Integrated urban water resources management strategy for a smart city in India
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ABSTRACT

Economic growth of any nation like India depends on growth of cities. In India 31% of the total population exists in urban areas. The smart city mission of India was established with the objective to deliver the basic requirements of the citizens in a sustainable manner. Madurai city located at Peninsular India with a 1.4 million population was taken for this study. The objective was to develop an integrated urban water management strategy after analysing all the components of the urban water cycle such as rainfall, runoff, groundwater and wastewater. The population forecast for 2021 was carried out for the Local Planning Area of 726.34 km² and the water demand was calculated as 109 Mm³/year. To meet the demand, runoff from the average rainfall was estimated as 393 Mm³/yr using the SCS-CN method. The storage capacity in the water bodies to store the surface water was estimated as 156 Mm³/yr and groundwater recharge potential was estimated as 22 Mm³/yr. The integrated urban water management strategy developed, shows that there is a huge potential for rainwater storage at the surface level and subsequent recharge through artificial recharge techniques.

Key words | population forecasting, rainfall analysis, runoff estimation, urban water resource management, wastewater reuse, water demand

HIGHLIGHTS

- An overview of an integrated urban water management strategy is projected for a smart city in India.
- The status of water demand and existing status of water resources is discussed.
- Need for groundwater recharge is debated.
- Abundance existence of wastewater and its potential to manage water demand is proposed.
- The study tries to state that water demand is more management than scarcity and stress.

INTRODUCTION

The rapid growth of population, urbanization, changes in living standards, increase in irrigated agriculture, and altering consumption patterns has increased water demand. Water management is gradually becoming a crisis faced by governments all over the world. The world population is expected to reach 9.1 billion in the year 2050 with 69% of people living in cities (93% of such increase is expected to happen in developing countries) resulting in a 55% increase in water demand (Connor 2013). Extractions of water have tripled in the past 50 years causing a decline in freshwater resources. By the year 2030 water supply is expected to be reduced by 40% as a result of urbanization and industrial development, thus impacting both the quality and quantity of available water resources (Van Leeuwen 2013). In the 21st century, the water crisis will be more related to management than scarcity and stress (Tundisi 2008). Climate
change, more recurrent and extreme weather events are known to change the quality, quantity, and seasonality of water available to the urban region and their economic condition (Singh et al. 2014).

Faced with all these challenges, there is a critical need to improve the existing sources of water with more sustainable alternatives. For improvements and augmentation many approaches, both modern and traditional, persist throughout the world for efficiently managing the available water. The conventional method of urban water management follows an isolated approach for each component of the urban water cycle (freshwater, storm water and wastewater) hence developing a new strategy for proper urban water management is required (Cosgrove & Loucks 2015).

The world is rapidly changing to integrated urban water management as it follows a synchronized approach considering all components of the urban water cycle. It is a paradigm shift to attempt to halt the growing water stress faced in several cities worldwide (Gambrill et al. 2016). It instils the practice of managing freshwater, wastewater, and storm water considering both urban development and basin management (Bahri 2012). So far, nearly 80% of countries have laid the foundation for integrated water resource management (UNEP 2012).

The smart city mission concept was initiated in India to meet the requirements of people residing in urban cities. The main focus of the smart city concept is the development of a model that can be reproduced in similar environments. Madurai is one among 100 smart cities selected by the government under the smart city mission. The area considered for the study was Madurai Local Planning Area (LPA) of 726.34 km². The purpose of forming an LPA is to take a detailed look at a specific area, identifying and analysing the various issues of relevance, before establishing and preparing a master plan for the future development of the area. The main aim of the study is to propose a suitable integrated water resources management strategy for Madurai LPA to manage the predicted water demand by the year 2021. The strategy was developed by estimating the status of different components of the urban water cycle such as rainfall, runoff, groundwater, surface water (river and water bodies), and treated wastewater in the study area.

**STUDY AREA**

Madurai, one of the ancient cities of India, is located at 9°93′N and 78°12′E. This city was identified as a smart city by the government of India in the year 2015. The corporation limit of the city was extended from 52.18 km² to 147.9 km² in 2011. The water demand of the city with a total population of 1.4 million (as per the 2011 census) was found to be 209 million litres per day (MLD). With the existing water resources, the city corporation supplies only 115 MLD for domestic use, resulting in a water shortage of 94 MLD. The temperature in Madurai was found to range from 21 °C to 38 °C with an annual average rainfall of 850 mm (Alagarsamy 2013).

The Madurai LPA covering 726.34 km² was formed in the year of 1974 based on the Tamil Nadu Town and Country Planning Act 1971. It comprises the Madurai corporation area (both old (52.18 km²) the existing area (147.9 km²)) and the environs (Figure 1). The total population in the study area was found to be 1.9 million (as per the 2011 census).

With the increase in population, Urban sprawl is expected to expand towards the Madurai LPA. Hence there is a need to ensure the status of water resources in the region and to propose a plan for its proper management.

**MATERIALS AND METHODS**

The methods adopted for this study are as shown in Figure 2. Initially, population data for Madurai LPA was collected for 7 decades (1951, 1961, 1971, 1981, 1991, 2001, and 2011) and the population for the year 2021 was predicted using the arithmetic mean method, geometric mean method, and incremental increase method. Water demand and wastewater generation rates were calculated for the year 2021 considering the projected population. Rainfall analysis was performed by adopting the Weibull method to find the 75% dependable rainfall using 10 years’ rainfall data collected from the Public Works Department (PWD), Madurai and overall average precipitation of the region was also estimated using the Thiessen polygon method using Arc Geographical Information System (GIS) software version 9.2. Then with the daily rainfall data and antecedent
Figure 1 | Study area.
moisture condition data, the runoff volume was estimated using the Soil Conservation Service – Curve Number (SCS-CN) method. A Land Use and Land Cover (LULC) map and Soil map required for runoff estimation were created using Arc GIS software version 9.2 with satellite images (Landsat, IRS-P6 of 2017 with 30 m resolution). The groundwater recharge potential was estimated using the fluctuation method by considering 12 years of water level data collected from the PWD, Madurai. The status of water bodies in the study region is also discussed based on the data collected from PWD. In addition to the above discussion, suitable methods and options for implementing artificial recharge techniques are also suggested. Finally based on the results an integrated water management strategy was developed.

RESULTS AND DISCUSSION

Population forecasting

The population estimation is essential to recognize the current and future water demands. The population data of the past 7 decades (1951, 1961, 1971, 1981, 1991, 2001, and 2011) were collected from the statistics department of Madurai, Sivagangai & Virudhunagar districts, and Census Reports. The population in the year 2021 was predicted using the arithmetic mean method, geometric mean method, and incremental increase method (Alagarsamy 2016). Of the above three methods, the value predicted using the incremental increase method (Table 1) was adopted for further water demand calculation.

Water demand & wastewater generation estimation

Water demand of the study area in the year 2021 was estimated using Equation (1) considering 135 litres per capita per day (lpcd) as water demand as per Central Public Health and Environmental Engineering Organisation (CPHEEO) norms (Reddy & Kurian 2010):

\[
\text{Water Demand}_{2021} = (\text{Population} \times \text{Per capita demand}) (1)
\]

Water Demand\textsubscript{2021} = 2.2 million × 135 litre/day = 297 MLD = 108405 ML/year = 109 Mm$^3$/year
It is estimated that 80% of the total water supplied will be generated as wastewater as per CPHEEO norms (Reddy & Kurian 2010). Therefore, wastewater generation in Madurai LPA by 2021 was found as 87 Mm³/year. The study area has two sewage treatment plants (STP) with the capacity to treat 171 MLD (62.3 Mm³/year) (Amarnath & Sridevi 2010) using Cyclic Activated Sludge Technology (Hardy 2018). Due to the lack of proper drainage network and channel connectivity, the treatment plants receive only 20–30% of wastewater currently generated in the city, while the remaining portion of wastewater is let out into the channel system and used for agricultural practice (Chandran et al. 2017). Hence effort should be taken to effectively utilize the existing channel systems and pumping station to collect and treat all wastewater generated in the city.

Rainfall analysis

Rainfall information is important for the assessment of water resources availability and water resources planning (Mishra et al. 2013). The rainfall analysis was performed by integrating 10 years (2004–2013) of daily rainfall data of nine rain gauge stations located within the study area. Frequency analysis was performed using the Weibull method (Rajendran et al. 2016) to identify the amount of rainfall that had occurred the maximum number of times in a particular area (i.e. in each taluk). The 75% dependency rainfall (Table 2) was calculated using Equations (2) and (3) (Rajendran et al. 2016):

\[
T_r = \frac{n + 1}{m} \quad (2)
\]

\[
P = \frac{1}{T_r} \quad (3)
\]

where:

- \(n\) is the total number of events in the data series
- \(m\) is the order number of each event when the data are arranged in descending order.

Precipitation is not uniform over the area, correspondingly temperature, humidity, and several other influencing factors also vary from place to place. Hence effective uniform depth of precipitation over the study area was also calculated using the Thiessen polygon method (Mishra et al. 2013) as shown in Figure 3. This is a graphical technique used to calculate rainfall based on relative area. The mean areal depth of rainfall over the study area was found to be 782 mm using Equation (4):

\[
P_{\text{avg}} = \frac{\sum_{i=1}^{N} (P_i A_i + \ldots + P_N A_N)}{A} \quad (4)
\]

where:

- \(P_{\text{avg}}\) is average rainfall in mm
- \(P_i\) is rainfall for an individual station in mm
- \(A_i\) is area of influence for an individual station in km²
- \(A\) is total area in km².
The overall analysis of the rainfall trend showed a non-linear variation and peak rainfall was observed during September, October, November, and December, i.e., during the North-East Monsoon. The rainfall pattern represented that Madurai LPA experienced a fluctuating drought and flood condition. Hence a sustainable strategy is needed to use the freshwater generated constantly both during the flood and drought conditions.

Runoff generation

Surface runoff another major component of the water cycle was estimated using the SCS-CN method. This is one of the important methods for calculation of runoff and was first introduced by the United States Department of Agriculture (USDA) (Satheeshkumar et al. 2017).

An LULC pattern for Madurai LPA (Figure 4) was prepared using Arc GIS 9.2 as it had several impacts on the hydrological cycle such as floods, droughts, runoff, water quality and it is one of the important parameters in CN generation. From the LULC map, it is known that a major proportion of the study area exists as wasteland (3%) followed by settlement covering 35% of the study area, 8% area of the industrial region, 8% of the area is occupied by water bodies, 7% area of the hills region and remaining 39% of the area is occupied by agricultural region.

Similarly, the Soil map was prepared using Arc GIS 9.2 software, and identified that the region is dominated by red sandy loam soil and it falls under Group C Soil classification with a moderate infiltration capacity of 0.0004–0.001 mm/s (Amutha & Porchelvan 2009). Using LULC, soil data and based on antecedent moisture conditions (AMC) the CN was generated for three conditions namely Dry, Normal,
and Wet (Amutha & Porchelvan 2009) as shown in Table 3. The average annual runoff generation was estimated as 248 Mm³, 393 Mm³, and 516 Mm³ (Dry, Normal, Wet) respectively.

The quantum runoff generation was calculated using Equation (5) and the result is represented in Figure 5:

\[ Q = \frac{(P - I_a)^2}{(P - (I_a + S))} \]  

(5)

where:

- \( Q \) is accumulated runoff or rainfall excess in mm
- \( P \) is rainfall in mm
- \( I_a \) is initial abstraction in mm (surface storage, interception and infiltration prior to runoff) and it is given by Equation (6):

\[ I_a = 0.2S \]  

(6)

where \( S \) is potential maximum retention and it is given using Equation (7):

\[ S = \left( \frac{25400}{CN} \right) - 254 \]  

(7)

where \( CN \) is curve number estimated using Equation (8):

\[ CN_w = \sum \frac{CN_i A_i}{A} \]  

(8)

where:

- \( CN_w \) is weighted \( CN \)

Table 3 | Curve number for all 3 AMC

| AMC | Condition | CN  | S    |
|-----|-----------|-----|------|
| I   | Dry       | 63.52 | 145.90 |
| II  | Normal    | 79.88 | 63.96 |
| III | Wet       | 90.29 | 27.31 |
CN<sub>i</sub> is curve number from 1 to any N
A<sub>i</sub> is an area with curve number CN<sub>i</sub> in km<sup>2</sup>
A is the total area in km<sup>2</sup>.

The estimated runoff values were correlated with the rainfall data. From this correlation, it is clearly understood that the antecedent moisture condition of the soil plays a dominant role in the quantity of runoff generated. From the runoff estimation, it is also clear that possibilities for dry conditions prevailed during the last two years (2012 and 2013), but during that case too, the runoff generated was enough to compensate the water demand in the study area.

**Groundwater recharge potential estimation**

The groundwater recharge potential was assessed to find whether there is enough storage capacity in the subsurface to store the runoff generated if we adopt suitable recharge options to improve the water source. Under the study area, 10 bore well stations and 5 open well stations were located and their monthly groundwater level data collected from the

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**Table 4** Comparison of water depth and rainfall data in the study area

| Sl. no. | Name of the blocks (Figure 1) | 2002 to 2004 (Average) in mm | 2005 to 2007 (Average) in mm | 2008 to 2010 (Average) in mm | 2011 to 2013 (Average) in mm |
|---------|-------------------------------|-----------------------------|----------------------------|-----------------------------|----------------------------|
|         | Rainfall | Water depth | Rainfall | Water depth | Rainfall | Water depth | Rainfall | Water depth |
| 1       | Vadipatti Block             | 805 | 80 to 100 | 1000 | 20 to 180 | 1031 | 50 to 60 | 687 | 90 to 200 |
| 2       | Madurai North (West Block)  | 906 | 40 to 80  | 1048 | 20 to 80  | 1048 | 20 to 80  | 716 | 20 to 80  |
| 3       | Madurai North (East Block)  | 717 | 60 to 130 | 923  | 40 to 100 | 970  | 40 to 70  | 745 | 50 to 100 |
| 4       | Madurai South Block         | 698 | 70 to 220 | 938  | 40 to 160 | 800  | 90 to 170 | 652 | 40 to 590 |
| 5       | Thirumangalam Block         | 791 | 100 to 110| 944  | 80 to 90  | 1093 | 10 to 60  | 743 | 10 to 80  |
| 6       | Manamadurai Block           | 1306| 140 to 240| 923  | 40 to 100 | 970  | 40 to 70  | 745 | 50 to 100 |
Table 4 represents block-wise comparison between water depth and rainfall data. It can be inferred from the table that regions (Madurai North, Tirumangalam) with agriculture as a predominant practice can maintain their water level despite variation in rainfall pattern, whereas regions (Vadipatti, Manamadurai, Madurai South) with increasing settlements, the encroachment of water bodies, lack of practicing agriculture were found to face fluctuation in the groundwater level.

The groundwater potential estimation (GWP) was carried out using the fluctuation method (Equation (9)) (Jeykumar & Chandran 2019) assuming specific yield for the region as 2% (CGWB 2007a).

Fluctuation method

\[
\text{Average groundwater potential (GWP)} = A \times \Delta S \times \Delta h \quad (9)
\]

where:

- \(A\) is area in km\(^2\)
- \(\Delta S\) is specific yield in % = 0.02
- \(\Delta h\) is average change in water level in m.

The groundwater potential estimated using the fluctuation method was 22 Mm\(^3\) as given in Table 5. There is a reasonable amount of groundwater potential to store the runoff generated from the rainfall. Hence it is necessary to

| Thiessen polygon region (Figure 3) | Well number | Area (km\(^2\)) | Pre monsoon | Post monsoon | \(\Delta h\) Change in water level (m) | Recharge potential volume (Mm\(^3\)) |
|-----------------------------------|-------------|-----------------|-------------|-------------|-------------------------------------|-------------------------------------|
| Andipatti                         | nil         | 30.92           | No well     | –           | –                                   | –                                   |
| Mettupatti                        | 21013D      | 74.2            | 5.3         | 5.6         |                                     |                                     |
|                                  | 21036D      | 4.2             | 5.3         |             |                                     |                                     |
|                                  | Average     |                 | 4.7         | 5.4         | 0.7                                 | 1.0                                 |
| Kallanthiri                       | nil         | 36.01           | No well     | –           | –                                   | –                                   |
| Sholavandhan                      | 83014B      | 82.6            | 5.3         | 4.7         |                                     |                                     |
|                                  | 21027D      |                 | 12.1        | 12.7        |                                     |                                     |
|                                  | 21008D      | 8               | 9.4         |             |                                     |                                     |
|                                  | 83025       | 8.6             | 9.7         |             |                                     |                                     |
|                                  | Average     |                 | 8.5         | 9.1         | 0.6                                 | 0.99                                |
| Thallakulam                       | 21014D      | 107.9           | 19          | 19.1        | 0.1                                 | 0.32                                |
| Chettampatti                      | 83016A      | 43.3            | 2.7         | 3.2         | 0.5                                 | 0.42                                |
| Thirumangalam                     | 21009D      | 74.9            | 10.1        | 10.3        |                                     |                                     |
|                                  | 83062A      | 8.8             | 9.5         |             |                                     |                                     |
|                                  | Average     |                 | 9.4         | 9.9         | 0.5                                 | 0.75                                |
| Airport                           | 21001D      | 153.3           | 12.2        | 11.7        |                                     |                                     |
|                                  | 21035D      |                 | 21.7        | 34.9        |                                     |                                     |
|                                  | Average     |                 | 17          | 23.3        | 6.3                                 | 19.3                                |
| Madurai South                     | 21010D      | 96.6            | 8           | 8           |                                     |                                     |
|                                  | 83075       | 5.3             | 4.4         |             |                                     |                                     |
|                                  | Average     |                 | 6.6         | 6.2         | –0.5                                | –0.87                               |
| Thiruppuvanam                     | nil         | 24.51           | No well     | –           | –                                   | –                                   |
| Kariapatti                        | 21005D      | 2.1             | 21.1        | 22.2        | 1.1                                 | 0.05                                |
| Total recharge potential          |             |                 |             |             |                                     |                                     |

21.51 Mm\(^3\) = 22
adopt suitable recharge options to enhance a sustainable water resource management plan.

**Artificial recharge**

Artificial recharge is one of the most efficient methods in groundwater management tools for controlling groundwater depletion. Augmentation of the groundwater by using artificial recharge works has been carried out in different parts of the globe (CGWB 2007b) for the consecutive four decades in arid or semi-arid areas (Sakthivadivel 2007). Before making suggestions on artificial recharge options, it is necessary to consider water depth variation (Figure 6) and other influencing factors for such variations like soil characteristics, rainfall, surface water source, etc. Among various methods of recharge techniques, water spreading, dug well/borewell recharge, and percolation ponds were suggested as suitable methods for geographical and topographical conditions of the city (Sharma et al. 2000).

The following two options can also be considered while adopting any of the above-mentioned recharge techniques:

Option 1: There are two STPs within the study area and they have the capacity to treat 171 MLD of wastewater. Hence wastewater generated in the region can be treated in the STPs to meet the standards (Sengupta 2000) and using 13 channels systems that exist within extended corporation limits (Hardy 2018) these treated wastewater can be stored in the water bodies (system tanks) through a cascade system. Nearly 8% of the study area is covered with water bodies. This stored treated wastewater can be further used for the non-potable purpose and indirectly the wastewater will also recharge the subsurface.

Option 2: Based on LULC classification it was identified that nearly 3% of the study area exists as wasteland. These lands can be used for executing recharge structures. Also, these lands can be planted with native vegetation to control runoff in the region, avoid evaporation of runoff water, and to enhance natural recharge in the region.

**Surface water status**

Madurai is a city with an average annual rainfall of about 850 mm. People depend upon surface and subsurface water resources to meet their water demand. To manage the water demand water bodies(tanks) status, and their potential as water recharge structures were also discussed in this study.

The details of surface water bodies located within the old corporation limit and LPA was collected from toposheet and the PWD. The total number of tanks within the old corporation limit was identified as 25. Out of it, only five tanks were found to be in good condition with a storage capacity

![Figure 6](http://iwaponline.com/ws/article-pdf/21/2/736/925411/ws021020736.pdf)
of 10.65 Mm$^3$. The remaining 20 tanks were found abandoned and encroached due to the construction of bus stands, housing board flats. The major reason for the abandoned tanks is uncontrolled and unplanned urbanization taking place in the city. If the same status continues, it is expected that by 2021 urbanization would take place encroaching nearly 50% of total available surface water bodies (Atkins 2014) in the study area as shown in Figure 7.

The total number of tanks within LPA was 259. Among the total 259 tanks, only 44 tanks are big tanks with water spread area greater than 0.5 km$^2$, and the remaining are small tanks. Out of 44 big tanks, details were obtained for only 21 big tanks from PWD and their water storage capacity was estimated as 145 Mm$^3$. Although all the water tanks are not considered, the capacity of a very few tanks represented itself was enough to store water required to meet the water demand of Madurai LPA. However, all the water bodies within the study area should be conserved by proper maintenance as their storage potential will be of great value in the near future.

Madurai city resides on the banks of the river Vaigai (non-perennial). In addition to water bodies, the river Vaigai is also considered as one of the main sources of water for the city. Currently, the city receives 42 Mm$^3$ of water every year through a pipe system from the Vaigai dam after proper treatment in the Panaipatti water treatment plant (capacity 72 MLD) which is located at a distance of 16 km from the Vaigai dam (Alagarsamy 2013).

**Integrated urban water management strategy**

Based on the results, an integrated urban water management strategy was developed as shown in Figure 8. It represents all possible ways by which the precipitation can be...
efficiently managed to reach the end-user (urban population) and their corresponding quantified values. With the predicted population of 2.2 million, the water demand is estimated as 109 Mm³/year. Currently, the city receives 42 Mm³ water from the Vaigai reservoir after proper treatment. The mean area depth of rainfall over the study area was found to be 782 mm per year. Based on LULC pattern, soil condition and antecedent moisture condition, the runoff generated under normal condition is quantified to be 393 Mm³.

The groundwater recharge potential to store the runoff generated in the subsurface is estimated as 22 Mm³. To enhance the recharge a few options are given: (a) Nearly 8% of the study area is covered with water bodies with a storage capacity of 156 Mm³. Implementing suitable artificial recharge techniques inside this surface water bodies such as big tanks, small tanks and temple tanks will improve the groundwater level. (b) Wastewater generation in the region was estimated as 87 Mm³/yr out which the installed treatment capacity is 62.3 Mm³/yr. This treated wastewater with 30 mg/l of BOD (as per Central Pollution Control Board Standard, 2000) may be stored in the small irrigation tanks and used for urban agriculture and groundwater recharge. (c) Residential, commercial and industrial establishments in the urban region are encouraged to carry out both roof water harvesting and recharge through dug well and bore well and percolation ponds to improve the groundwater level. (d) Wasteland area of 3% is available within the LPA where the artificial recharge structure and cultivation of native trees can be implemented to control runoff and evaporation. By adopting such a strategy the complete cycle of water (from source to discharge and reuse) within the urban space can be managed effectively.

**CONCLUSIONS**

The smart city mission of India focuses on sustainable, inclusive development and to create a replicable model which will act like as a light house to other aspiring cities.
Keeping this as a point of focus this study was undertaken for Madurai, a smart city with 1.4 million population. By assessing the existing water resources potential of the city an integrated urban water management strategy was developed. The results of the study reveal the following:

- Population of the study area is forecasted for 2021 using an incremental increase method as 2.2 million. The present water supply system can satisfy only 38% of predicted water demand hence, all other feasibilities are explored in this study.
- The mean area depth of rainfall was estimated as 782 mm and the runoff generation was 393 Mm³/yr which is 3.6 times higher than the predicted water demand (109 Mm³/yr).
- Groundwater recharge potential was estimated as 22 Mm³. By adopting suitable recharge techniques in the LPA area of 726.34 km² especially in the water bodies around 40% of runoff generated can be stored efficiently. But the interconnecting systems between the river, channels and system tanks have to be restored to their original condition that existed 5 decades before.
- The predicted urban population will be generating 87 Mm³/yr wastewater, out of which 71% of wastewater can be treated with existing advanced treatment facilities functioning with the technology of the Cyclic Activated Sludge Process. As this treated wastewater met the standards prescribed by the government (BOD 30 mg/l), this can be stored in water bodies and used for urban agriculture which has been practiced in this region for more than 35 years.
- Integrating the various sources such as treated water from the Vaigai reservoir, surface runoff generated from the rainfall, groundwater recharge using artificial recharge structures and reuse of treated wastewater will meet the future demand.

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CONFLICT OF INTEREST

The authors have no conflict of interest

DATA AVAILABILITY STATEMENT

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

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