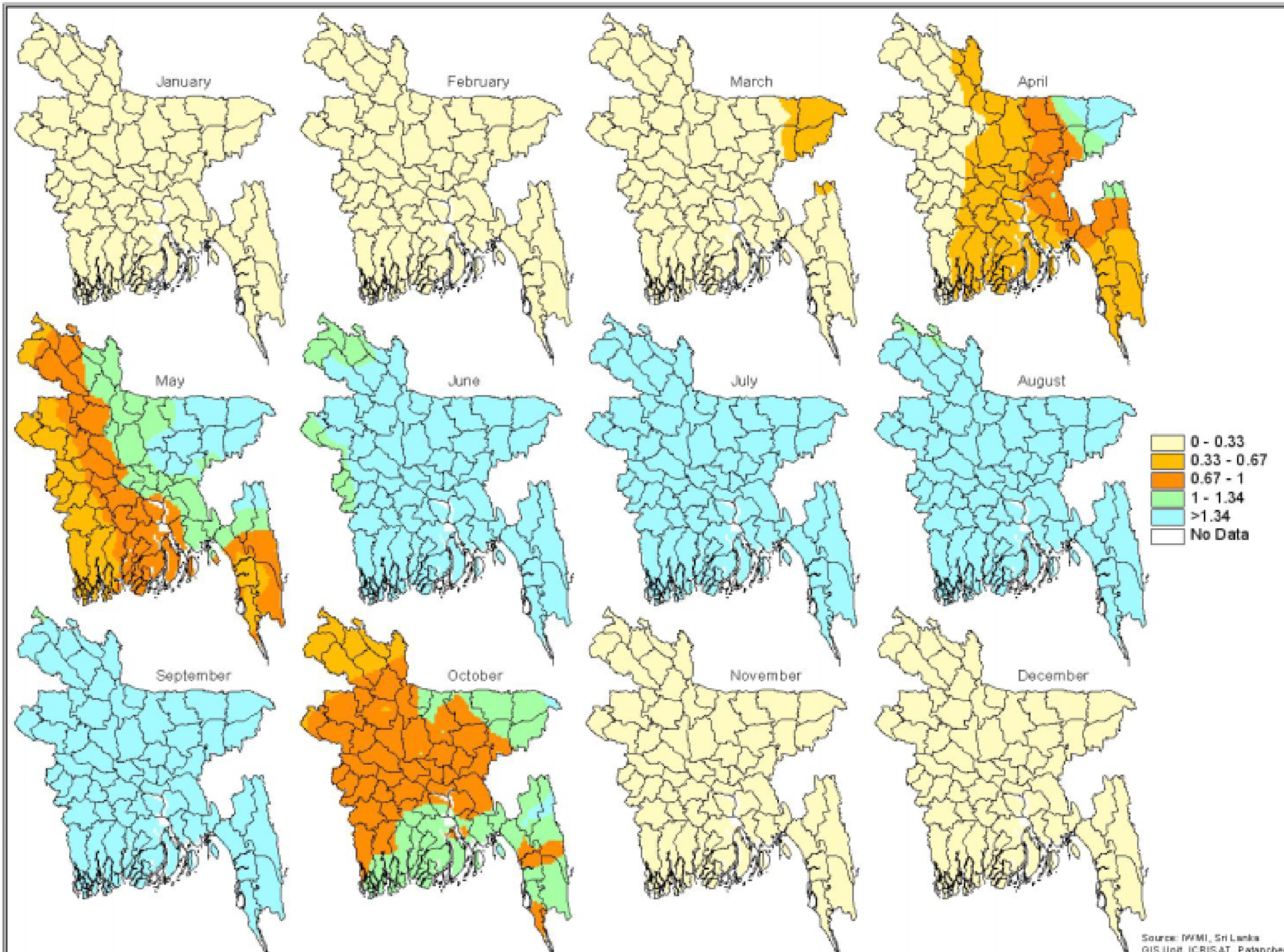


Figure 3.2.6 Moisture availability index in Bangladesh.

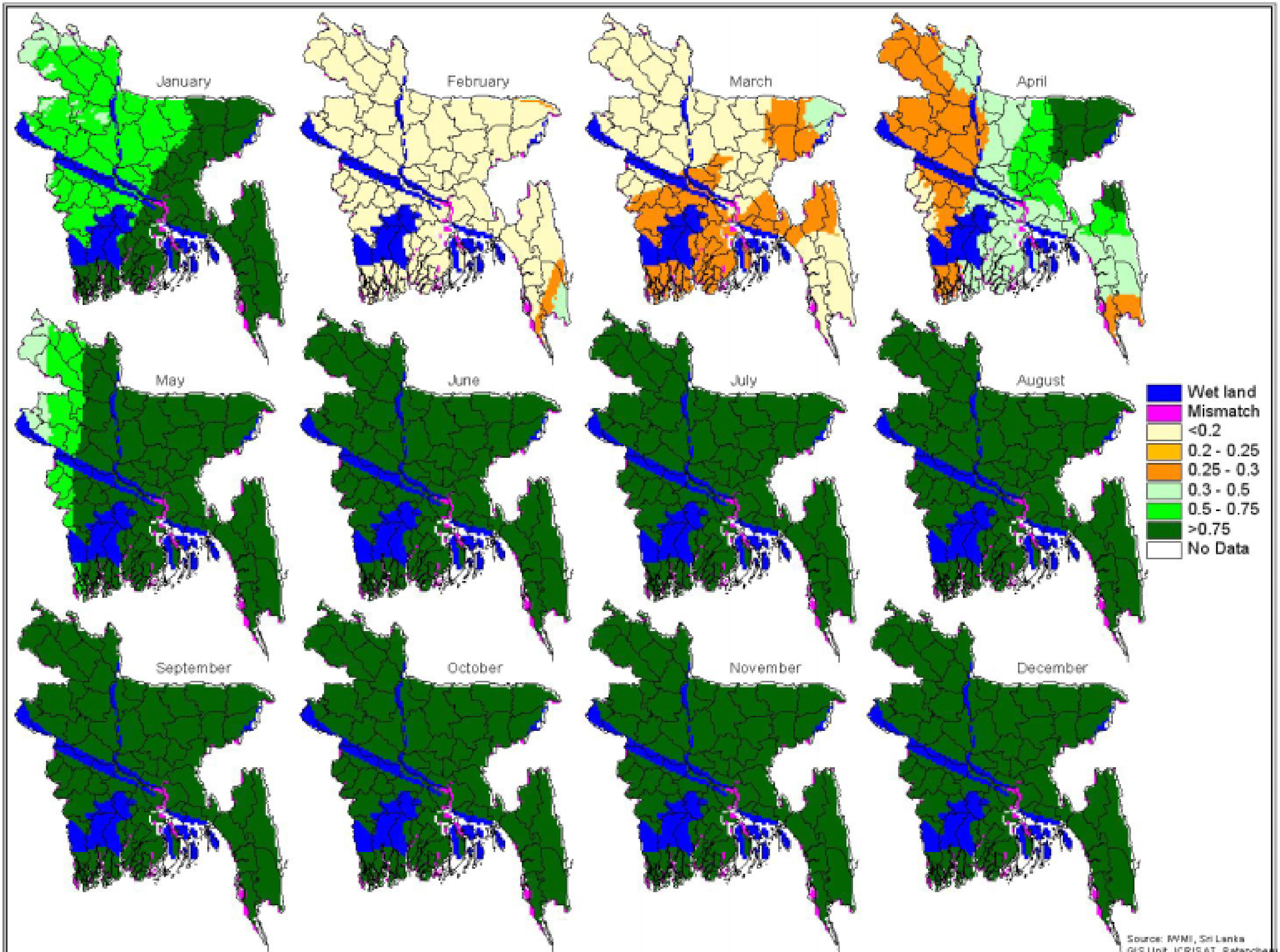


Figure 3.2.7 Actual evapotranspiration / Potential evapotranspiration in Bangladesh.

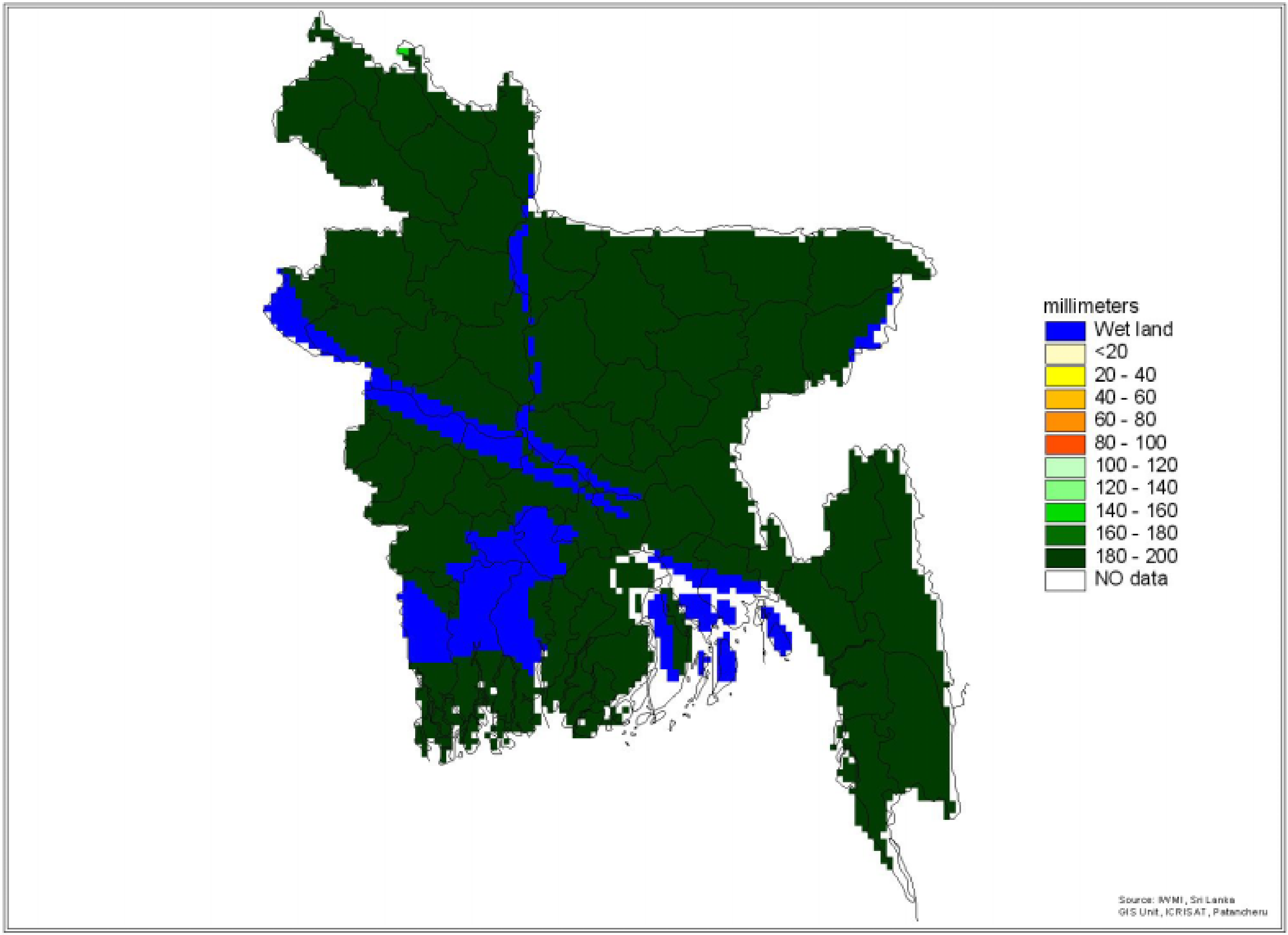


Figure 3.2.8 Soil water holding capacity in Bangladesh.

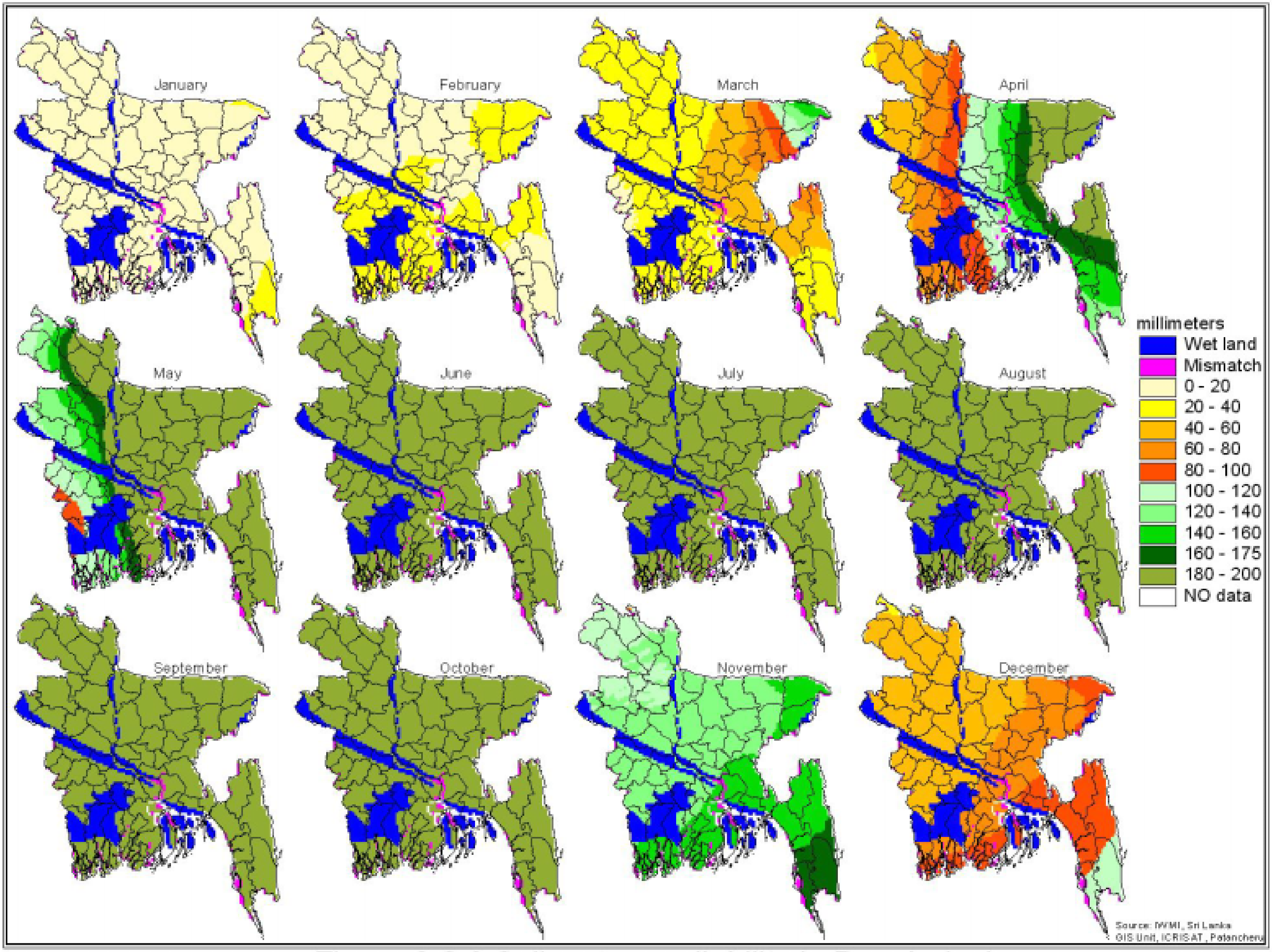


Figure 3.2.9 Soil water availability in Bangladesh.

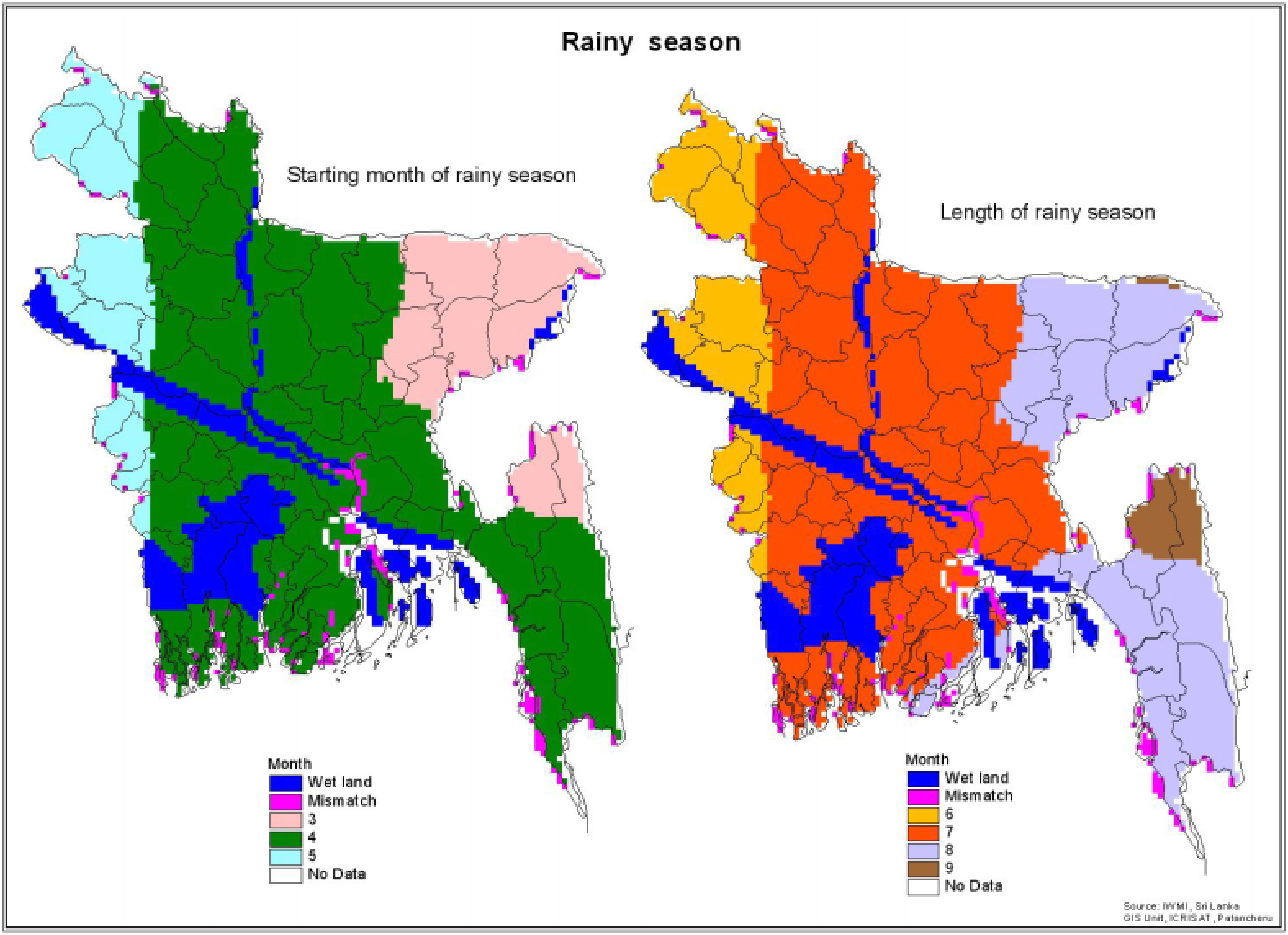
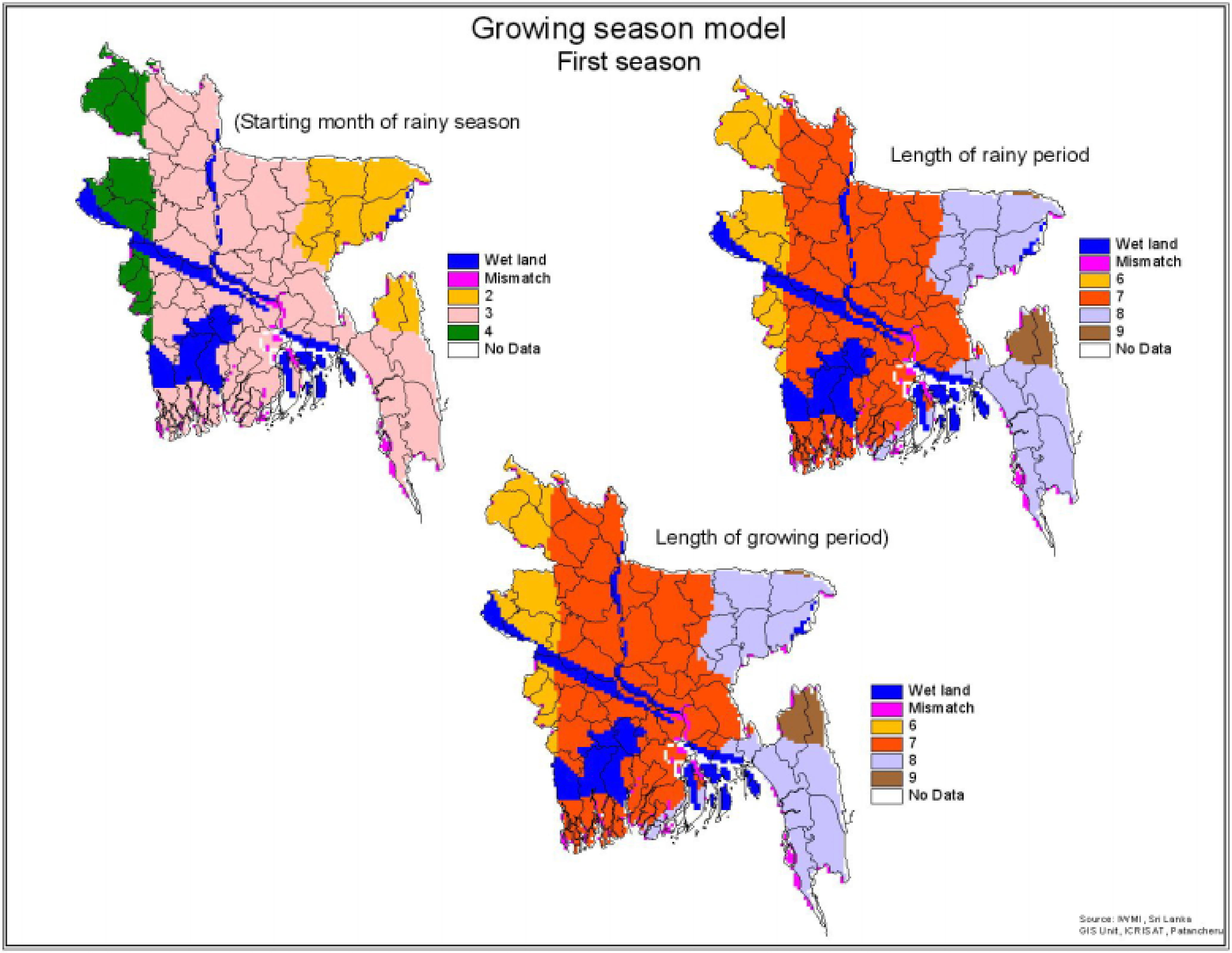


Figure3.2.10 Precipitation / Evapotranspiration model, Bangladesh.


Growing season model
First season
(Starting month of rainy season
Wet land
Mismatch
2
3
4
No Data
Length of rainy period
Wet land
Mismatch
6
7
8
9
No Data
Length of growing period)
Wet land
Mismatch
6
7
8
9
No Data
Source: IWMI, Sri Lanka
GIS Unit, ICRISAT, Patancheru

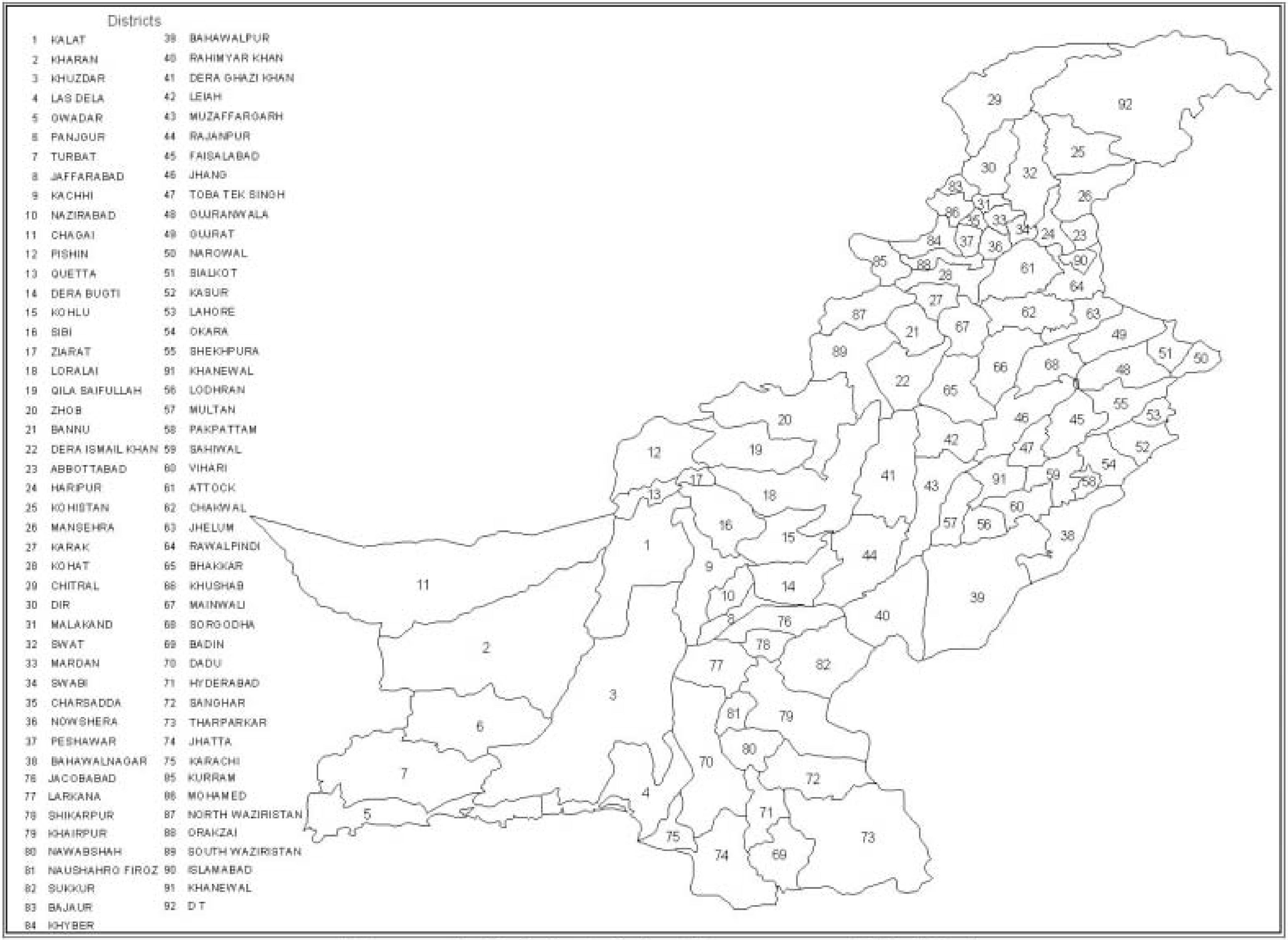


Figure 3.3 Administrative map of Pakistan

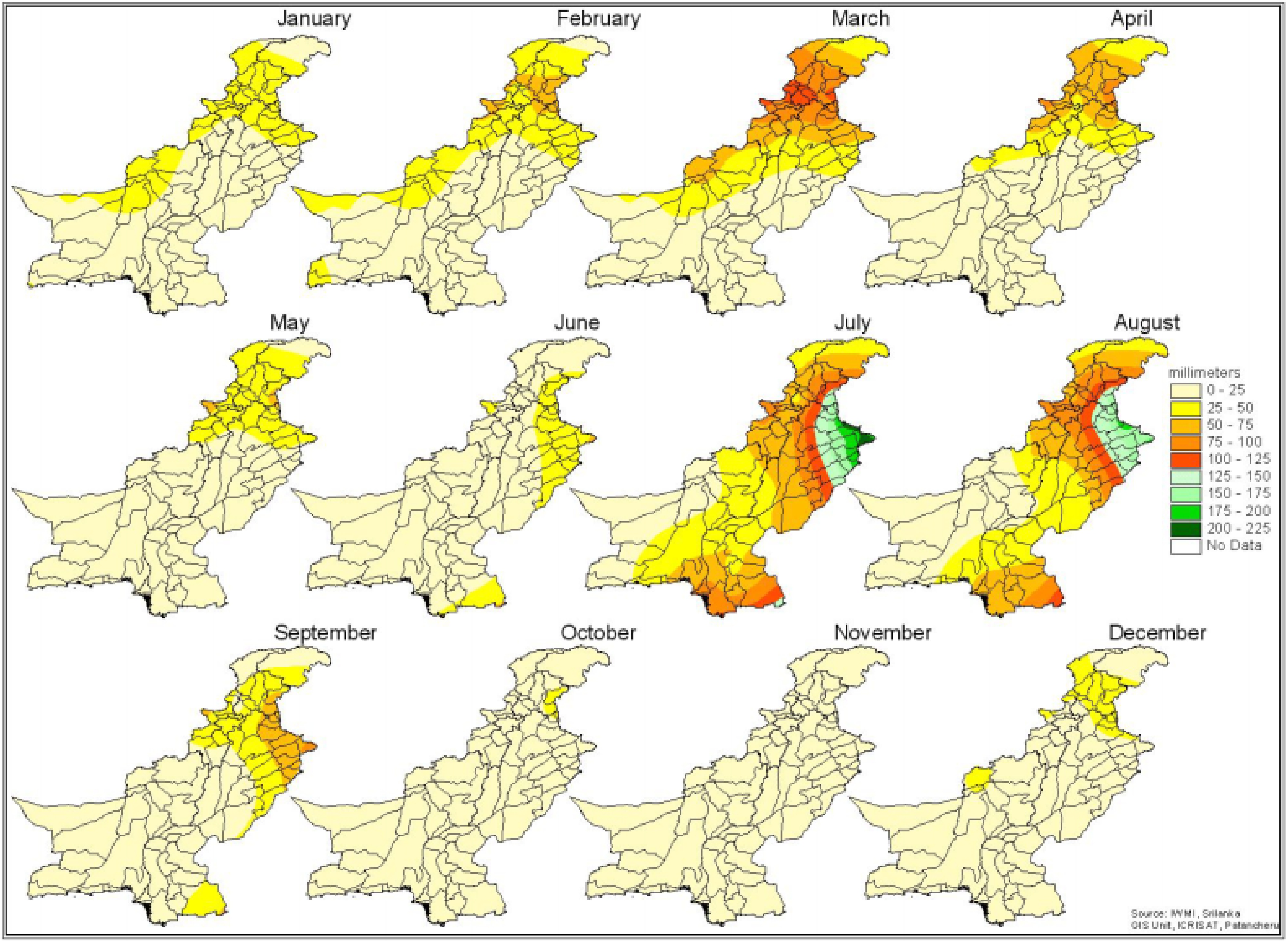


Figure 3.3.1 Rainfall in Pakistan.

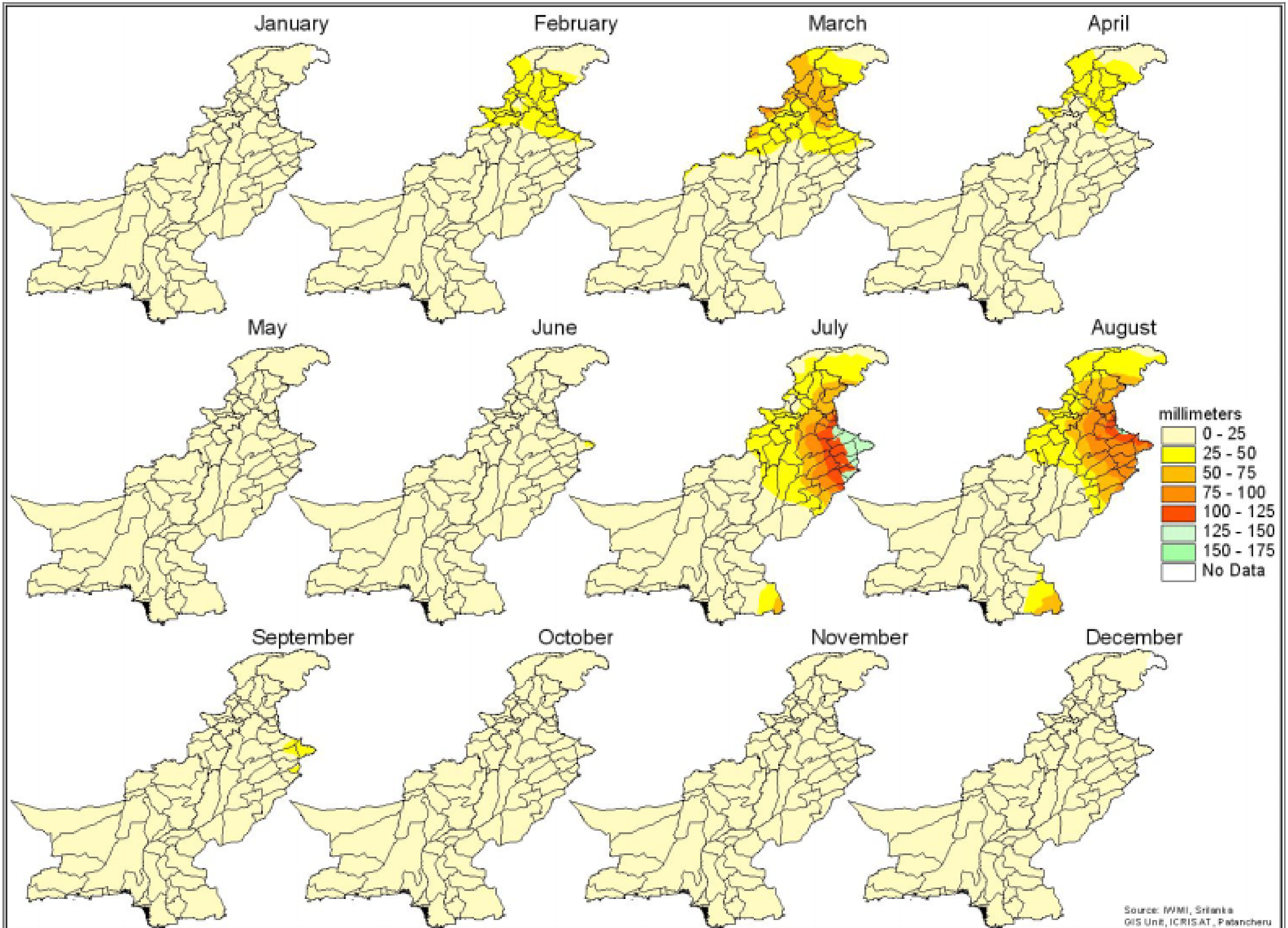


Figure 3.3.2 Dependable Precipitation in Pakistan

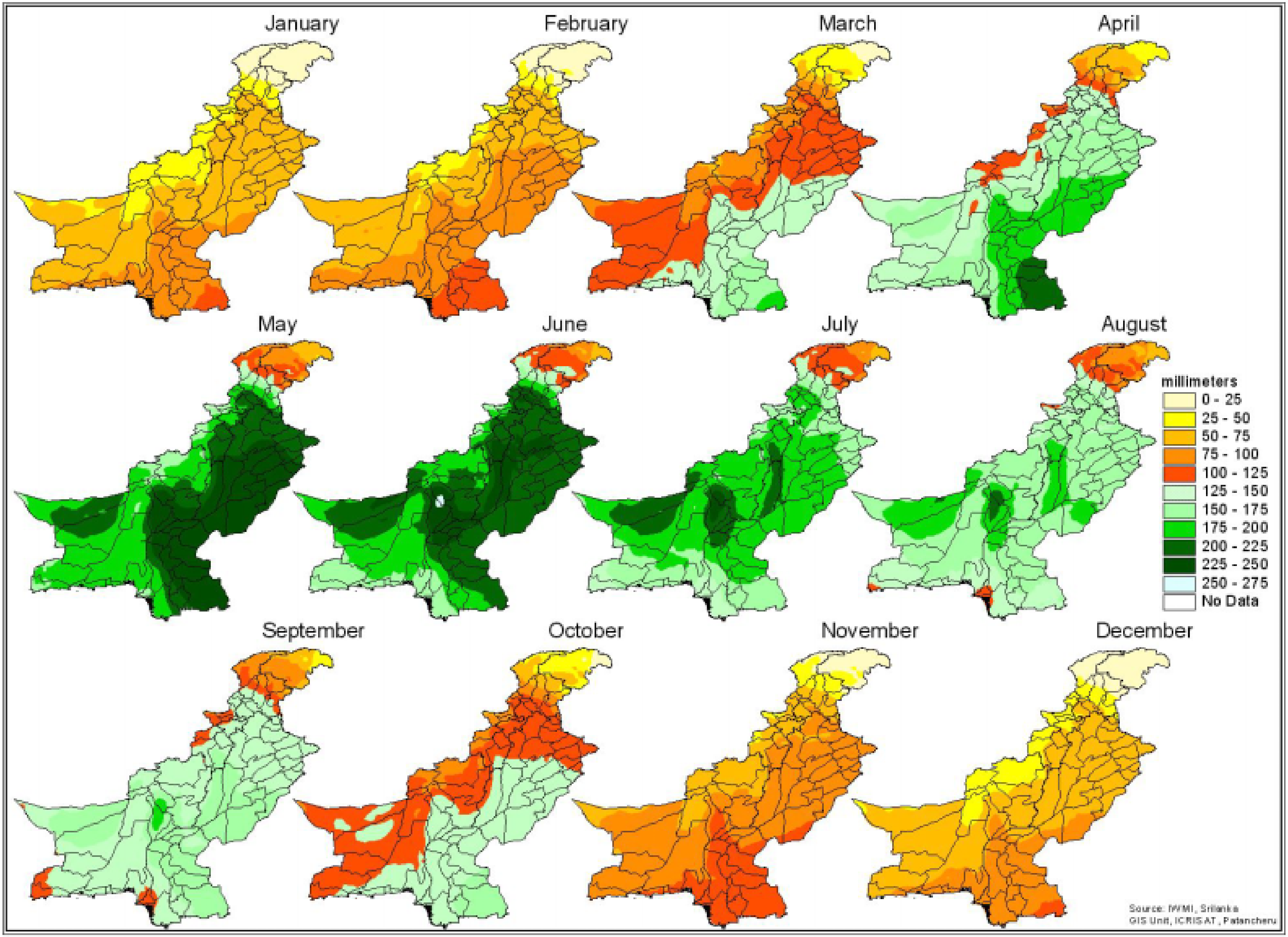


Figure 3.3.3 Evapotranspiration in Pakistan.

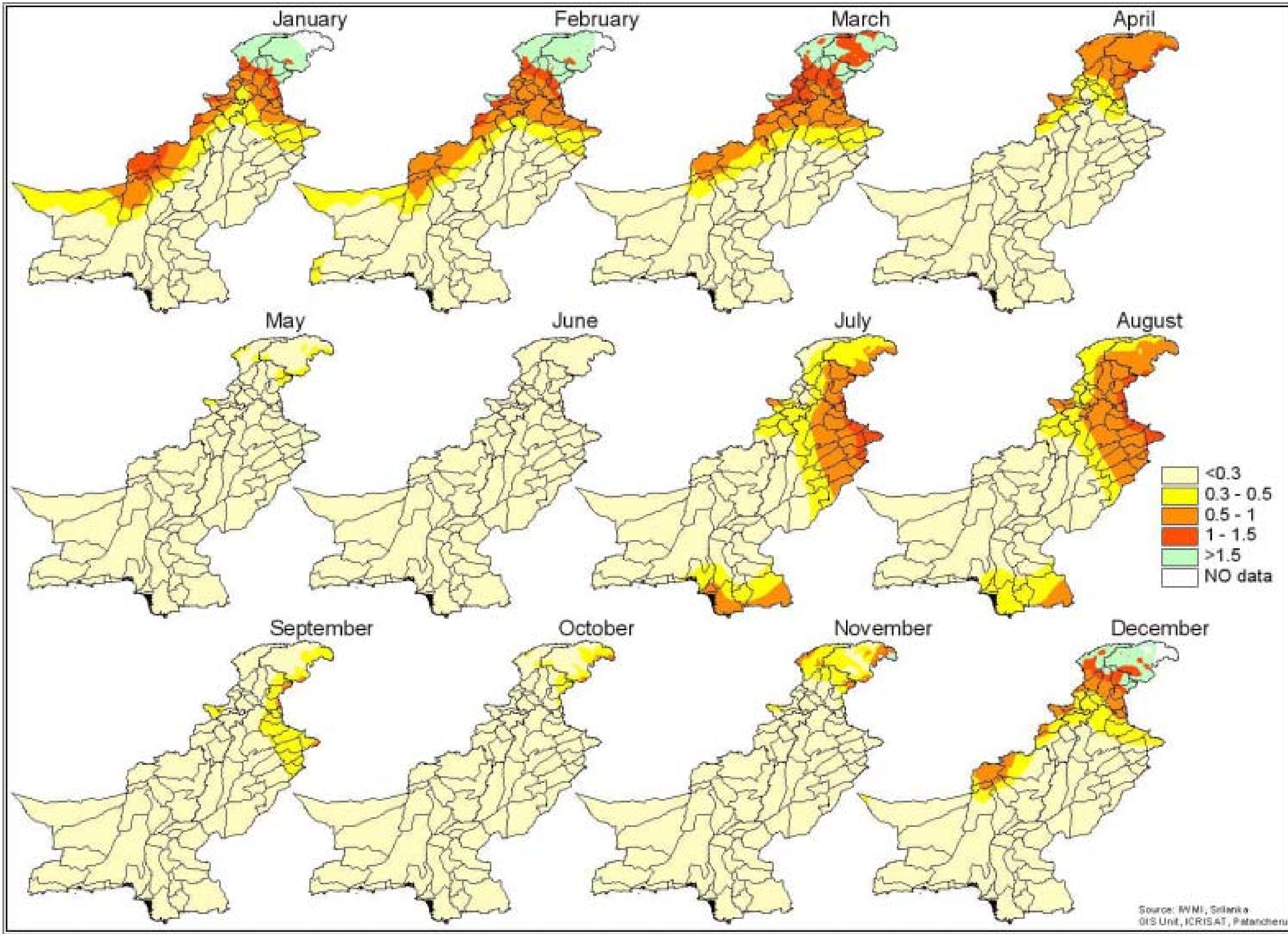


Figure 3.3.4 Precipitation / Potential evapotranspiration in Pakistan.

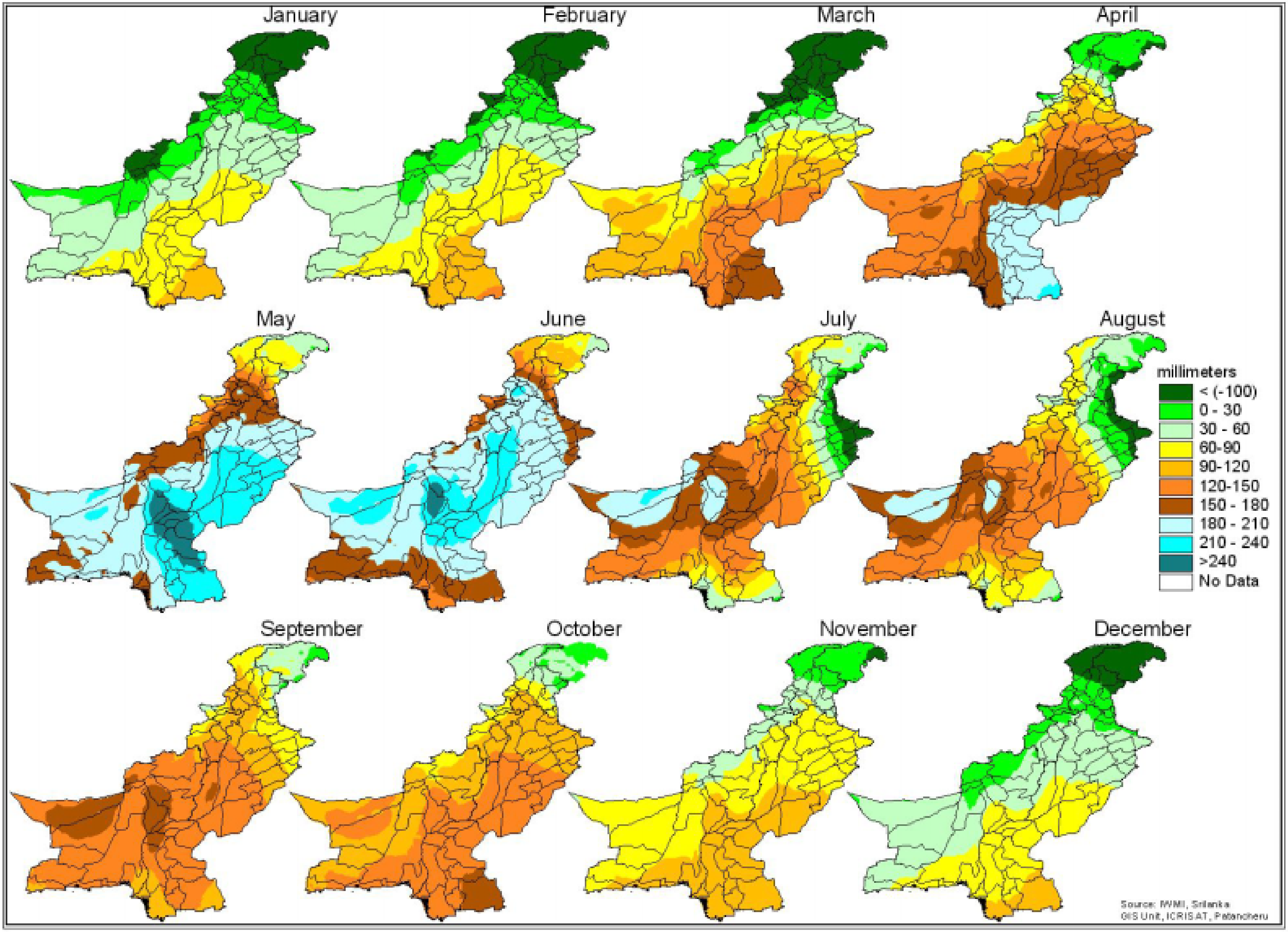


Figure 3.3.5 (Potential evapotranspiration) - (Precipitation) in Pakistan.

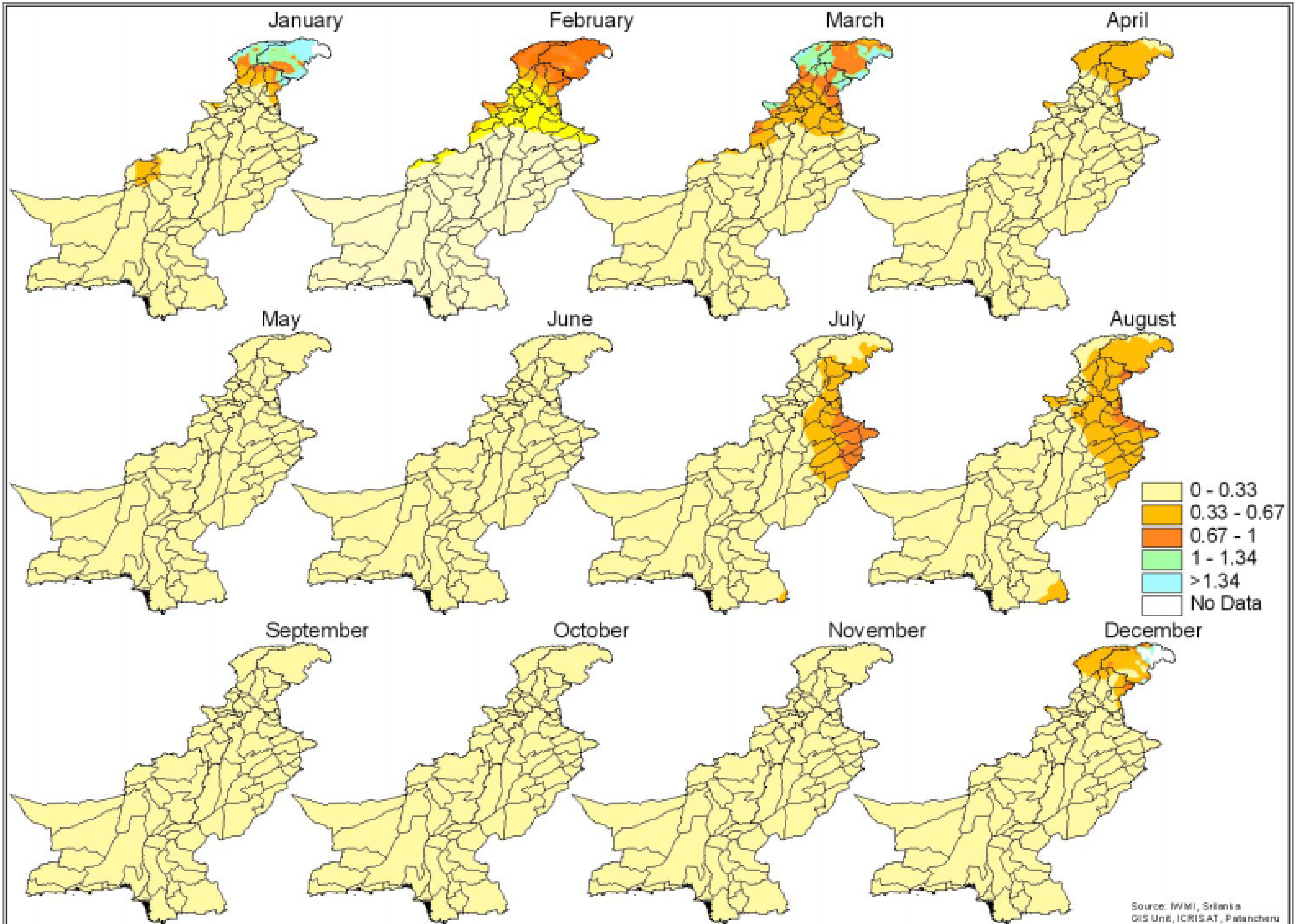


Figure 3.3.6 Moisture availability index in Pakistan.

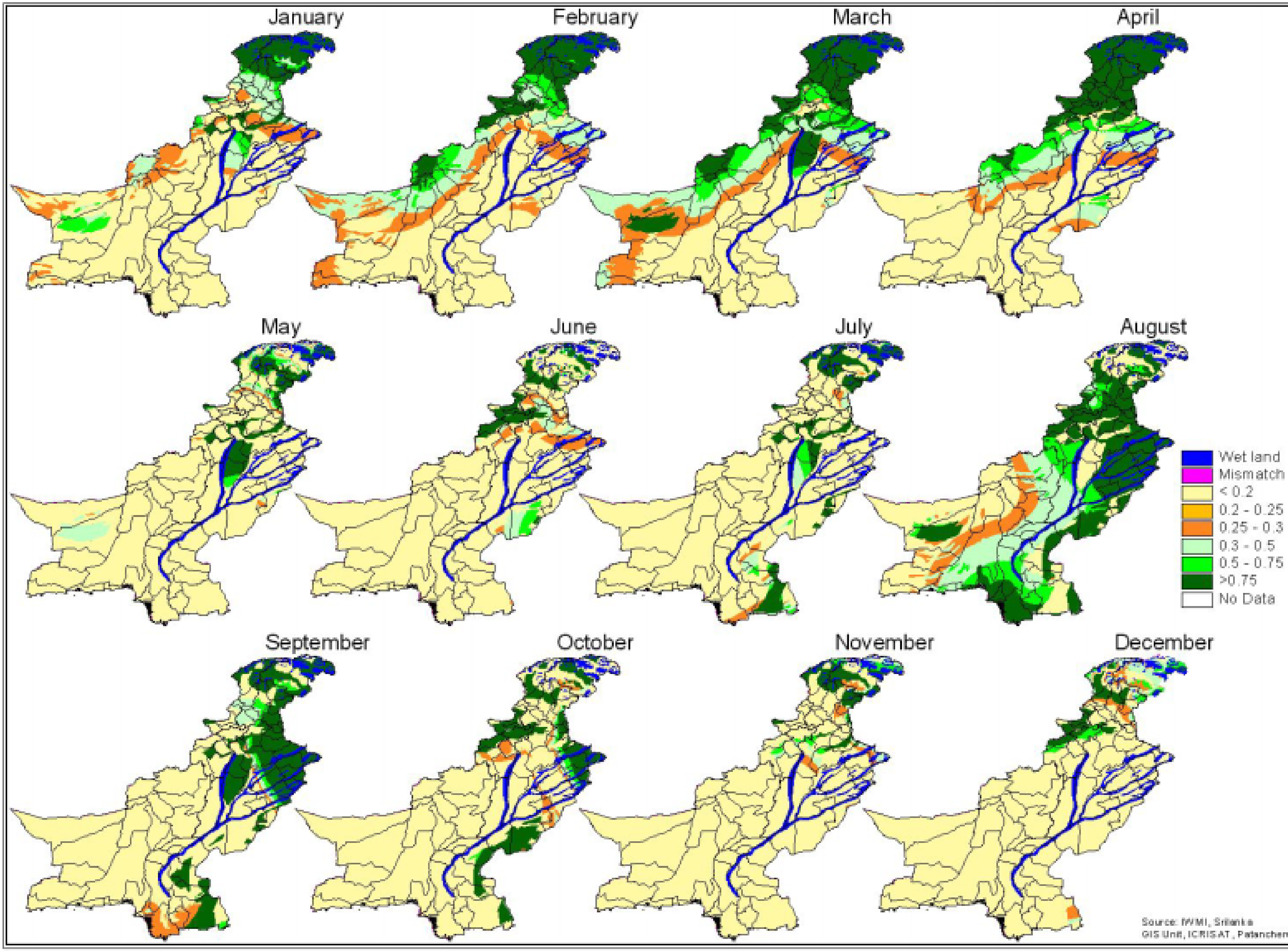


Figure 3.3.7 Actual Evapotranspiration/Potential Evapotranspiration in Pakistan.

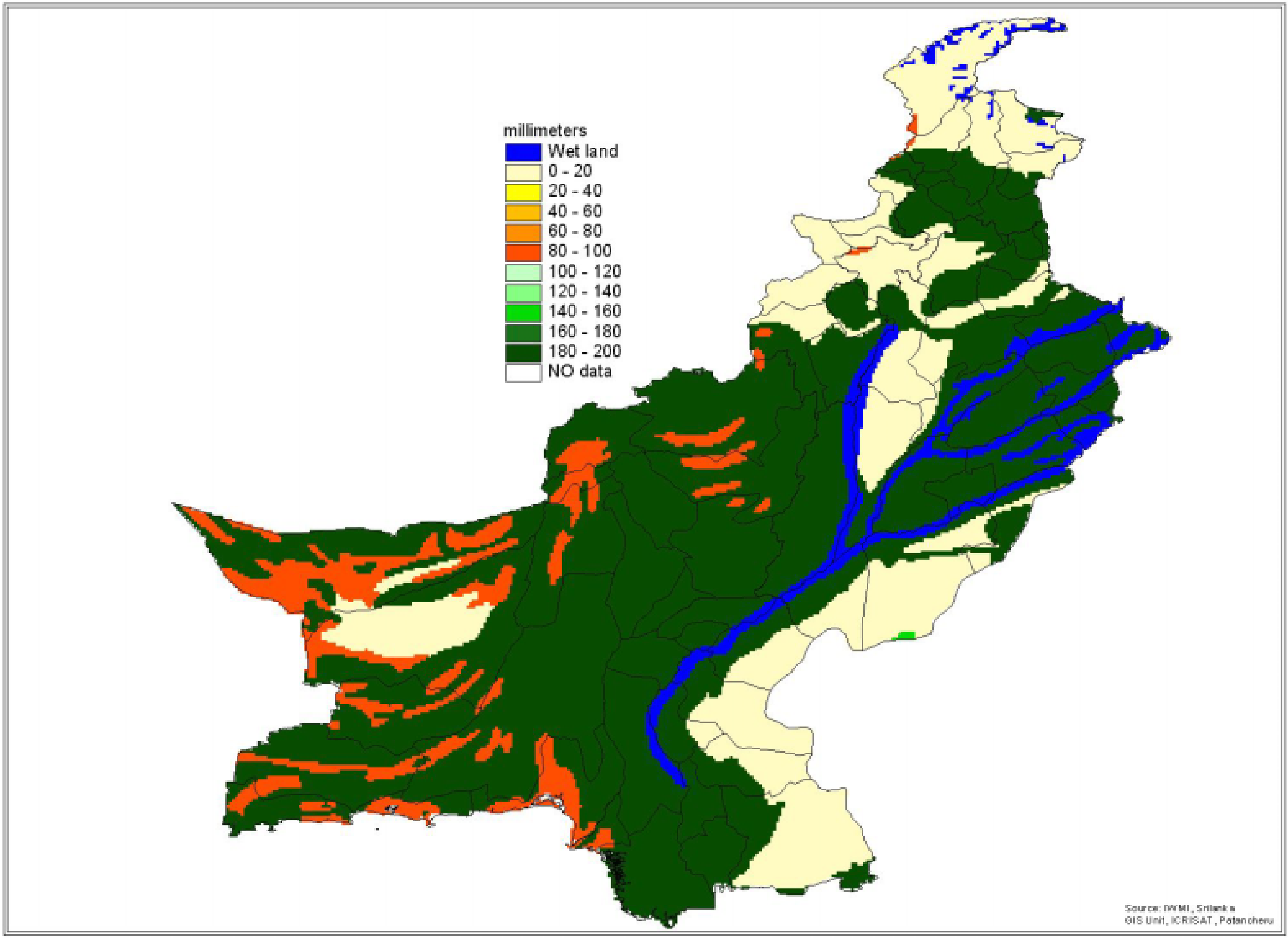


Figure 3.3.8 Soil water holding capacity in Pakistan.

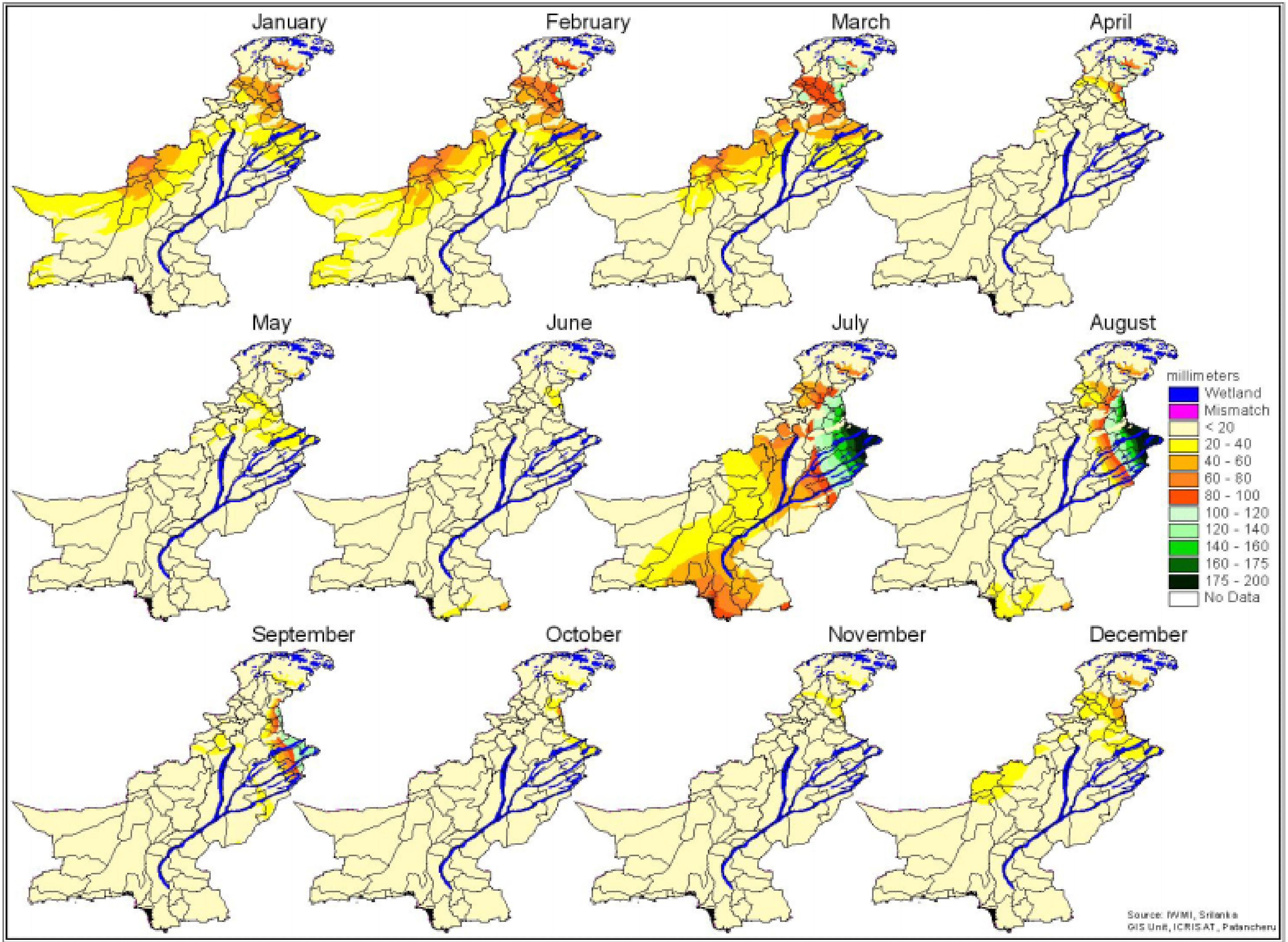


Figure 3.3.9 Soil water availability in Pakistan.

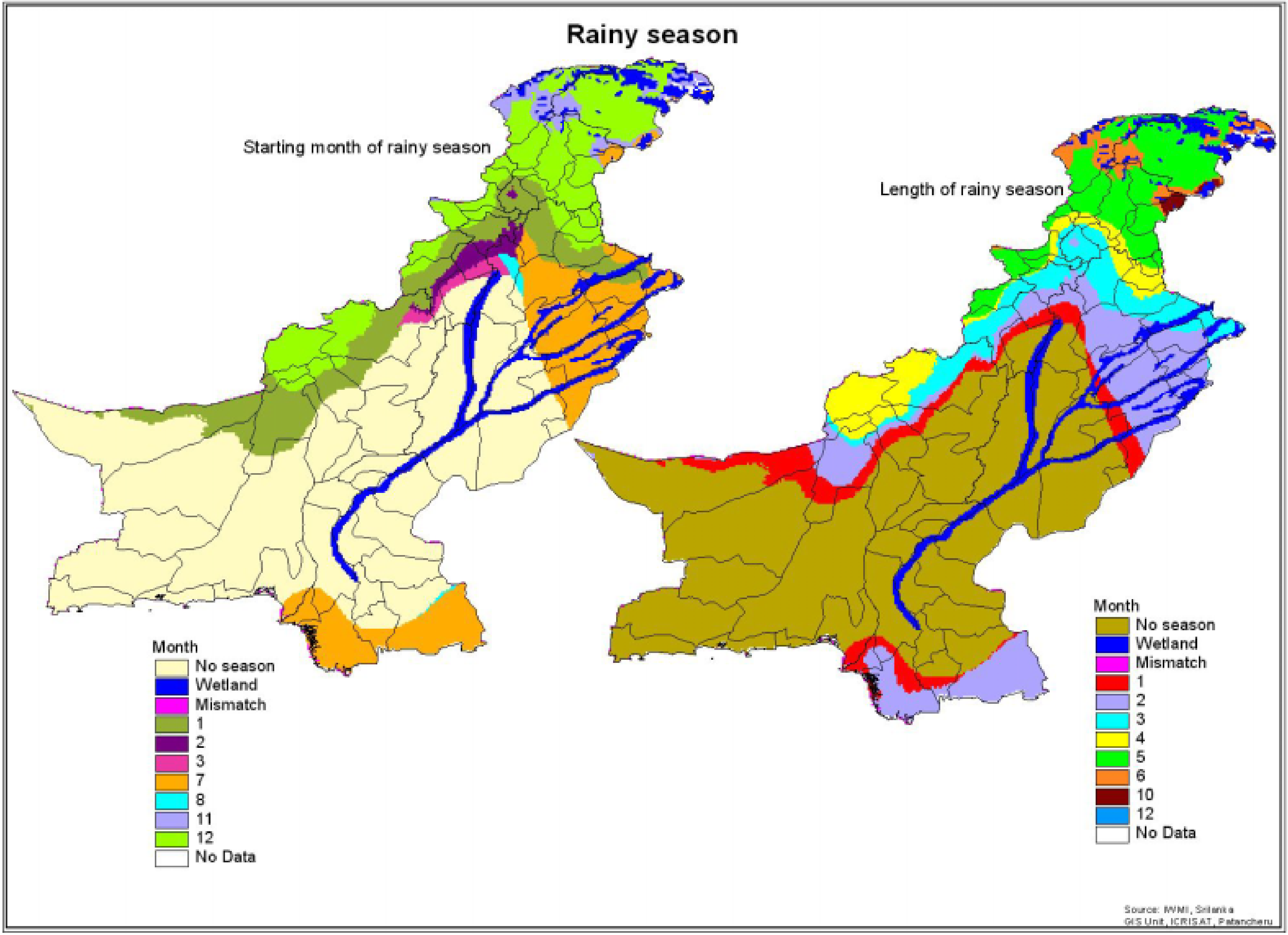


Figure 3.3.10 Precipitaton / Evapotranspiration model in Pakistan.

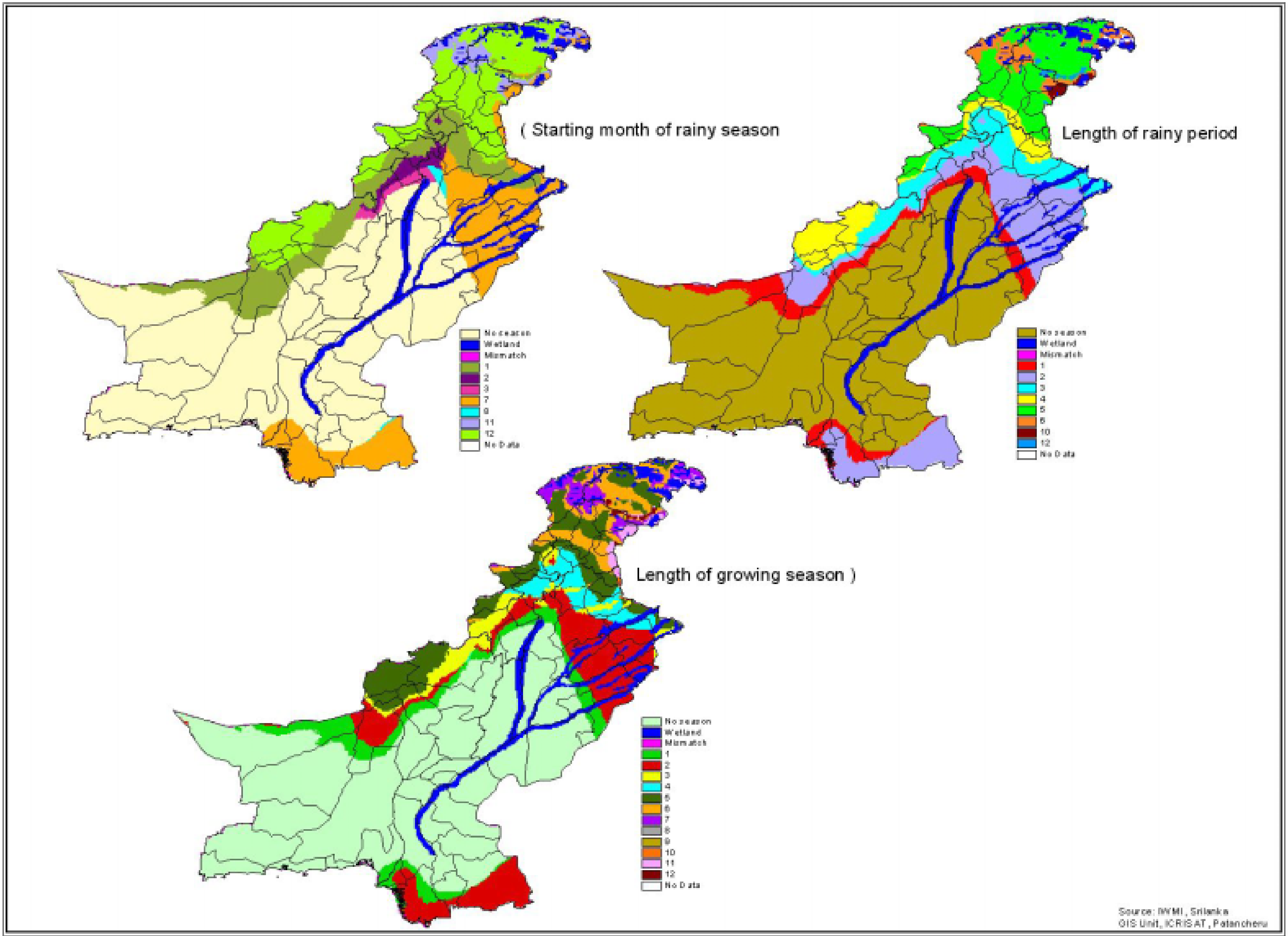


Figure 3.3.11 Growing season model (First season) in Pakistan.

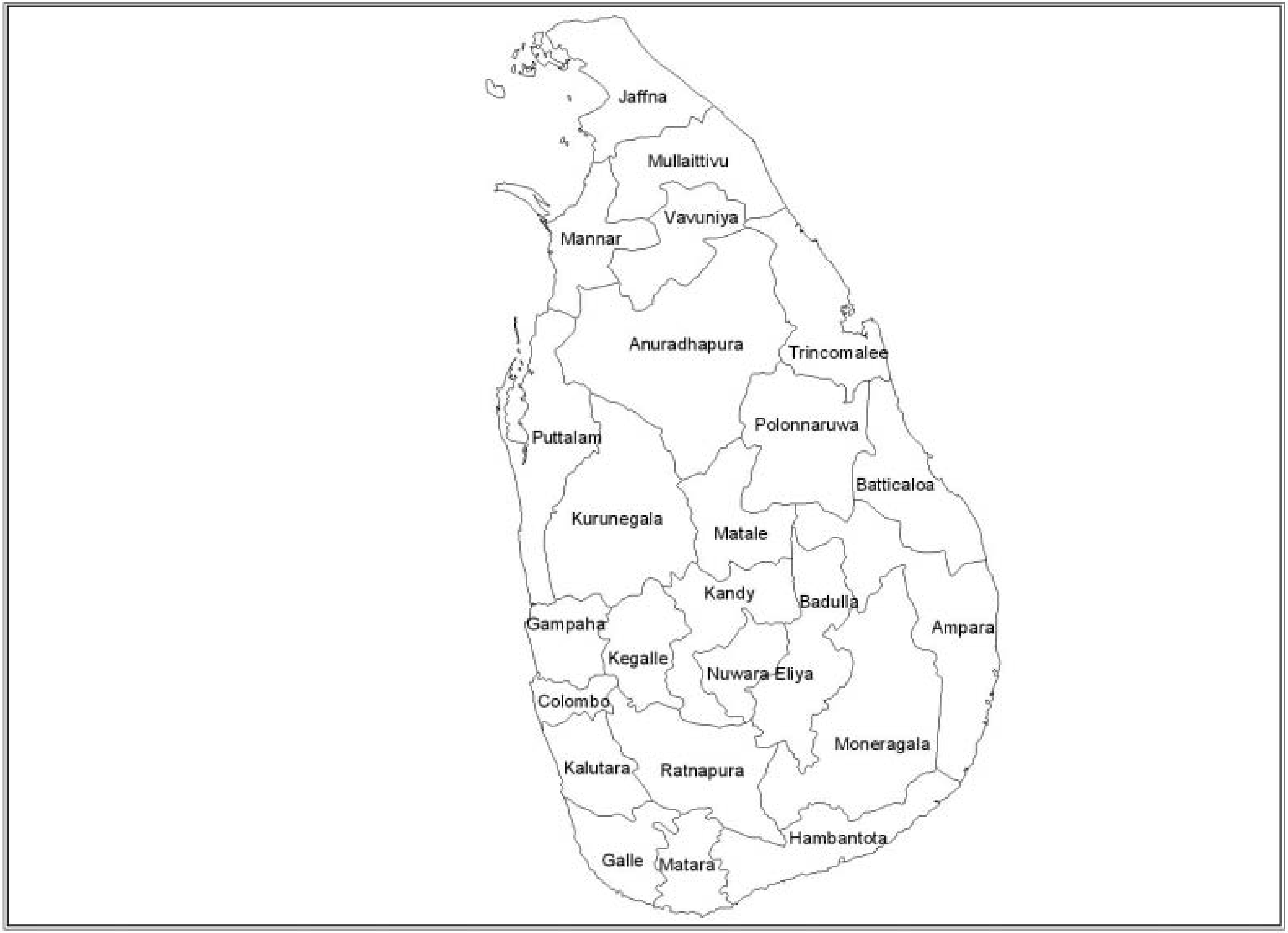


Figure 3.4 Administrative map of Srilanka

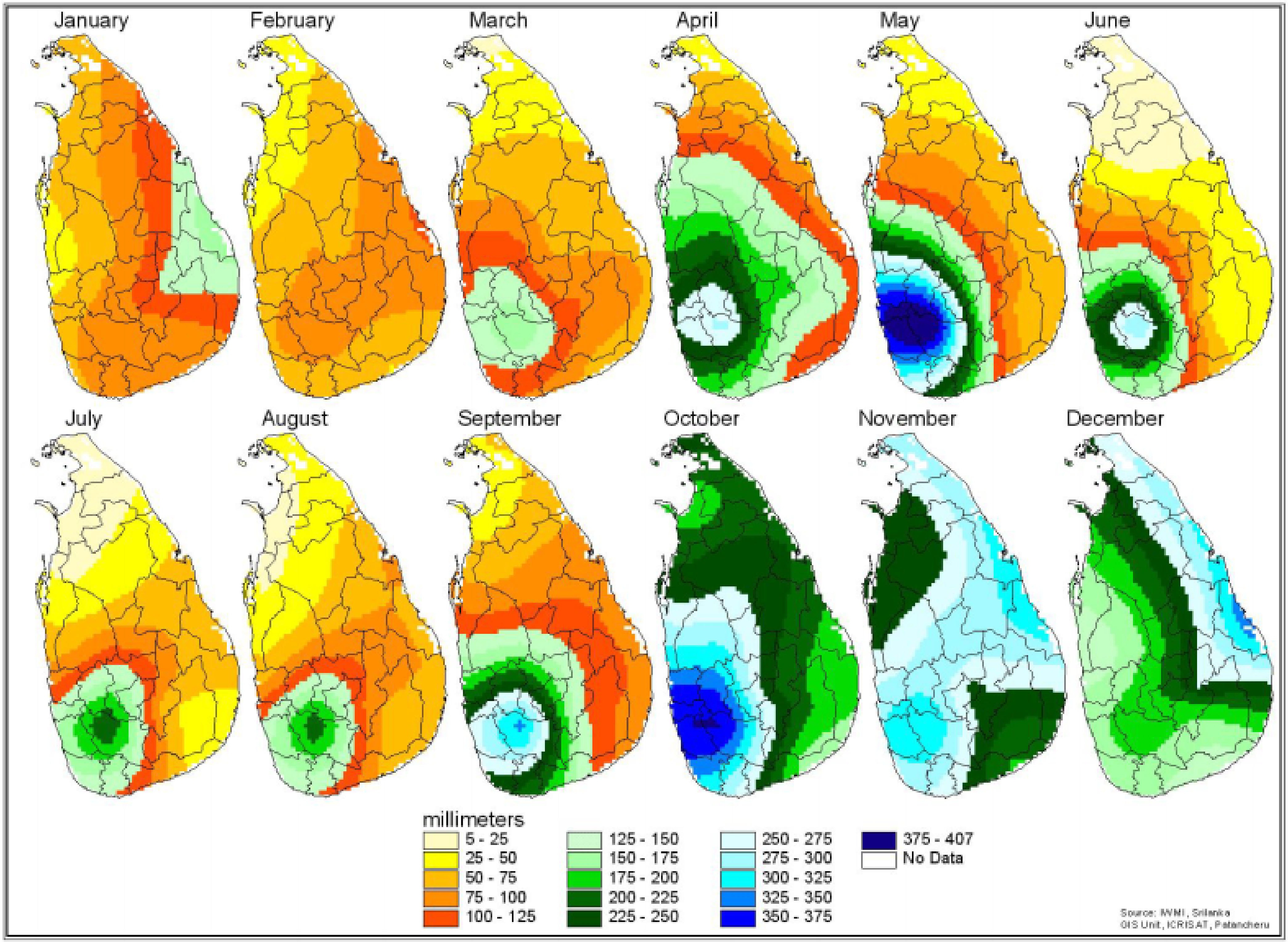


Figure 3.4.1 Rainfall in Srilanka.

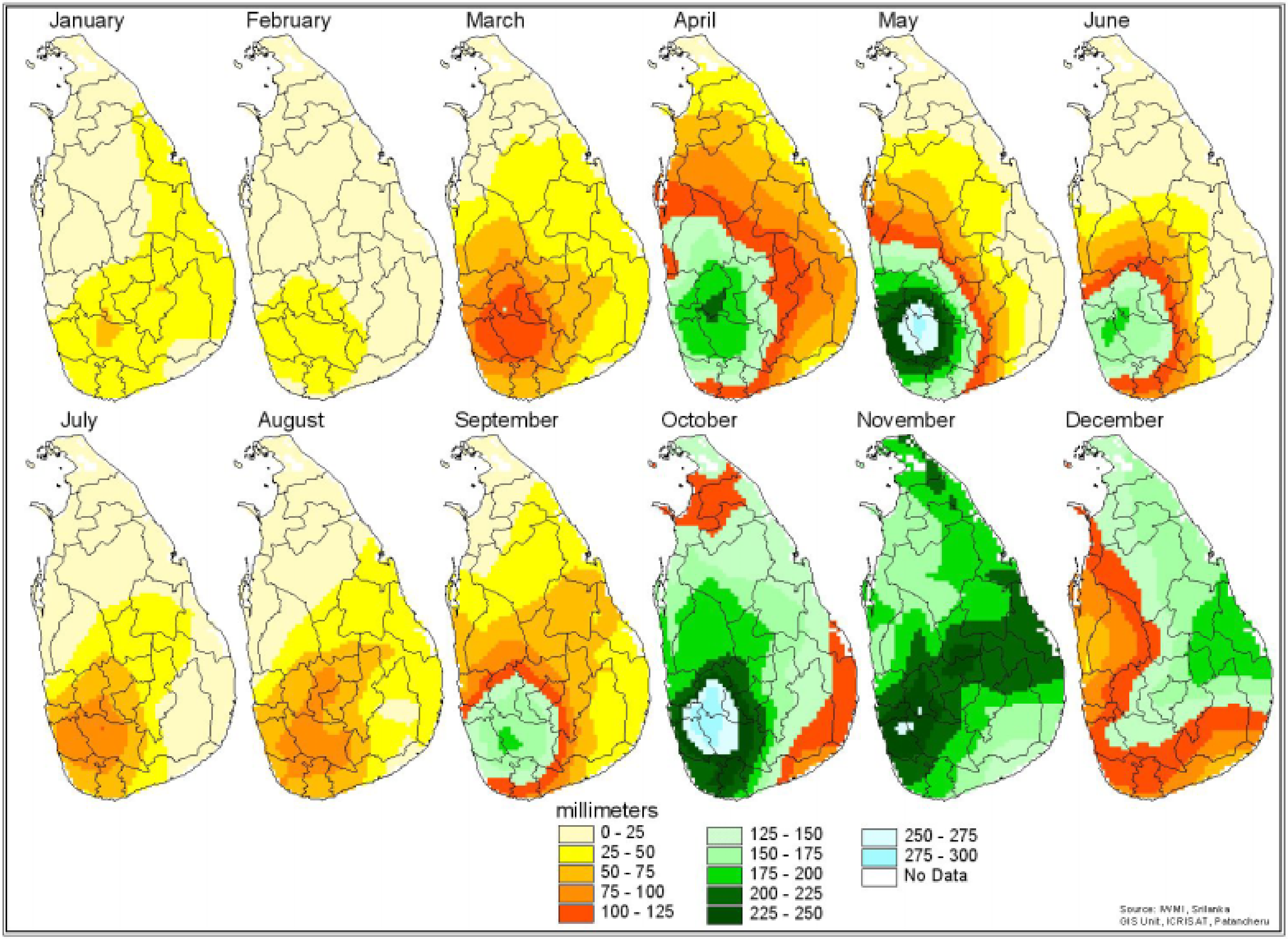


Figure 3.4.2 Dependable precipitation in Srilanka.

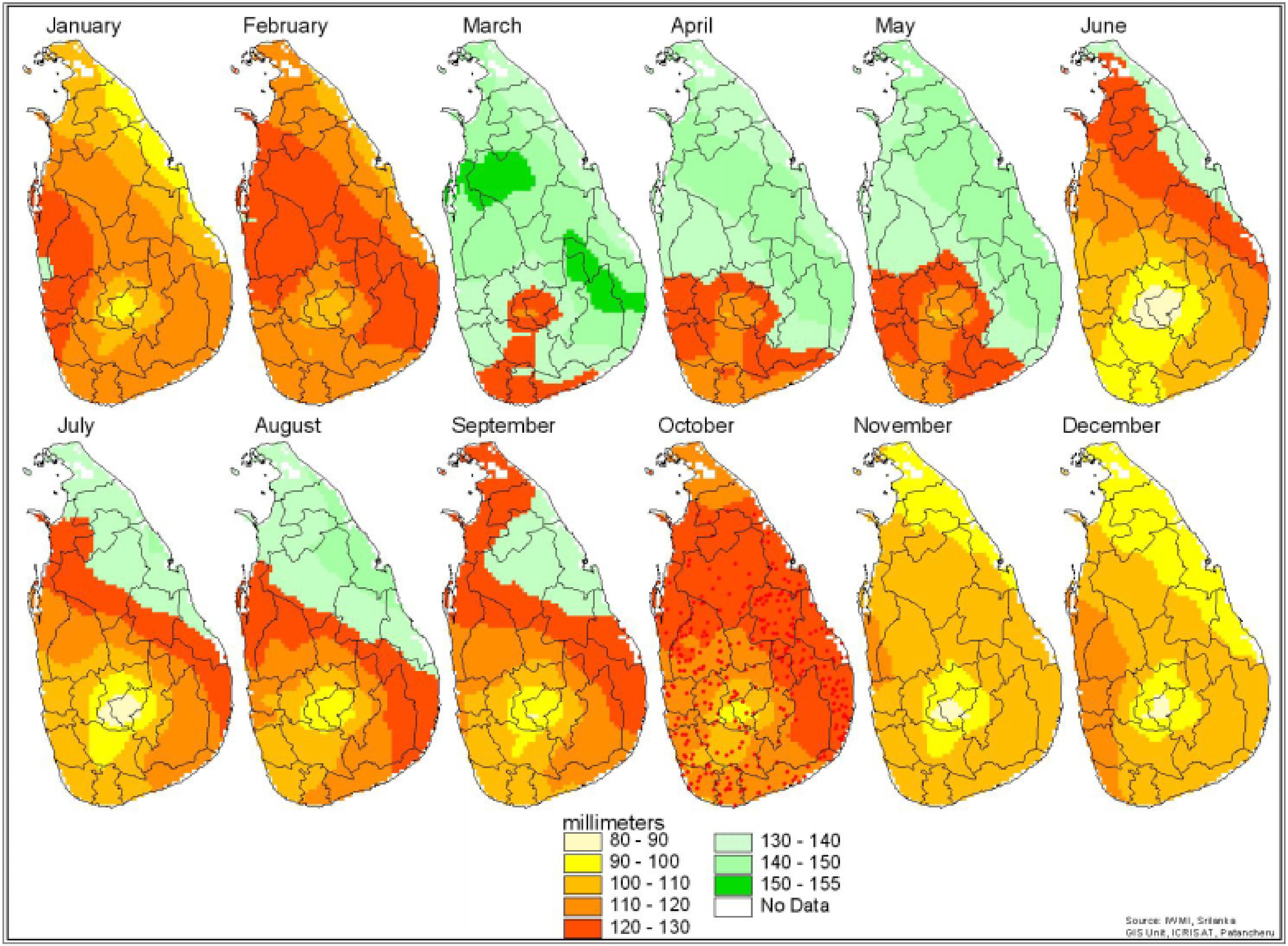


Figure 3.4.3 Evapotranspiration in Srilanka

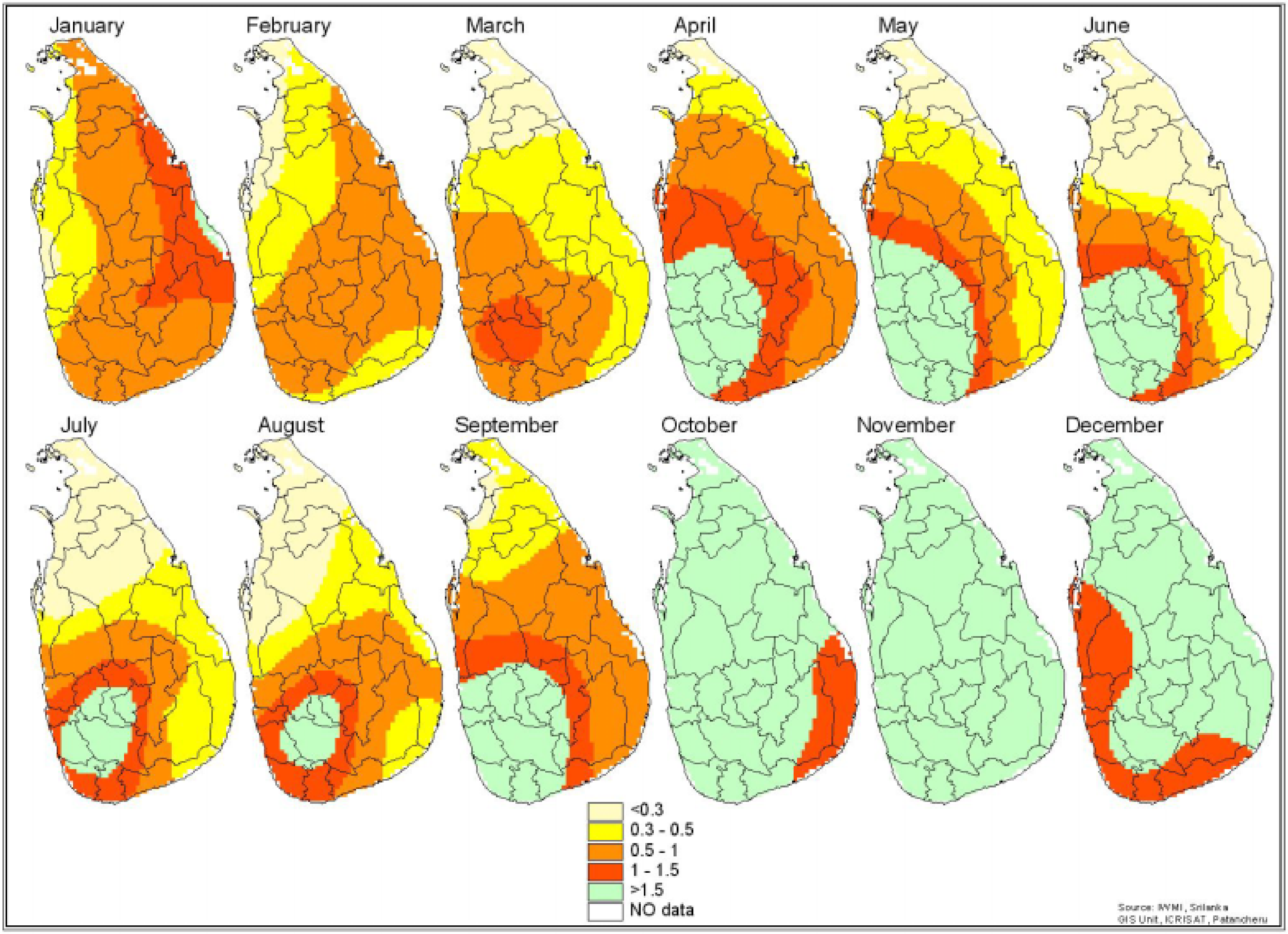


Figure 3.4.4 Precipitation/Potential evapotranspiration in Srilanka

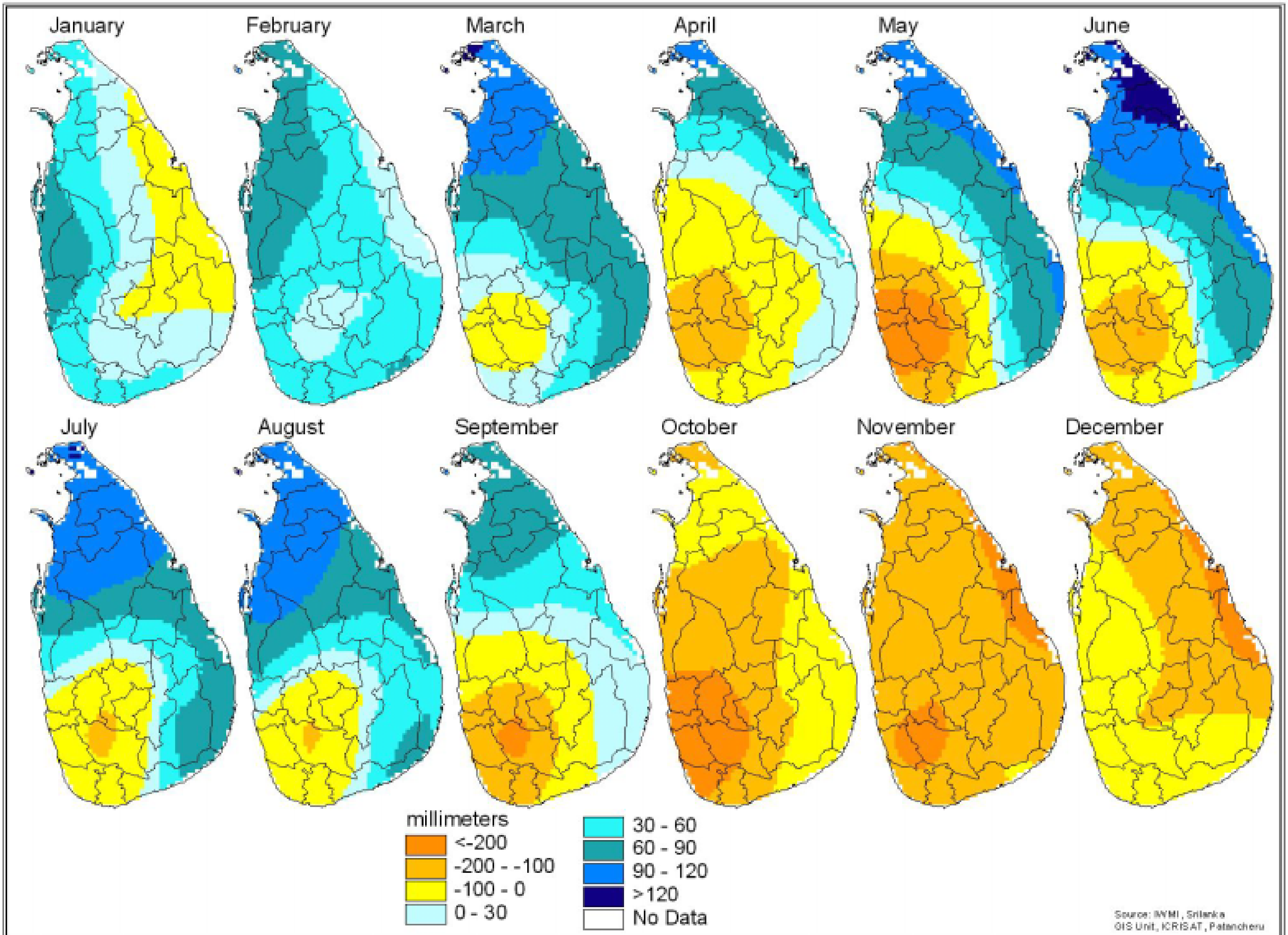


Figure 3.4.5 Potential evapotranspiration - Precipitation in Srilanka.

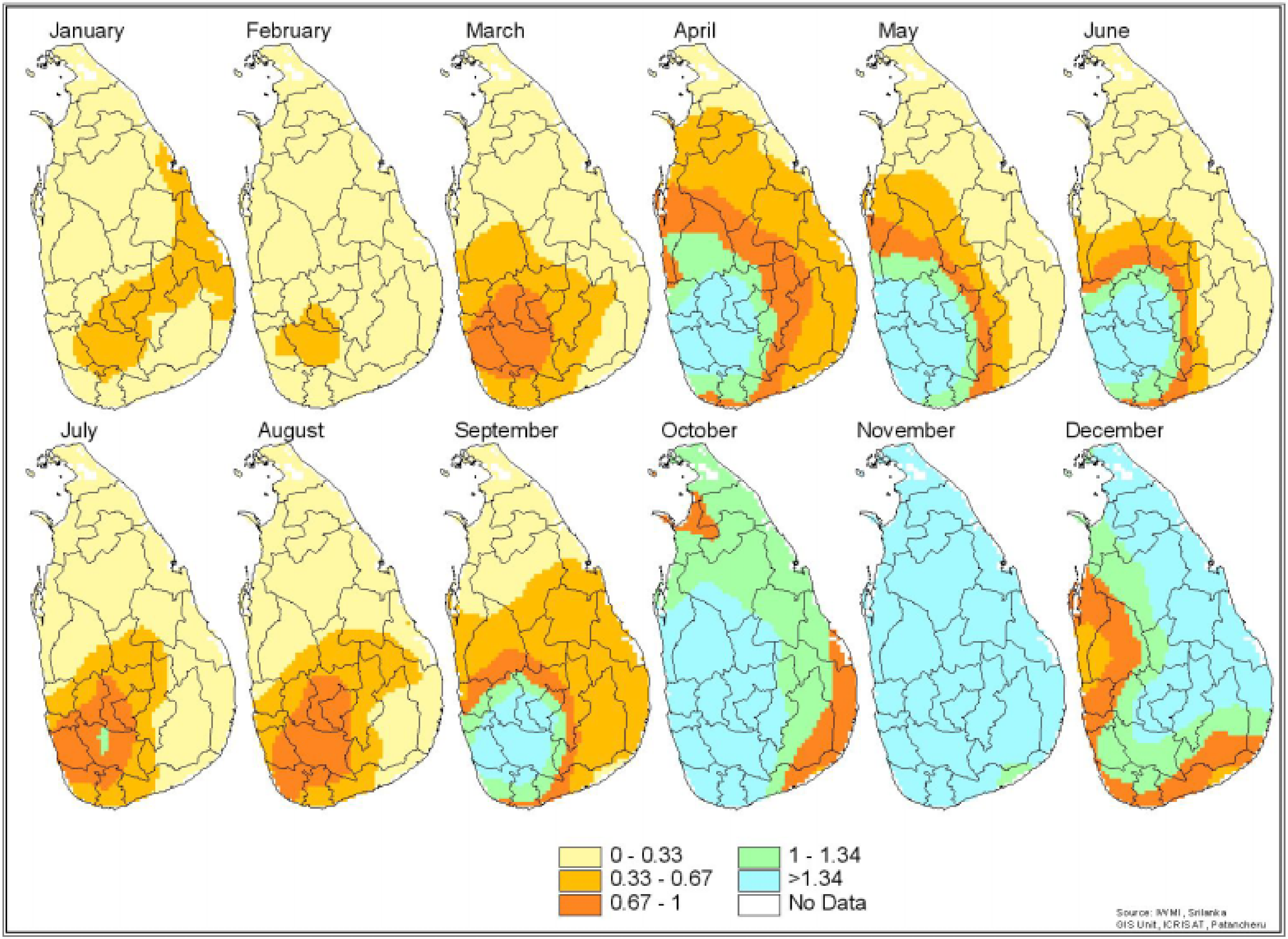


Figure 3.4.6 Moisture Availability Index in Srilanka.

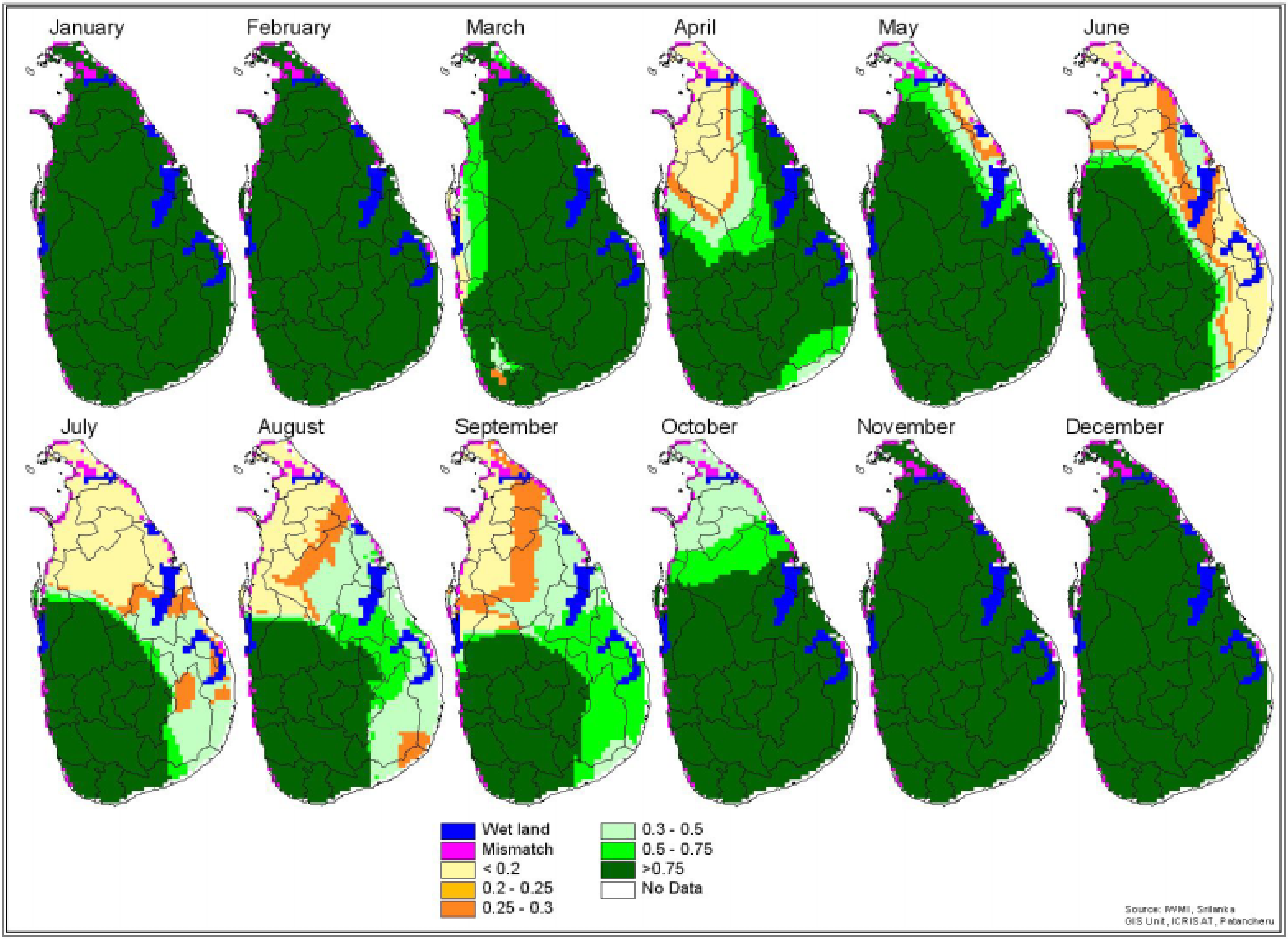


Figure 3.4.7 Actual evapotranspiration / Potential evapotranspiration in Srilanka.

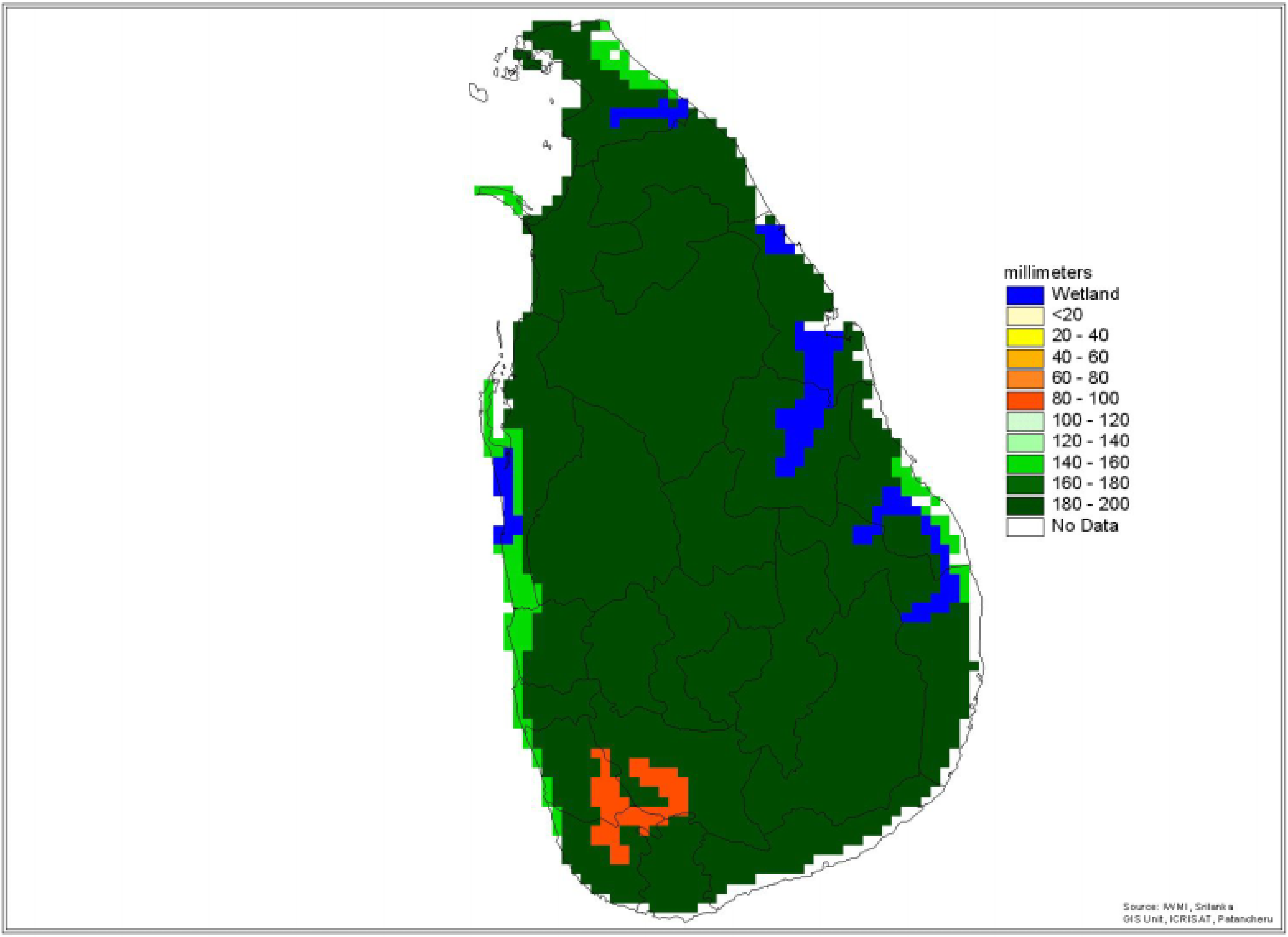


Figure 3.4.8 Soil water holding capacity in Srilanka.

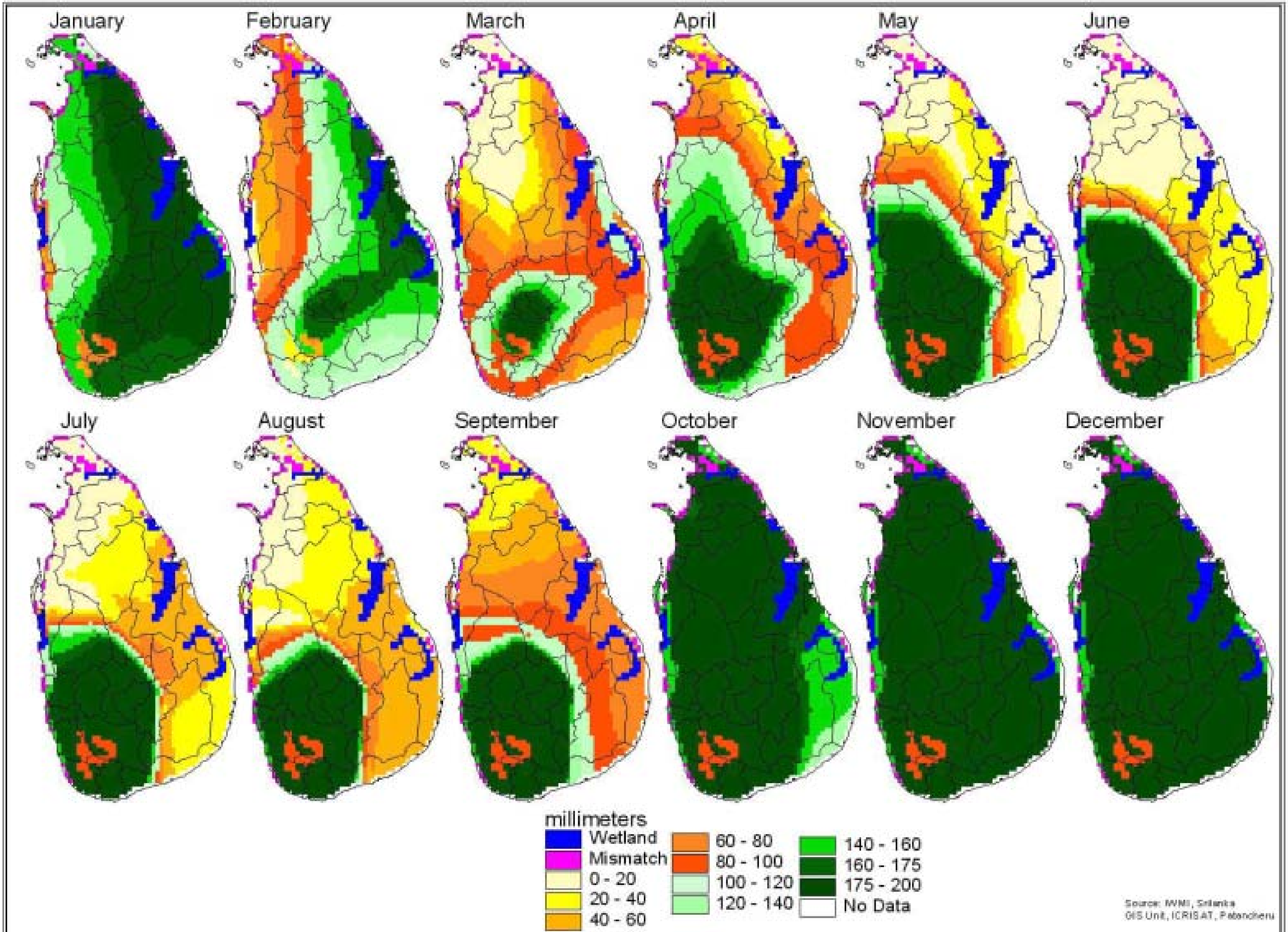


Figure 3.4.9 Soil water availability in Srilanka.

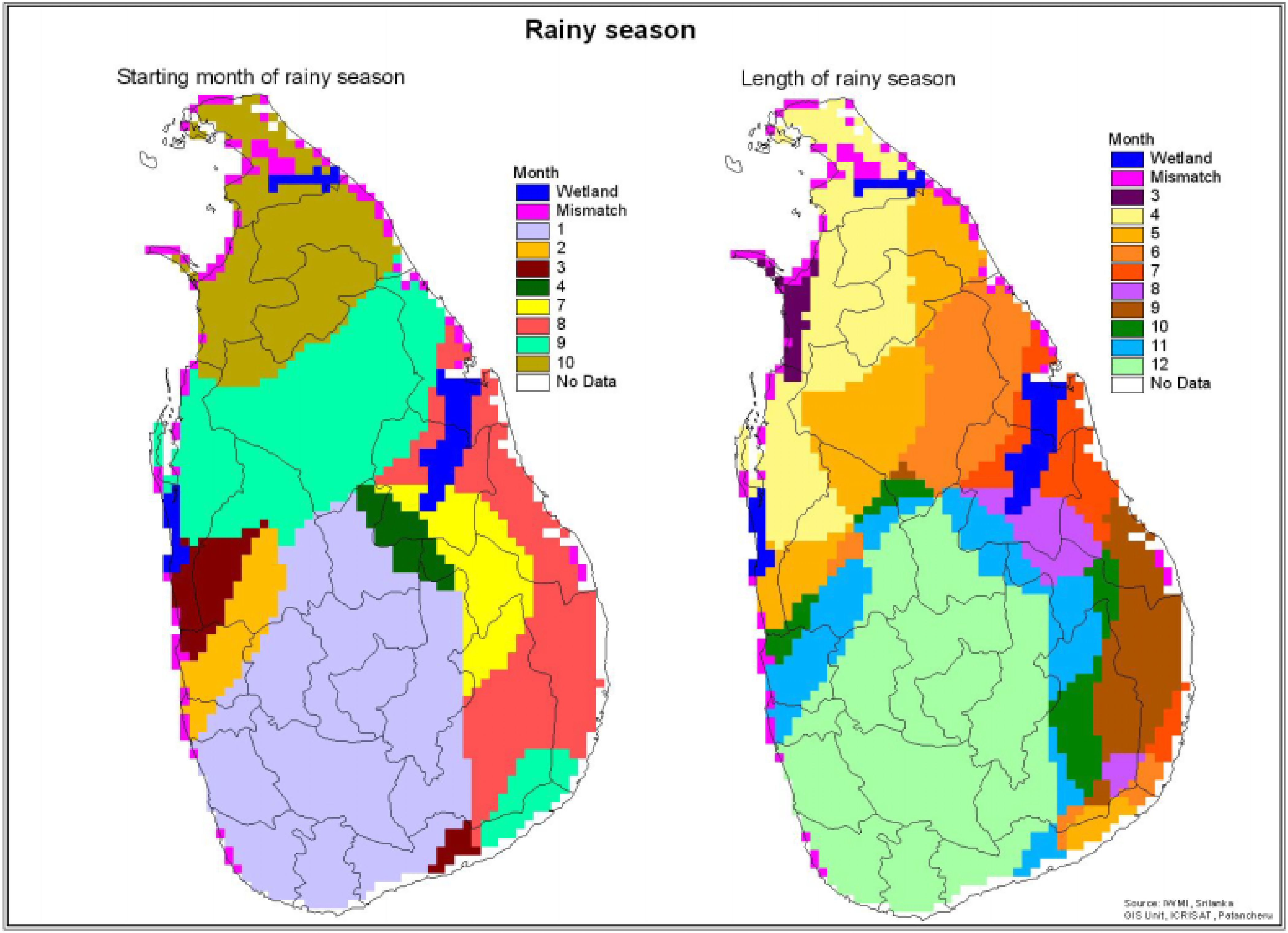
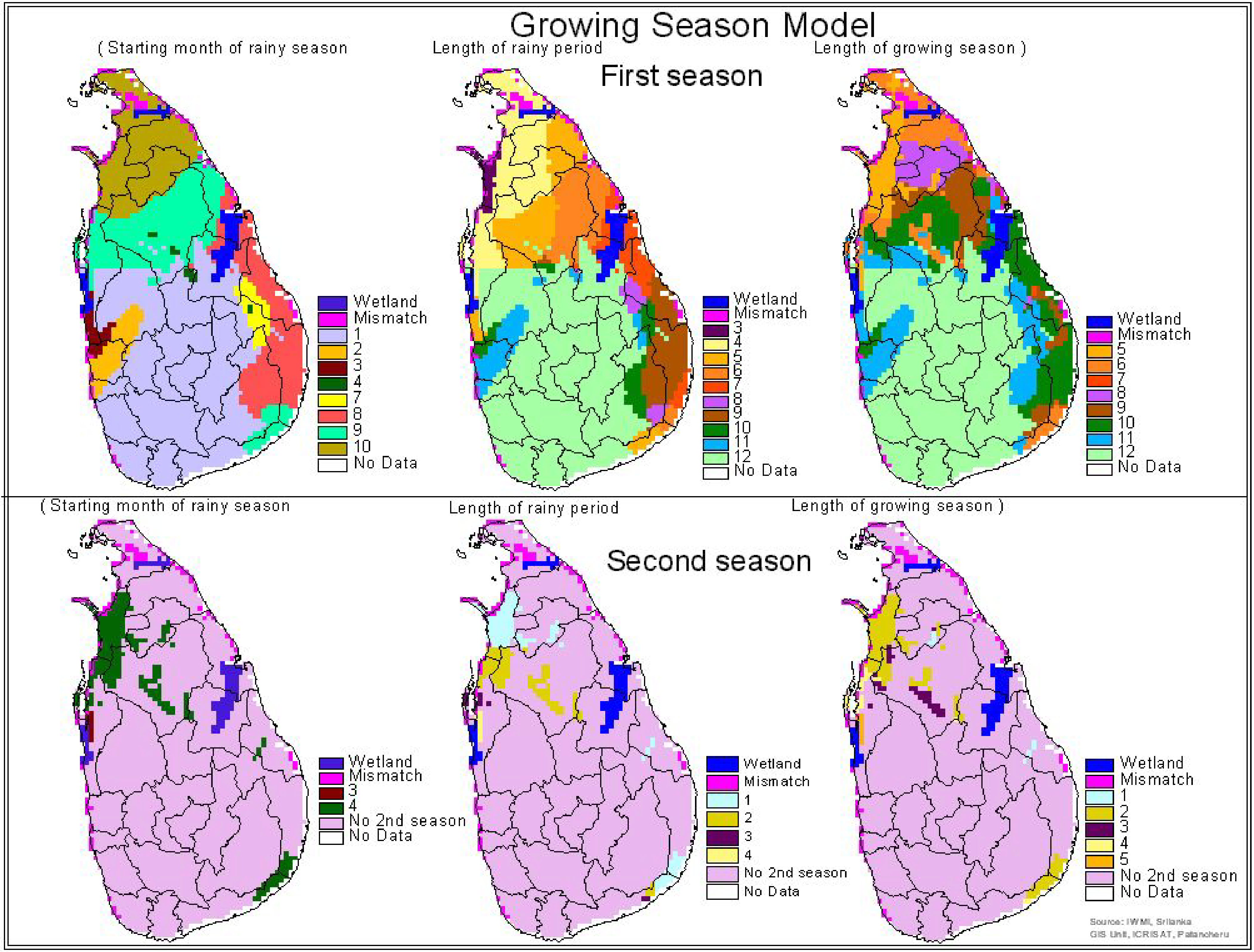


Figure 3.4.10 Precipitation / Evapotranspiration model, Srilanka.


Growing Season Model
(Starting month of rainy season
Length of rainy period
Length of growing season)
First season
Wetland
Mismatch
1
2
3
4
7
8
9
10
No Data
Wetland
Mismatch
3
4
5
6
7
8
9
10
11
12
No Data
Wetland
Mismatch
5
6
7
8
9
10
11
12
No Data
(Starting month of rainy season
Length of rainy period
Length of growing season)
Second season
Wetland
Mismatch
3
4
No 2nd season
No Data
Wetland
Mismatch
1
2
3
4
No 2nd season
No Data
Wetland
Mismatch
1
2
3
4
5
No 2nd season
No Data
Source: IWMI, Srilanka
GIS Unit, ICRISAT, Patancheru

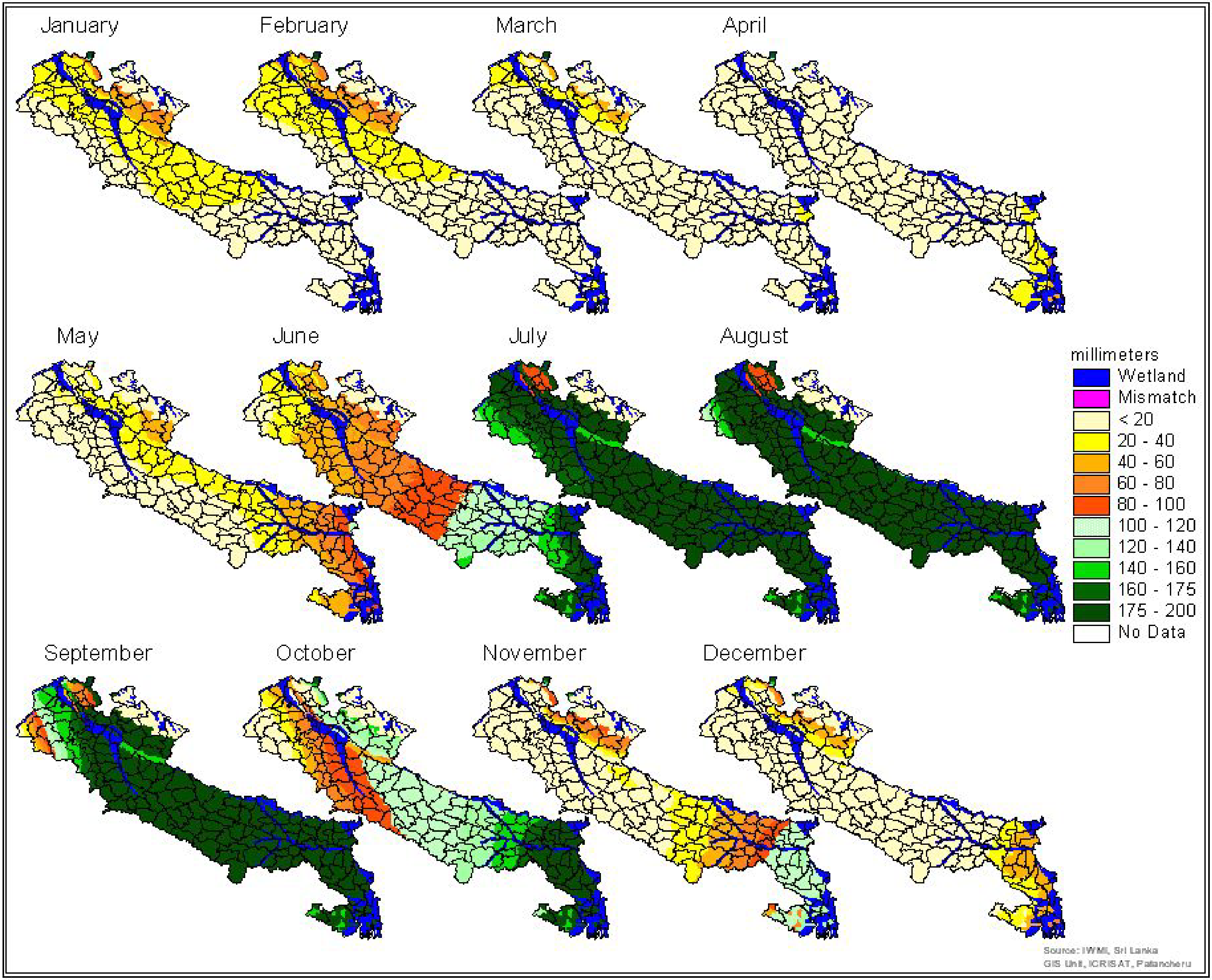


Figure 3.1.9. Spatial and temporal variation soil-water storage (mm) in the Indo-Gangetic Plain.

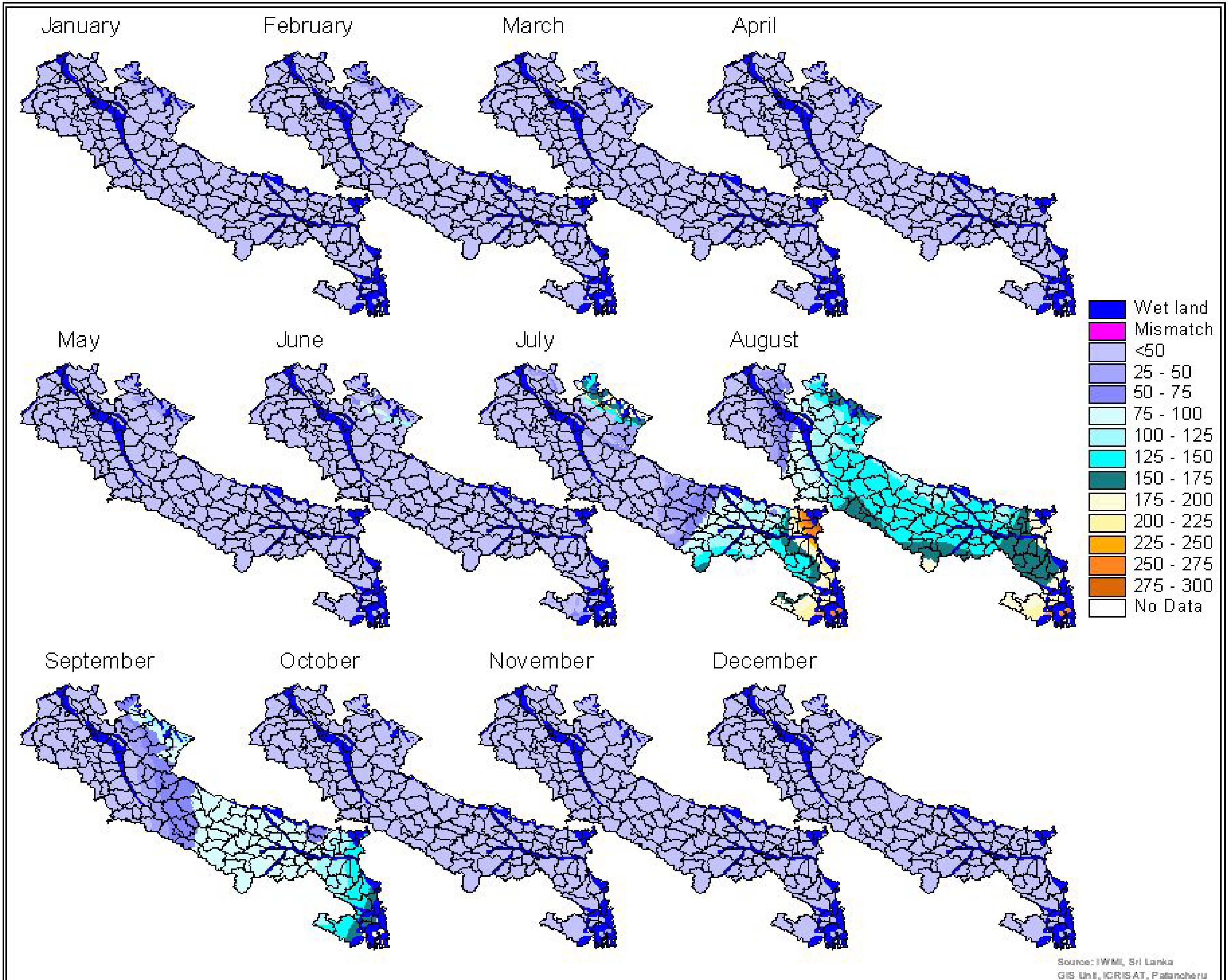


Figure 3.1.10. Spatial and temporal variation in surplus water (mm) in the Indo-Gangetic Plain.

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