Addressing water security of an Urban settlement through multisource modeling

Auroville Centre for Scientific Research

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Executive Summary

Water has always been a primary need for development of life. Human history has recorded flourishing civilizations in different areas of the planet, in different periods, and different cultures, all having in common access to water. On the opposite, civilizations and towns built in regions without easy access to water have failed to sustain, and disappeared.

The Indian subcontinent has provided since millennia examples of flourishing and long-lasting societies along rivers and water bodies, creating systems to preserve or even augment water availability throughout the year, even during dry seasons. The main source of water was always rain, either collected directly in harvesting structures purposely built, or left to percolate into the ground to replenish aquifers, and then accessed through shallow open wells.

Recently, due to growing population and developmental needs, exploitation of water is no longer balanced by natural recharge cycles of aquifers, with the result that these cannot supply the demand of water in many areas. Further, deep borewells have been juxtaposed to traditional open wells, thus unbalancing deeper aquifers too. Additionally, traditional water retention tanks have been neglected or disused, resulting in runoff of large volumes of rainwater eventually ending into the sea.

The issue is then defined as shortage of water quantity available for all uses. This is particularly evident when groundwater is used as the only available source.

An attempt to counteract this situation consists in evaluating the different sources of water for different uses: it involves identifying the available sources, evaluating their quantities and qualities, implementing systems of collection, treatment and storage, identifying their usage accordingly, applying governance procedures to maintain the system. This project focuses on the first two points, identification of sources, and evaluation of their potentials.

In CSR, a specific activity cell has been created, CSR Geomatics, to research and accomplish the project aims. The findings during the project led to the definition of a complex set of scientific methods and procedures for evaluating the potential of different water sources, in particular through quantification of potential sources like rain/storm water and treated wastewater, in the Area of Interest (AoI), being it the Residential Zone of Auroville.

A team has been assembled to collect specific, standardized data with very high accuracy, using advanced technology for topographic survey and water sources-related data. Team members were trained to process information through concepts of normalisation of data and use of complex workflows, from field to finish, including processing of large volumes of topographic data, creation of geospatial database, processing of aerial imagery through already existing plugins of Geographic Information Systems, or purposely-created algorithms for evaluation of geospatial datasets.

For evaluation of rain/storm water potential, a model for quantification of minimum potential runoff from rain and storm water was developed, starting from a detailed topographic survey conducted in the Residential Zone of Auroville: ground levels and built-up surveyed features allowed for detailed terrain knowledge. An UAV (Unmanned Aerial Vehicle, drone) survey has been conducted to gather additional information on vegetational cover, and test reliability and accuracy of drone survey. Infiltration data about the area has been gathered and analysed from previously conducted studies. The model makes use of the extensive collected data, through algorithms created specifically for the purpose. The methodology allows to automatically compute runoff volumes with minimal human input,
through simulation approach, in a high resolution, distributed deterministic static (event-based), physically based model in ungauged catchment.

For evaluation of wastewater, collection of available water consumption data and consequent calculation of wastewater generated is attempted. To reach the goal, a quantified assessment on a “per capita per day” basis on the overall water consumption is necessary to quantify the actual needs; given the difficulties in retrieving consistent, reliable data on consumption, a series of assumptions and projections have been undertaken.

Parallelly, monitoring systems for groundwater levels and rainfall and other weather parameters have been established. Besides providing accurate data, the sharing of all collected information also allows for updating the involved stakeholders on the actual situation: an attempt to raise public involvement about the water resources crisis, trying to start a participatory process to consider reduction of water consumption, and suggesting effective ways towards water conservation. Important also, it emphasises the order of magnitude that is required to integrate other potential water sources to meet the overall demand.

Concluding, a calculation of water requirements versus water sources potential is proposed.

All collected data are published online at gis.auroville.org.in, a specifically-built web platform which acts as the graphic interface between a large PostGreSQL database and its geospatial representation.

Once the model is further calibrated and validated, the largely positive water budget resulting from the computation indicates the need of an executive plan of action for capturing the other accessible water sources to address water security in urban settlements.

The project will initially benefit Auroville residents with the aim to evolve a water security model. The program can be used by town planners as an effective integral water management tool. At the same time, the potential beneficiaries will be the inhabitants of surrounding villages in the bioregion.

The project outcome provides a model for a multisource water approach, elaborating the requirements for rigorous collection, storage and data processing to evolve and propose a plan of action for increasing water security at urban, peri-urban, rural and regional levels.

Government agencies, architectural, engineering firms and industries can develop practical solutions for rainwater harvesting from built-up features in urban contexts, and designing multiple distribution systems of water with different quality for all new buildings both publicly and/or privately owned.

If industries and agencies involved in design and implementation of wastewater treatment systems can ensure a high quality of treated sewage and effluent, this segment of water source can then be integrated into urban water distribution cycle for specific types of usage, thereby reducing dependency on a single water source (groundwater/rivers/lakes) to factually contribute towards water security.
Considerations and recommendations

Data acquisition:
Estimation of overall water consumption, even in pre-selected places, is a very challenging exercise, even harder if the consumption per capita is to be evaluated. Reliability of data, structure of data acquisition devices, outlays of water network and distribution systems, not to mention the local, individual changes and exceptions to the overall system, pose a considerable challenge to any attempt of estimation, not knowing even the margins of error. Results, interpolations and/or projections might be far off the reality, thus impacting severely the correctness of proposed actions to be taken.

Accurate metering of water consumption
Eliminating assumptions when proper data are not available, will require the installation of flow meters as a principal requirement, thereby largely ending the exercise of having to estimate water consumption patterns.
Technology is available to provide for automatic flow meters, transmitting data remotely, allowing for storage in databases and building of dashboards for each user. Dashboards can show consumption even by minute, allowing a personal awareness, and an opportunity towards a more efficient use of the water resources.

Metering of water for irrigation
Irrigation, both at farm and at domestic level, is still the activity using the largest quantity of water. Installation of meters at least at farm/community level will improve proper use of the resources, with implementation of smart practices for irrigation timing and duration. Opting for irrigation/watering systems, like drip irrigation systems or smart irrigation systems will contribute considerable to saving water.

Proper maintenance of metering facilities
Maintenance and most of all regular calibration of all meters are to be considered absolute necessity to avoid inaccuracy of readings over time, thus hampering the reliability of water quantification results.
Periodic upgradation of the equipment provides opportunities for integration of new technological innovations.
Financial investment will be required for maintaining and/or upgrading technical equipment to maintain their technical standard and reliability.

Networking of databases
It is advisable to have one point of entry for data sources management; even if different databases exist or are built with regard to specific subjects (water, energy, housing, assets, etc): having them linked with each other through a common database field will facilitate interconnection between different disciplines, cutting down time for accessing diverse data, thereby making all planning exercises easier.
A by-product of this approach will be a culture of sharing scientific and technological data and expertise, promoting scientific collaboration among institutions, enhancing collaborative research in cross-disciplinary areas, at the same time providing solid ground for appropriate capacity building in different sectors.
Design of new buildings with a need to integrate multisource water management

Designing new buildings, infrastructure should allow for multisource water management: having dedicated pipelines and systems for use of different types of water will favourably and strongly impact on water consumption patterns, and on overall water balance.

Maintenance of existing potential sources of water

Existing wastewater treatment plants should be considered as “gold mines”: this source of water is already available, it needs to be properly maintained and/or upgraded with latest concepts and technologies. Ensuring that this largely untapped water source follows quality standards to guarantee for safe human activities will facilitate its proper usage.

Manpower training

Constant monitoring of water resources, like well levels and volume of rainfall, as well as quantities of wastewater generated, making use of proper new technological devices requires skills for which trained manpower pool is required. Having operators who understand what is the impact of their work will contribute their commitment and dedication to their tasks, encouraging personal networks of acquaintances to become knowledgeable with the water scenario and perhaps engage in water conservation actions.

Need for monitoring and collecting data in the surrounding villages

Auroville is not an isolated place, it lives together with lakhs of people in a water stressed area. The project could be the catalyst for actions to be undertaken in the wider region. Auroville can provide skills and expertise gained through years of experience and innovative approaches.

Dissemination

Science and technology are disciplines meant for the widest number of beneficiaries possible: dissemination of activities conducted and results obtained, including failures and successes, will help good practices and examples to benefit whoever wants to learn; sharing facilities with other institutes/individual researchers and students to enhance research and training, and organization of capacity building programmes at different levels for water management are to be elaborated.
Note of appreciation

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CSR Geomatics
CSR-Auroville Centre for Scientific Research
Auroshilpam, Auroville – Tamil Nadu, 605101 – INDIA
csrgeomatics@auroville.org.in

CSR Geomatics current team members
Giulio Di Anastasio  Tency Baetens  Philippe May
Pushparaj M        S Ramkumar  Selvarani Karunagarane  Bala Ramachandran

Past team members
Pavneet Kaur  Swathi D’Souza  Meera Natarajan  Jeanne Latusek
Debojyoti Mallick  Ashish Garg  Dorian Naraud  Eric Conesa

Inputs and collaborations
“Tom” Gerard Gablier  Gundula Dieterle-Vernet  Justine Lejoly
Julia Wohlers  Aditi Rosegger  Ramesh Ramalingam
Simona Fabre  Gilles Boulicot  Margarita Correa
Shankardevy Dhanasekaran  Azhaganandhan Veerappan  Akash Heimlich
S P Balan  Sanal Jagdishan  Vasanth Palani
K Vijai  S Panneerselvam  Johan van den Bor
Deoyani Sarkot  Island Lescure  François Gautier

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Summary of methodology adopted for project development

A detailed, standardized topographic survey has been conducted, using DGNSS (Differential Global Navigation Satellite System) system combined with Total Station. More than 61,000 ground level points have been surveyed in the Area of Interest (AoI), with 3D accuracy between 1 and 2.5 cm.

All existing features visible on the terrain have been surveyed, to generate a topographic map.

Eighteen missions have been conducted on in the AoI with an Unmanned Aerial Vehicle (drone), to obtain a georeferenced aerial orthophoto mosaic.

A survey of existing collective Sewage Treatment Plants, and a preliminary STP health check-up assessment have been conducted. An attempt to quantify treated water has been made through regular collection of water consumption data in specific areas having metering devices.

Daily rainfall readings from sixteen manual raingauges, and several weather parameters as measured by an automatic weather station have been regularly recorded.

Water levels in 51 wells have been weekly monitored and their readings recorded for at least two years.

A LORA-Wan radio receiving base station has been installed on a dedicated tower.

One automatic pressure sensor has been installed into selected well to automatically monitor water table level fluctuations, and regularly transmits data to a receiving base station; several more sensors are ready for installation when borewell preparations are completed and permissions obtained.

Two ultrasonic digital flow meters have been installed to automatically measure water flowing through selected pipelines, and regularly transmit data to a receiving base station.

An Open Source software has been coded to process all data received and stored into a PostGRE-SQL database, a web interface has been published to share all collected data.

Through the combination of all above information and data, a complex geospatial algorithm has been created to theoretically quantify runoff potential in AoI.
Future research activities

Calibration and validation of Runoff model
The studied Runoff model proposed requires to be calibrated and validated: volumes of runoff as estimated by the model need to be verified during rainfall events, in order to calibrate the runoff coefficients used for each area. This can be achieved through installation of measuring devices in particular locations, where origin area of occurring runoff is well defined and runoff is not generated from areas with mixed parameters. The easiest place is of course the measurement of runoff in built-up features, where source can be easily identified and measured.

Vegetation classification processing
Additional work is needed in order to improve vegetation classification, through both refinement of processing methods going from raster to vector (reduction of pixel-effect on vector polygons boundaries), and processing of suitable satellite photos to increase coverage area of the model. This would result in a higher accurate vegetation-cover map allowing computations for areas outside the AoI.

Antecedent soil moisture conditions
The soil moisture conditions could be added to improve the quantities of runoff volumes generated during rainfalls, mostly in terms of increase in volume: in fact, the as-is model considers the soil being dry at the beginning of rainfall, providing a conservative approach, tending to use values generating the lowest volumes. Introducing soil moisture degree will increase calculated volumes of runoff especially for natural terrain (non-built-up) areas.

Completion of topographic survey of Auroville
The topographic survey should be completed for the whole Auroville area, in order to have an accurate base map for all future planning and development issues at a very detailed level.

Use of UAV (drone) for large areas
The model uses detailed topographic data obtained through meticulous survey: while this method has the clear advantage of high accuracy, it is very time-consuming, and involving higher budgets.

Territory of villages neighbouring Auroville might be surveyed using UAV (drone), because of the advantages:
- large areas can be surveyed in shorter time
- smaller budgets are required
- vegetation cover is much lower than the forested areas of Auroville.

Infiltration tests in village areas
Infiltration tests are required in those areas where the runoff model is to be run, to estimate the water-absorbing capacity of soil during rainfall, and build the map of infiltration to be used during the model computation.
**Expansion of software interface to include other categories**

The software and the underlying database are meant to store information of any type, provided they have a geographic location. Consequently, maps of vegetation, of particular species of trees (e.g. species under risk of extinction), of fauna, and/or maps of assets, buildings, number of people, infrastructure, water consumption, water distribution networks, etc, can be easily integrated into a single point of access with many different data, with the ability to provide factual information for each geographic feature.
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1 Project Context

1.1 Project Area Definition

Auroville is located in South-East India, specifically in the state of Tamil Nadu (Villupuram District) and in the United Territories of Pondicherry.

Auroville bioregion spreads over an area of about 1,500 km² hosting a population of about 1.4 million (14 lakhs); it is mainly characterized by its topography, its shared ground and surface water resources and common environmental traits.

It is situated along the Coromandel Coast of Tamil Nadu, Bay of Bengal, on a stretch of 60km, from Marakkanam to Cuddalore, and about 30 km inland from the coast up to Tindivanam.

Auroville is an evolving township for a population of up to 50,000 people sourced from around the world. It is an international intentional community, with 3,173 residents coming from 57 Countries (as on December 2019 (Peter, 2019)), spread out over about 180 small settlements on Auroville-owned land.
As envisioned since the beginning, Auroville is comprised of a City Area, in a circle with 1.25 km radius, and a surrounding annular Green Belt circle, having a radius of 2.5 km. The City Area is planned as divided in Residential Zone, Cultural Zone, Industrial Zone and International Zone, with several parks and green areas. The Green Belt is conceived mostly for farming and forestry.

1.1.1 Auroville context

Auroville territory falls within the Kaliveli – Pondicherry basin, which spans over 1,000 square kilometres, in South-East India, specifically in the state of Tamil Nadu, District of Villupuram, Vanur Block, and partly in the United Territories of Pondicherry.
Figure 1—3 Auroville – Puducherry – Kaliveli bioregion Map
1.1.1.1 Geology

A synthetic description of the Auroville region geology can be found in Vincent and Violette, 2017. “The sedimentary pile of the basin rests unconformably on an Archean charnockite bedrock, which outcrops in the West part of the basin. It is part of the Pondicherry sub-basin of the Cauvery tectonic basin (Chari et al., 1995).

All sedimentary layers form a monocline, with an average slope of 1–3% towards the sea, and towards the South (Sundaram et al., 2001). All layers get thicker from their outcrop towards the South. The oldest sedimentary layers are Cretaceous (Singh et al., 1992; Sundaram et al., 2001): just above the charnockite is the Ramanathapuram sandstone (aquifer) and the Ramanathapuram clay (confining unit), then the Vanur sandstone (or Valudavur formation, late Maastrichtian; Sundaram et al., 2001), which is the most important aquifer layer, followed by the Ottai clay (confining unit, also known as Mettuveli formation, late Maastrichtian; Sundaram et al., 2001), and the Thuruvai limestone (aquifer). Those layers are also known all together as the Arilayur group (Singh et al., 1992). Above them lie the Tertiary layers: the Kadaperikuppam limestone (aquifer, also known as Kasur formation, Danian, Paleocene; Singh et al., 1992; Sundaram et al., 2001), the Manaveli clay (confining unit, Selandian, Paleocene; Singh et al., 1992; Sundaram et al., 2001), and, unconformably with the previous layers (Singh et al., 1992), the Cuddalore sandstone, aquifer formation which is the product of the charnockite alteration during the Miocene and Pliocene, forming in the East the main relief of the basin, the Auroville plateau — about 50 m amsl (above mean sea level) — and covering in the West the Ramanathapuram sandstone, and partly the Vanur sandstone.
Cretaceous and Tertiary layers outcrop from the South of the Kalivelis swamp to the North of the Gingee River (Chenjiyaru), except for the Ramanathapuram formation, which never outcrops. Quaternary alluvium, fluvial alluvium near the Kalivelis swamp and the Ponnaiyar and Gingee rivers, and sand dunes along the coast (Violette et al., 2009), cover the rest of the basin (Bourgeon 1988; Jaya Kumar et al., 1984; Lacarce and Fleutry, 2001; Subramanian and Selvan, 2001). Faults affect the area, following a North-East/South-West direction along the Bay of Bengal, and following an East–West direction along the Gingee River (Subramanian and Selvan, 2001); however, their locations are not precisely known.

1.1.1.2 Hydrogeology
In the geological stratigraphic series several formations are defined as aquifers. In particular in Auroville territory, Cuddalore Sandstone is defined as the first aquifer, Kadaperikuppam-Thuruval Limestone as the second, and Vanur Sandstone as the third. Ramanathapuram Sandstone, though can be technically considered as an aquifer, has high sulphate-rich mineralization (d’Ozouville et al., 2006; Gassama et al., 2012) which renders water unusable.

In this multi-layered coastal aquifer system, the main aquifer of the whole region is the Vanur Sandstone formation, confined to the East by the Ottai clay, to the North and South by Alluvium, and covered to the West by the Cuddalore formation. The Vanur Sandstone aquifer has been the subject of several hydrogeological studies, including groundwater modeling (d’Ozouville et al., 2006; Vincent, 2007; Vincent and Violette, 2017)

All aquifers in the area are intensively exploited: a survey in 2003 inventoried 5,832 tube wells used or abandoned, within an area of 260 km², so an average of more than 22 wells/km² (Vincent and Violette, 2017). In the National Compilation on Dynamic Ground Water Resources of India 2017, published by Central Ground Water Board, Government of India, in 2019, in Annexure II, “District-Wise Ground Water Resources Availability, Utilization And Stage Of Development (As In March 2017)” under the “Dynamic Ground Water Resources of India 2017” states that in Villupuram district the “Stage of Ground Water Extraction” is at 91.21% (page 99 of the Compilation), and in Annexure V (B) the “Comparison Of Categorization Of Assessment Units (2013 to 2017)” states that in Villupuram District the Stage of Ground Water Extraction 2013 was at 92.47%, Categorized as “Critical”, while Stage of Ground Water Extraction 2017 was at 109.56%, Categorized as “Over Exploited” (page 210 of the Compilation).
Data collected through weekly monitoring of 51 wells in Auroville territory (See Annexure 01) show a seasonal variability: water levels are higher at the end of the North-East monsoon season (with a peak around December every year), and lower at the end of the arid season (lowest levels between July and October). Aquifers are recharged mostly by the North-East monsoon (from October to December).

As already observed earlier, water levels keep falling every year, highest levels are not recorded any longer, while lower and lower levels have become the norm.

The Vanur aquifer, almost not used by Auroville wells, is highly exploited in the bioregion. The over-exploitation of the Vanur aquifer in the Northern part of the basin has led to a critical drop in its water levels: up to 50 m in 35 years.

![Figure 1 — 6 Vanur aquifer groundwater extraction (Mm$^3$/year), and observed and simulated water levels (m MSL) at Katterikuppam well, 1950–2006 (Vincent and Violette, 2017)](image)

In October 2005, water levels ranged from −50 to −2 m amsl, which means that aquifer water levels were below sea level in this low water period: a situation which could result in a seawater intrusion; and indeed, electrical conductivity (EC) measurements in the Vanur aquifer was relatively high, some above 3,500 μS/cm.

Unlike what was expected, the registered salinity in the Vanur aquifer is not due to seawater intrusion across the coastline, but instead to highly sulphate-rich mineralized water upconed from underlying Ramanathapuram sandstone, as revealed by a geochemical survey conducted in 2000 (Vincent and Violette, 2017; d’Ozouville et al., 2006).

1.1.1.3 Regional social context

The Auroville bioregion, from Marakkanam in the North, to Tindivanam in the West, Villianur in the South-West, and Cuddalore in the South, has a total population of about 14,00,000 inhabitants. Population is distributed as under (Indian Census, 2011):

- Kandamangalam Community Development Block 1,45,181 persons
- Marakkanam Community Development Block 1,47,713 persons
• Vanur Community Development Block 1,64,696 persons
• Puducherry District 9,50,289 persons

A large majority of the population lives in rural areas, where water main consumption is for agriculture. Crops are cultivated both for local consumption (rice, leguminous plants, vegetables, etc.) and for sale (the so-called cash crops, such as cashew nuts, coconut or casuarina).

1.1.1.4 Climate and surface hydrology

The climate is tropical dry sub-humid, with one dry season, and two monsoon seasons. The first monsoon season (South-West Monsoon) starts in June till end of September, while the second starts in October, till the end of December. Months from January till May included are considered as in the Dry season.

Rainfall readings have been recorded through a manual raingauge in Aurogreen (Green Belt, North-East of center of Auroville), regularly since April 1989\(^1\). All Aurogreen monthly readings are listed in Annexure 02.

![Figure 1](image)

Summarized, over 30 years of data collection, a total of 9% of annual rainfall is recorded in the five months of Dry season, a total of 28.9% in the four months of South-West monsoon season, and a total of 62.1% in the three months of North-East monsoon season.

The average yearly rainfall over the period 1990-2019 is 1,364 mm, with extremes at 2,088 mm in 2015, and 681 mm in 2016.

The average annual temperature is 28 °C (24 °C in winter months, 31 °C in summer months). Highest temperatures occur during the Dry season, during the months of May and June, with maximum going over 40 °C (Vincent, 2007). CSR weather station, operational since June 2019, has recorded its maximum at 38.8 °C on the 20\(^{th}\) June, 2019 at 3.00 pm.

\(^1\) Charlie (Aurogreen) is in charge of the raingauge, and he is regularly sharing all collected data since April 1989.
Potential evapotranspiration (PET), from the Thornthwaite method (Thornthwaite and Mather 1957), is on average of 1,988 mm/year (calculated during 1972–1981 and 2001–2005 time periods) (Vincent, 2007).

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Yearly PET</th>
<th>Station</th>
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<tr>
<td>1972-81</td>
<td>77</td>
<td>91</td>
<td>141</td>
<td>204</td>
<td>276</td>
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<td>179</td>
<td>156</td>
<td>108</td>
<td>81</td>
<td>2065</td>
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</tr>
<tr>
<td>2001</td>
<td>80</td>
<td>87</td>
<td>135</td>
<td>171</td>
<td>280</td>
<td>241</td>
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<td>207</td>
<td>174</td>
<td>138</td>
<td>111</td>
<td>81</td>
<td>1935</td>
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</tr>
<tr>
<td>2002</td>
<td>84</td>
<td>83</td>
<td>140</td>
<td>198</td>
<td>292</td>
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<td>220</td>
<td>183</td>
<td>126</td>
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<td>72</td>
<td>1970</td>
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<td>124</td>
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<td>173</td>
<td>185</td>
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<td>143</td>
<td>101</td>
<td>2002</td>
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</tr>
<tr>
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<td>142</td>
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<td>212</td>
<td>169</td>
<td>132</td>
<td>82</td>
<td>80</td>
<td>1914</td>
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<td>Average</td>
<td>83.5</td>
<td>89.2</td>
<td>132.1</td>
<td>199.2</td>
<td>255.2</td>
<td>262.2</td>
<td>231.0</td>
<td>216.7</td>
<td>179.0</td>
<td>145.3</td>
<td>108.7</td>
<td>88.0</td>
<td>1988.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 1—1 Potential Evapotranspiration values calculated using Thorntwaite’s method for the period 1972-2005 (1972-1981 Station: Certitude – Auroville; 2001–2005 Stations: Puducherry and Vanur) (Vincent, 2007)

Irrespective of the year for which it has been calculated, it is evident that PET is higher than the yearly rainfall: in the year 2005, for instance, the difference between Precipitation and PET has been positive only in the months of August (6 mm), October (130 mm), November (525 mm), and December (155 mm): this indicates that for eight months in that year there was no excess water available for soil moisture, recharge and runoff.

For the years 2001 to 2005, Auroville climate can be classified as “Dry Sub humid” according to World Atlas of Desertification (UNEP, 1992), being the Aridity Index (Ai = P/PET) for those years between 0.4 and 0.8.

1.1.1.5 Hydrology and surface water

Auroville and its bioregion have no perennial rivers: even the main two rivers reaching the Bay of Bengal South of Puducherry, the Ponnaiyar and the Chenjiyaru, have water only in the monsoon season.

Due to lack of perennial surface water, a completely artificial system had been created in the whole Tamil Nadu, starting from the Chola period around the XIII century AD (1,200 AD). This water management system was composed of interconnected erys (village tanks), built to harvest and store rainwater and to ensure that excess water received during heavy rains was overflowing, simply due to gravity, toward other erys placed at lower elevations. The erys system was effective not only for surface water management but also for flood control, being big portion of rainfall and consequent surface runoff directed and stored into the tanks.

The erys system, which was managed at the village level, fell into disuse during the colonial period, i.e. 1757–1947 (Agarwal and Narain 1997; Mosse 2003; Mukundan 1988).
The Green Revolution in the 1970s, along with use of standardized seeds and chemical fertilizers and pesticides, introduced a major change in irrigation practices. The historical rainwater harvesting system of erys, already dysfunctional, has largely been replaced by individual irrigation systems supplied by inexpensive bore-well facilities. Village tanks have then been neglected, often encroached, and even if several programs aimed at their restoration
have been initiated, they remain today largely unused and ineffective as water storage structures.

Since the beginning, Auroville inhabitants have successfully carried on a work of re-afforestation on what was earlier a barren plateau. Millions of trees have been planted, to help improve the microclimate, and to facilitate percolation of rain into the underground. In fact it has been reported that, before this work took place, most of rainwater was running off toward the Bay of Bengal, with subsequent deep erosion along the runoff paths: deep (up-to more than 10 meters) canyons have developed especially on the Eastern side of the plateau, with the result that rainwater runoff moved at high speed toward its base line, the ocean. This general situation obstructed percolation and consequent recharge of underlying aquifers.

To change the scenario and increase percolation, several check dams have been built along some of the canyons, aiming at decreasing speed of runoff water so increasing its infiltration. Parallelly, earth bunding of land plots, aiming at retaining runoff water within the bunds thus facilitating its percolation, has been done systematically on all Auroville-owned land, with the consequent effect of decreasing runoff speed toward lower elevations. Percolation ponds have been dug to increase the efficiency of the overall environmental rehabilitation work, mostly in areas with favorable geology, on the Eastern side of the plateau where the Cuddalore Sandstone formation outcrops: this formation has a very high infiltration rate, and constitutes the first aquifer for the whole Eastern side of the plateau.

After fifty years of existence, Auroville cannot rely on the strategy put in place at the beginning to guarantee water security any longer: thousands of surrounding drilled borewell, together with over-extraction and absence of coordinated efforts to enable aquifers recharge in the bioregion, have caused the overall drop of groundwater levels in all water-bearing geological formations.

1.1.1.6  Water distribution and consumption

In Auroville water is accessed either through a distribution network, mainly in the so-called City Area, or through individual wells, each serving one or more small dispersed communities.

Over time, about three hundred wells have been drilled, with different depth, tapping into one or more aquifers, according to local available conditions.

1.1.1.6.1  Residential Zone Distribution network

The distribution network, operated by Auroville Water Service, has a 40,000 liters overhead tank in the Residential Zone and a 2,00,000 liters underground tank in the Industrial Zone; tanks are fed by about ten wells drilled in different locations.

Auroville overall water consumption cannot be quantified, due to absence of flow meters in communities’ wells. On the distribution network few meters are installed, some having problems of reading reliability due to high mineral content (mostly lime and iron oxides) in the water.

Shared data by Auroville Water Service in the period from April 2017 to march 2018 for water distributed to 25 residential communities having a total number of 623 residents, show an average consumption during that period of about 210 liters per head per day.
The figures reflect insufficient information on several sides:

- number of residents is not accurate\(^2\)
- population fluctuations in holiday months is not accounted for
- number of adults vs number of children is not reported
- number of floating population (housemaids, daily workers, visitors, guests) is not included
- detected leakage are included in the consumption

Considering all non-accounted-for users, the daily consumption per capita is then expected to be lower.

---

\(^2\) Number of residents has been provided by Auroville Residents Service on January 12, 2019.
Similar inaccuracies are reflected in the data of some communities.

1.1.1.6.2 **Community: Courage**

In Courage community, in the period from 5 November, 2019 till 19 February, 2020 an average consumption has been calculated as being 181 liters per capita per day, for 98 residents.

1.1.1.6.3 **Community: Transformation**

In Transformation community, a flow meter has been temporarily installed and related data have been acquired for the period from 9 August till 11 November, 2019. Again, data reflect the same inaccuracies. Nevertheless, the average water consumption in that period for the 24 residents there is 295 liters per capita per day.

In few situations, some more accurate data have been collected, in particular from some single communities.

1.1.1.6.4 **Community: Dana**

In Dana community (Cultural Zone, not in AoI), accurate data have been regularly acquired on a daily basis in the period from 29 April, 2018 till 14 October, 2019; data include accurate number of Residents, daily workers, etc. The average consumption amounts to 303 liters per capita per day.

---

2 Meera Natarajan, Selvarani Karunagarane and S Ramkumar have collected the flow meter readings on a daily basis.

4 “Tom” Gerard Gablier, member of Auroville Water Group, has diligently collected the data over the mentioned period.
liters per capita per day, for 74 persons including daily workers. The higher per capita consumption here is mainly due to extensive use of water for garden irrigation.

1.1.1.6.5 Community: Kalpana

Accurate data, including resident and floating population, have been collected in Kalpana community (Residential Zone, within AoI) as well, in the period from 1 January till 31 December, 2019.5

Kalpana community

Average consumption (liters per capita per day)
January 2019 - December 2019
Total average Population: 88 PE
Summer average Population: 55 PE (Apr - May - Jun)

<table>
<thead>
<tr>
<th>Month</th>
<th>Monthly average consumption (liters per capita per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-19</td>
<td>168</td>
</tr>
<tr>
<td>Feb-19</td>
<td>168</td>
</tr>
<tr>
<td>Mar-19</td>
<td>160</td>
</tr>
<tr>
<td>Apr-19</td>
<td>218</td>
</tr>
<tr>
<td>May-19</td>
<td>187</td>
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<tr>
<td>Jun-19</td>
<td>143</td>
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<tr>
<td>Jul-19</td>
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<td>Aug-19</td>
<td>107</td>
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<td>Sep-19</td>
<td>98</td>
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<td>Oct-19</td>
<td>111</td>
</tr>
<tr>
<td>Nov-19</td>
<td>113</td>
</tr>
<tr>
<td>Dec-19</td>
<td>130</td>
</tr>
</tbody>
</table>

Average consumption (liters per capita per day) **144.17**

Table 1—4 Kalpana community average water consumption – January 2019 – December 2019
(courtesy: Margarita – MG Ecoduties – Auroville)

The average consumption has been calculated as being **144.17** liters per capita per day, for 88 Person Equivalent. In this case consumption is lower due to use of recycled treated water for garden irrigation, approximately 6 liters per capita per day (treated wastewater is metered in this community).

---

5 Margarita from MG Ecoduties has collected the data.
1.1.6.6 Community: Humanscapes

Accurate data (but without considering the floating population) have been collected in Humanscapes community (Residential Zone, within AoI), from October 2018 till February 2020.

Humanscapes community

Average consumption (liters per capita per day)
October 2018 - February 2020
Total average Population: 31

<table>
<thead>
<tr>
<th>Month</th>
<th>Monthly average consumption (liters per capita per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct-18</td>
<td>118.52</td>
</tr>
<tr>
<td>Nov-18</td>
<td>108.56</td>
</tr>
<tr>
<td>Dec-18</td>
<td>104.22</td>
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<tr>
<td>Jan-19</td>
<td>134.00</td>
</tr>
<tr>
<td>Feb-19</td>
<td>139.02</td>
</tr>
<tr>
<td>Mar-19</td>
<td>111.04</td>
</tr>
<tr>
<td>Apr-19</td>
<td>124.04</td>
</tr>
<tr>
<td>May-19</td>
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<td>Jun-19</td>
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<tr>
<td>Jan-20</td>
<td>118.41</td>
</tr>
<tr>
<td>Feb-20</td>
<td>152.16</td>
</tr>
</tbody>
</table>

Average consumption (liters per capita per day) **119.50**

Table 1—Humanscapes community average water consumption – October 2018 – February 2020 (courtesy: Aditi Rosegger – Humanscapes community)

The average number of users in the period amounts to 31, with an average consumption of 119.5 liters per capita per day.

In this case too, consumption is low due to use of recycled treated water for garden irrigation (not metered).

---

6 Aditi Rosegger from Humanscapes community has shared the data.
1.1.1.6.8 Community: Centre Field

In Centre Field community (Residential Zone, not in AoI), an ultrasonic flow meter automatically transmitting readings using wireless LoRaWAN technology has been recently installed to quantify the water extraction from the local well. Water used in the same system by a Guest House and few residents linked to it, is equally metered by another ultrasonic flow meter automatically transmitting readings using wireless LoRaWAN technology, and is not considered here, being data on users’ number not available.

![LoRaWAN flow meter](image1)

Figure 1—9 LoRaWAN flow meter before installation in Centre Field: side view (top), top view (bottom)

Regarding the other 12 residents served by the system, in the period from 5 February to 23 February, 2020 (19 days), their total consumption has been equal to 65.5 cubic meters, equivalent to 287 liters per capita per day. It is to be noted that water is also used for some small agricultural activities here.
### Center Field Water Consumption Assessment – February 2020

#### Center Field Water Distribution System

<table>
<thead>
<tr>
<th>Date and Time</th>
<th>readings (cubic meters)</th>
<th>Date and Time</th>
<th>readings (cubic meters)</th>
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<td>349.587</td>
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<td>351.549</td>
</tr>
<tr>
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<td>22/02/2020, 09:47:45</td>
<td>361.821</td>
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<td>22/02/2020, 11:50:42</td>
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<td>23/02/2020, 17:47:45</td>
<td>364.909</td>
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<tr>
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<td>761.44</td>
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<td>---</td>
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<tr>
<td>23/02/2020, 07:52:47</td>
<td>761.796</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>23/02/2020, 11:43:43</td>
<td>765.231</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>24/02/2020, 11:04:43</td>
<td>773.648</td>
<td>24/02/2020, 09:47:44</td>
<td>371.012</td>
</tr>
<tr>
<td>24/02/2020, 12:24:43</td>
<td>773.648</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>25/02/2020, 11:32:44</td>
<td>784.05</td>
<td>25/02/2020, 09:47:44</td>
<td>378.045</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>25/02/2020, 11:32:44</td>
<td>378.045</td>
</tr>
</tbody>
</table>

**Initial Reading (05/02/2020)** | 570.265 | 232.333 |
**Final Reading (25/02/2020)** | 784.05 | 378.045 |

Total consumption (cubic meters) **213.785**  **145.712**

### Water Consumption Assessment for Center Field Area excluding Center Guest House distribution

- Total consumption (excluding Guest House network and including small agricultural activities) (cubic meters) **68.073**
- Users Number (excluding Guest House network) **12**
- Number of days from 12 noon on 05/02 to 12 noon on 25/02 **20**
- Consumption per capita per day (excluding Guest House network and including small agricultural activities) (cubic meters) **0.28364**
- Consumption per capita per day (excluding Guest House network and including small agricultural activities) (liters) **283.64**

Table 1—6 Center Field water consumption assessment – February 2020
1.1.1.6.9 Community: Verite

In some other situation, for example Verite community (Industrial Zone, not in AoI), even though extraction from the well serving the community is metered, proper data on number of users are not available: in Verite in fact there are not only residents, but also guests staying in the guest house, and people attending the numerous workshops held there almost daily. There is anyhow a slight difference in water consumption pattern when average daily consumption are compared, for low season (e.g. November 2019, when number of guest and number of workshop/courses are lower) and high season (January 2020): in particular, for the period from 7 November to 7 December, 2019 (31 days), the daily average consumption has been 11,895 liters, while in the period from 18 January to 17 February, 2020 (31 days) the daily average has been 14,550 liters.

The situation is even more complex when public eateries like Visitor Centre and Solar Kitchen, or other type of facilities, like Visitor Centre Parking, are considered, due to the difficulty in collecting information on consumption, population served, etc.

1.1.1.6.10 Public eateries: Visitor Centre

The Visitor Centre (International Zone, not in AoI) is the main daily visitors’ entrance to Auroville, thanks to a large parking for private and public vehicles, and to presence of receiving facilities, including eateries, souvenir shops, toilets, permanent exhibitions on main Auroville concepts. In Visitors Centre there is also an office where visitors can get passes to be allowed to visit the main attraction, the Matrimandir Gardens.

Visitor Centre management has installed meters in June 2019, on each pipeline serving the Visitor Centre as a whole, the Cafeteria and the Parking: daily readings are recorded for all the meters since their installation.

The number of water users is difficult to evaluate: nevertheless, in this case a record is kept on number of visitors getting a pass to visit the Matrimandir gardens, which is assumed to cover 90% of all people in Visitor Centre.

Moreover, a family of four (two adults and two kids) resides in the compound, its water consumption not being quantified.

Finally, purified water is distributed at a public tap to overall public, including local population, which is not quantified.

In the period from 14 June, 2019 to 17 February, 2020 totaling 247 operating days (discarding the only two days when Visitors Centre was closed to all⁷), 5,98,632 passes have been issued. Projecting an extra 10% to account for visitors not needing pass, the total number of visitors amounts to **6,58,495**.

In the same period the total water consumption for Visitors Centre and Cafeteria together (thus considering the main facilities used by visitors) amounts to 8,612 cubic meters.

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⁷ These two days were the 27th of October 2019, when Visitor Centre was closed due to Diwali celebrations, and 23rd December, 2019 for the visit of His Hon’ble President of India.
Considering a consumption of 135 liters per day per adult\(^8\) (CPHEEO, 1999), and 65 liters per day per child, the total consumption in the period, by the family of four can be calculated as being 400 cubic meters.

Water consumption assessment - Visitors Centre - June 2019 - February 2020

<table>
<thead>
<tr>
<th>Ref. Description</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>a Number of operating days considered</td>
<td>247</td>
</tr>
<tr>
<td>b Number of passes issued</td>
<td>5,98,632</td>
</tr>
<tr>
<td>c 10% Visitors without passes</td>
<td>59,863</td>
</tr>
<tr>
<td>d Total number of Visitors</td>
<td>6,58,495</td>
</tr>
<tr>
<td>e Number of residing family members</td>
<td>4</td>
</tr>
<tr>
<td>f Total number of persons for the period from the residing family (a x e)</td>
<td>988</td>
</tr>
<tr>
<td>g Total number of water user in the period (d + f)</td>
<td>6,59,483</td>
</tr>
<tr>
<td>h Total water consumption of Visitor Centre compound (cubic meters)</td>
<td>8,612</td>
</tr>
<tr>
<td>i Assumed daily purified water distributed by Cafeteria tap (cubic meters)</td>
<td>2</td>
</tr>
<tr>
<td>j Total purified water distributed by Cafeteria tap (cubic meters) (a x i)</td>
<td>494</td>
</tr>
<tr>
<td>k Average daily minimum water availability in India (adult) ((^*))</td>
<td>135</td>
</tr>
<tr>
<td>l Average daily water consumption in India (child)</td>
<td>65</td>
</tr>
<tr>
<td>m Total daily water consumption of residing family</td>
<td>400</td>
</tr>
<tr>
<td>n Total water consumption of residing family for the period (liters) (a x m)</td>
<td>98,800</td>
</tr>
<tr>
<td>o Total water consumption of residing family for the period (cubic meters) (o / 1000)</td>
<td>98.8</td>
</tr>
<tr>
<td>p Assumed total daily water consumption for mix use, including residing family (cubic meters)</td>
<td>5</td>
</tr>
<tr>
<td>q Total water consumption for mix use, including resident family, in the period (a x p) (cubic meters)</td>
<td>1,235</td>
</tr>
<tr>
<td>r Total water consumption for mix use, excluding resident family, in the period (q - o) (cubic meters)</td>
<td>1,136.2</td>
</tr>
<tr>
<td>s Total water consumption for visitors in the period (h - j - o - r) (cubic meters)</td>
<td>6,883</td>
</tr>
<tr>
<td>t Daily average water usage by visitors in the period (s / d) (cubic meters)</td>
<td>0.0105</td>
</tr>
<tr>
<td>u Daily average water usage by visitors in the period (t x 1000) (liters)</td>
<td>10.5</td>
</tr>
</tbody>
</table>

(\(^*\)) CPHEEO, 1999

Table 1—7 Calculation of water consumption in Visitor Centre

Further on, considering a daily average quantity of purified water distributed at the tap in the Cafeteria to general public as 2 cubic meters\(^9\), the amount of purified water distributed in the period is calculated as being 494 cubic meters.

Finally, other uses of water (cleaning, irrigation, etc.) can be estimated at 5 cubic meters per day\(^10\).

\(^8\) In the Code of Basic Requirements of Water Supply, Drainage and Sanitation (IS: 1172-193) as well as the National Building Code, a minimum of 135 liters per capita per day has been recommended for all residence provided with full flushing system for excreta disposal. [...].” in: Central Public Health & Environmental Engineering Organisation (CPHEEO), 1999.

\(^9\) On Diwali day, when the Visitors Centre was closed to public, the flow meters recorded 2 cubic meters for the Cafeteria (where the tap for purified water distribution is located. On the day of President of India visit, there is no consumption at all, being the place fully vacated for security reasons.

\(^10\) Again, on Diwali day, when the Visitors Centre was closed to public, the flow meters recorded 5 cubic meters for the whole Visitor Center compound, which is assumed to be the consumption of the family of four, and the quantity for garden irrigation and overall cleaning.
Taking into account all assumptions specified earlier, the average water consumption is calculated at **10.5** liters per visitor per day.

1.1.1.6.11 Public eateries: Solar Kitchen

The Solar Kitchen (Residential Zone, not in AoI) is the facility providing food to a large number of Auroville residents, along with volunteers and few guests. It is located in a compound where two more smaller eateries are present, one open to public (La Terrace), the other open only to residents (Pour Tous Distribution Center). Number of meals is not recorded, or data are not easily available. All these facilities receive water through a pipe line with a common meter: readings have been recorded for the period from 24 October, 2019 to 19 February, 2020. The total consumption for the period is 3,057 cubic meters, with an average daily consumption of 25.6 cubic meters (25,600 liters) a day.

1.1.1.6.12 Other facilities: Visitor Centre Parking

In the Visitors Centre Parking (International Zone, not in AoI), where there are few toilets and one more public tap for distribution of purified water to general public, in the same period a total consumption has been metered as being 6,988 cubic meters. Here, on the two days when Visitors Centre was closed to public, the consumption recorded for use of toilets and mainly for dispensing purified water is above 30 cubic meters, which should be considered carefully, being the average consumption in the period equal to 28 cubic meters. Therefore, any attempt to calculate daily average consumption per visitor is prone to wrong assumptions, and will not be proposed here.

1.1.1.7 Wastewater treatment

In Auroville, wastewater treatment has always been considered a way to get additional valuable water especially for garden irrigation purpose. Rather than one centralized treatment system, several de-centralized systems have been integrated in the development of collective housing, like apartment blocks, or in small communities.

In order to evaluate the potential contribution of wastewater as a source to the overall consumption, even though for specific non-domestic uses (irrigation, concrete curing, unpaved roads wetting), a survey of all collective treatment system has been conducted in Auroville City Area in 2018. The survey has identified 68 collective plants, and collected info on location of the plants, as well as, wherever possible, number of people served, capacity, status, designer, date of installation, origin of wastewater, and details regarding components of each system.

After this survey, a preliminary Health Check-up has been conducted on all the systems. It has been found that one system was still under construction, five other systems have been decommissioned because the communities served by them have been connected to the newly built collective Residential Zone treatment system; four more systems have been identified as lacking some basic components, therefore they cannot be considered proper treatment systems. Of the remaining 58 systems, 16 have been found functional, 32 in need of repairs and/or maintenance, 10 fully dysfunctional. Full list and details are given in Annexure 03.

A standardized template has been created to enable proper reporting of each Health Check-up; one example is included in Annexure 04.

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11 The survey on wastewater treatment plants has been conducted by Meera Natarajan and Jeanne Latusek.
12 Health Check-up has been conducted by Meera Natarajan, Dorian Nadaud and Bala Ramachandran.
2 Equipment
Specific equipment has been acquired in order to conduct the research. Details and technical specifications of each equipment, along with procedures put in place and standards followed, are provided here below.

2.1.1 Topographic Survey
State-of-the-art topographic survey equipment has been acquired at the onset of the project. More specifically, a DGNSS (Differential Global Navigation Satellite System) comprising of one antenna for base station, and one antenna for roving station, along with one Smart Total Station, have been purchased, brand being Leica Geosystems. See Annexure 05 for Data sheets.

Previous DGNSS surveys conducted in Auroville in 2012 by a contractor have defined a Coordinates Reference System (CRS) based on a UTM projection. The Survey Contractor had provided a GPS Report in a table format (see Annexure 06), with columns divided into two main groups, as:

- UTM-Projection Coordinates
- Plane UTM-Coordinates

In the first Group, coordinates columns are labelled as:

- WGS84-Spherical Coordinates - >Latitude
- WGS84-Spherical Coordinates - >Longitude
- UTM-Projection Coordinates - >Easting
- UTM-Projection Coordinates - >Northing

In the second Group, coordinates columns are labelled as:

- Easting
- Northing

Being contacted for explanation on inconsistency of Easting and Northing values in the two Groups, the Survey Contractor verbally communicated that UTM Projection Coordinates had been modified to enable survey works to be done with total stations on long distances, to reduce scale errors, and that the modified coordinates had been named “PLANE UTM COORDINATES”. These
had been obtained through reprojection of points from UTM to OM (Oblique Mercator), and subsequently to TM (Transverse Mercator). Parameters for TM re-projection had been documented in the report, but the base point used at that time to conduct the GPS survey is no longer accessible, being it located inside Puducherry airport. Moreover, source of coordinates of the same base point used at that time had not been documented.

Looking at the GPS Report, differences between UTM projected coordinates and modified CRS for same point range between a minimum of 0.003 m to a maximum of 0.466 m in Easting, and a minimum of 0.368 m to a maximum of 1.192 m in Northing, without constant ratio for different points, due to scale factor of UTM projection.

While checking the metal benchmarks placed in the ground during the GPS survey in 2012, where engraved are a set of information, as:

- on the left-hand side, is the indication of the projection (WGS 84 UTM 44)
- at the center, top, are the value of Easting (E) and Northing (N), in meters
- on the right-end side, is the indication of the location
- at the center, bottom, is the Orthometric height, in meters
- at the center, is the benchmark point

it has been noticed that values of Easting and Northing coordinates engraved on the metal plaque do not match the “UTM-Projection Coordinates” of GPS Report, but instead the “Plane UTM-Coordinates”. This poses an insurmountable problem due to impossibility of replication of the CRS because the base point in Puducherry airport is not accessible any longer.

Repeated efforts have been undertaken to replicate the modified CRS using several points in the GPS report (to be noted: several benchmarks do not exist any longer having been removed, or their position modified), still existing on the ground as benchmarks, as Base points for establishing old benchmarks network, and set new reference points when needed, in that reference system, so to have legacy maps consistent with new survey. The resulting error has always been in the range of 10-20 cm thus hampering accuracy of new survey, and rendering vain the capabilities of newly procured survey equipment.

Setting of a new CRS had then become necessary; office of Survey of India, Chennai had been officially asked, via a letter sent from Secretary of Auroville Foundation, to provide coordinates of
a reference point in Auroville region in order to be able to conduct surveys using their same reference system. Survey of India, Chennai then directed to Survey of Tamil Nadu, Chennai, which in turn directed to Survey of Tamil Nadu, Villupuram, which in turn directed to Survey of Tamil Nadu, Vanur, which again directed to Villupuram, which redirected to Chennai. No reference points had been made accessible, and a new approach was required, as follows.

A concrete pillar for DGNSS base station has been erected on a convenient location, with accessories fixed in a way such that any time the base antenna is mounted on, coordinates and height of the same will not change but are rather fixed in the same exact position in x, y and z, so minimizing the hurdles of base mounting and calibration of parameters for survey procedures.

![Base pillar erected on the roof of main CSR building](image)

Figure 2—3 Base pillar erected on the roof of main CSR building

A long static observation with collection of raw data had been conducted with base antenna mounted on the pillar. Raw data had been submitted to Geoscience Australia through their facility named AUSPOS\(^\text{13}\), defined as “[...] a free online GPS data processing facility provided by Geoscience Australia. It takes advantage of both the IGS Stations Network and the IGS product range. AUSPOS works with data collected anywhere on Earth.”

Final processing report had been received from AUSPOS (see Annexure 07), with geodetic coordinates computed for the fixed Base antenna point, as 12° 00' 57.79560'' N, 79° 48' 35.96164'' E, with a “Derived Above Geoid Height” of 58.730 meters. Geodetic Coordinates are calculated on GRS80 Ellipsoid, in ITRF2008 System. Positional Uncertainty of the point amounts to 0.064 m for Longitude, 0.026 m for Latitude, 0.113 m (up) for Ellipsoidal Height. The uncertainty of Ellipsoidal Height is higher than AUSPOS boundary (0.085m), and the report recommends to use it with caution.

In absence of any accurate and documented alternative, geodetic coordinates values of Base antenna point have been accepted, and used for all subsequent survey works.

\(^{13}\) For info, visit https://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/auspos
In order to proceed with survey work, geodetic coordinates have been projected to a TM (Transverse Mercator) projection, with parameters as:

- Map Projection: Transverse Mercator (TM)
- False Easting: 370455.6300
- False Northing: 1328608.9940
- Latitude of Origin: 12°00'57.79560"  12.01605433
- Central Meridian: 79°48'35.96164"  79.80998934
- Scale Factor: 1.0000000
- Zone Width: 6.0°

It is important to note that, being all areas to be surveyed within 5 km from the Base point, Scale Factor of 1.0 is acceptable.

Same parameters in PROJ\(^4\) format are:

- +proj=tmerc +lat_0=12.01605433 +lon_0=79.80998934 +k=1 +x_0=370455.630 +y_0=1328608.994 +ellps=WGS84 +towgs84=0,0,0,0,0,0,0 +units=m +no_defs

Having so defined a projection, all collected geographic information and data can be easily re-projected to any other projection through GIS (Geographic Information System) software.

2.1.1.1 Survey Process Definitions

2.1.1.1.1 Survey

Measurement of physical reality according to the set standards, and translation of numeric data coming from the measure into a readable map.

Examples:

- building corners;
- level of ground.

2.1.1.1.2 Base Map

The map on which all buildings and infrastructure are represented, as well as selected vegetation, fencing and elevations.

2.1.1.1.3 Thematic Map

Map extracted from the Base Map, which serves a specific purpose.

Examples:

- land use map;
- water infrastructure map;
- distribution of population map;
- contour line map.

2.1.1.1.4 Control Point / Benchmark

Points with known coordinates that serve as a reference for Surveys and Stakeouts when DGPS coordinates are not available.

The Benchmark is permanent, whereas a Control Point can be temporarily defined at one specific point in time and not re-used.

2.1.1.1.5 Footprint

A footprint is the top view of an object (without specific architectural details in case of a building), such as the balloon view, perpendicular to the earth’s surface.

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\(^4\) PROJ is a generic coordinate transformation software that transforms geospatial coordinates from one coordinate reference system (CRS) to another. This includes cartographic projections as well as geodetic transformations. https://proj.org/. (PROJ contributors, 2019)
2.1.1.6 Total Station
The Total Station is an electronic/optical instrument, composed of an electronic theodolite integrated with an Electronic Distance Meter (EDM). It is used to measure distances and angles with high accuracy (millimetre), through the infrared and laser technology. Data are expressed as relative distances, and/or relative or absolute coordinates, and can be plotted on CAD applications.

2.1.1.7 GNSS
The Global Navigation Satellite System (GNSS) is a space-based measurement system that provides accurate location and time information in all weather conditions, anywhere on or near the Earth where there is an unobstructed line of sight to four or more GNSS satellites.

At the time of composing this document, it includes the satellites constellations of GPS (Global Positioning System – USA), GLONASS (Globalnaya navigatsionnaya sputnikovaya sistema, or "Global Navigation Satellite System - RUSSIA). In future, also GALILEO (European Global Navigation Satellite System - EUROPE), NAVIC (NAVigation with Indian Constellation – INDIA), BEIDOU (CHINA), QUASI-ZENITH (JAPAN) constellations will be included in GNSS.

2.1.1.8 DGNSS
Differential Global Navigation Satellite System (DGNSS) is an enhancement to the Global Navigation Satellite System (GNSS) that provides improved location accuracy, from the 15-meter nominal GNSS accuracy to about 1 cm in case of the best implementations.

DGNSS uses a network of fixed, ground-based reference stations to broadcast the difference between the positions indicated by the GNSS satellite systems and the known fixed positions.

2.1.1.9 Project
The whole Auroville territory to be surveyed covers an approximate area of 20 square kilometres. For ease of coordination, it has been divided in smaller areas, each one identified as “Project”.

2.1.1.2 Standardized procedures of topographic field survey
A set of standardized procedures have been defined and implemented with the aim to conduct accurate, standardized and replicable survey of topographic features in the field.

2.1.1.2.1 Datum and Map Projection
The Datum is the CRS (Coordinates Reference System) that gives the relationship between coordinates and a point on the earth.

The following Datum (reference ellipsoid) shall be used: WGS84 (EPSG: 4326): World Geodetic System, last revised in 1984.

A Map Projection is the systematic way in which a curved surface is represented on a flat plane, through mathematical transformations.

The following projection of WGS84 ellipsoid shall be used:
- TM: Transverse Mercator, defined for field work and GIS application;
- UTM44 N (EPSG: 32644): Universal Transverse Mercator, zone 44 North (to enable exchange of GIS data with other Organizations).

The Vertical Datum, which is the reference for all elevations, shall be the Height Derived Above Geoid Height, and assumed as Mean Sea Level (msl), as calculated by Auspos – Geoscience Australia.

If data are collected with hand held devices (e.g. portable GPS), they are assumed to respect WGS84 datum, being it the default GPS datum. While compiling any report of these data, the international standard for representation of Longitude, Latitude and Elevation for geographic point locations ISO6709 shall be applied, with the exception related to the order of presenting the coordinates, as follows: Longitude, Latitude, Elevation.

It shall always be specified if the elevation refers to the WGS84 ellipsoidal Height, or to the mean sea level.

2.1.1.2.2 Geographical Point Definition
The following requirements shall be met for the definition of a geographical point:

2.1.1.2.2.1 Point Coordinate Standard
A geographical point shall be specified by the following four parameters:
- the horizontal definition coordinate (x), which shall give the Easting or Longitude;
• the horizontal coordinate (y), which shall give the Northing or Latitude;
• the vertical coordinate (z), which shall indicate the Elevation (on mean sea level);
• the datum used.

2.1.1.2.2 Coordinate Recording Standard

The following requirements have been defined to standardize coordinate recording:

Coordinate values (Eastling, Northing, Elevation or Longitude, Latitude, Elevation) shall be delimited by commas;
The decimal delimiter shall be a point;
Coordinates of multiple points shall be written in separate lines;
If coordinates are in TM and/or UTM44N, they shall be expressed in meters, with three digits in the decimal part, thus indicating millimetres (e.g. 370115.352,1327028.589,45.328);
If coordinates are in WGS84/LatLong, they shall be expressed either in decimal degrees (preferably) with an accuracy of minimum six digits in the decimal part (e.g. 79.11853,12.239754), or in sexagesimal fractions (Degrees, Minutes, and Seconds), with an accuracy of minimum two digits in the decimal part of the Seconds (e.g. 79°11'25.31'');
Degrees, minutes and seconds shall be followed by the symbols ° (ASCII code: U+00B0), ' (ASCII code: U+0027), and " (ASCII code: U+0022), without spaces between the number and the symbol;
When Minutes and Seconds are less than ten, leading zeroes shall be shown;
East Longitude and North Latitude shall be indicated as positive values;
On the Auroville territory all Latitude values are North of the equator and shall thus be indicated by an "N" immediately after the digits;
On the Auroville territory all Longitude values are East and shall thus be indicated by an "E" immediately after the digits;
The Elevation shall be given in meters (m), with three digits in the decimal part thus indicating millimetres;
Units of elevation or depth shall be given in meters (m) immediately after the digits;
Elevation below reference level or depth above reference level shall be indicated by a minus sign (-).

Examples:
• TM / UTM44N: 371203.548,1327639.201,55.040m
• WGS84 decimal degrees (dd): 79.136543N,12.398103E,123.450m
• WGS84 sexagesimal degrees (DMS): 79°14'46.461"N,12°48'26.533"E,123.450

2.1.1.2.3 Survey measurement

The Survey operations shall be conducted strictly respecting the parameters and requirements for Coordinate Reference System (CRS) and Datum, and Geographical Point Definition, as defined above.

2.1.1.2.3.1 DGNSS survey

The Surveyor performs the measurements and stores any required data in the DGNSS Controller, ensuring the following points are respected:
Roving antenna is set in the Controller, and CRS set, before starting the measurement;
Roving antenna is mounted on the pole with attached bipod to ensure stability;
The rover pole is always held vertical, with constant check on the installed circular bubble;
All measurements for elevation data are done uniformly, preventing the rover pole from penetrating into the ground for more than 0.005 m (0.5 cm);
Height of roving antenna is measured;
RTK is initialized
All point codes comply with the Field Codes List as defined in “CAD Layer Naming” paragraph under “Field Survey Data Processing” further ahead in this chapter;
While starting the measure, 3D quality must be lower than 0.050 m (5.0 cm). In case 3D quality is higher, measure cannot be started due to higher error.
While storing the point in the Controller, 3D (x, y, z) quality must be less than 0.025 m (2.5 cm). In case 3D quality is higher, measure cannot be stored due to higher error.
Point is properly stored in the Controller.
2.1.1.2.3.2 Total Station survey
The Surveyor performs the measurements and stores any required data in the Total Station, ensuring the following points are respected:
The prism pole is always held vertical, with constant check on the installed circular bubble;
Accuracy of measurements is the best allowed by the equipment;
All measurements for elevation data are done uniformly, preventing the rover pole/prism pole from penetrating into the ground for more than 0.5 centimetres;
All point codes comply with the Field Codes List as defined in “CAD Layer Naming” paragraph under “Field Survey Data Processing” further ahead in this chapter;
All Change-Station Data are checked 3 (three) times before confirming and changing the station point. Horizontal Error does not exceed 0.010 m (1.0 cm), Vertical Error does not exceed 0.025 m (2.5 cm). If any of these errors is higher, the Change-Station process must be repeated;
Any error during the whole measuring process never exceeds 0.010 m (1 cm). If the error is higher, the measurement must be repeated;
All permanent Control Points / Benchmarks are numbered, coded, photographed, and registered into the field notebook. Any remarks on exact location of the Control Point / Benchmark, and how to reach it, are registered into the field notebook;
All offset measurements are recorded in the field notebook, with clear indication of offset distance and offset direction from the offset reference point. A field sketch must be drawn on the spot to facilitate data processing;
Any other comment, remark, tip, note, useful for point identification or processing, must be hand written on the field notebook;
Any line joining points (fences, walls, electric lines, etc.) are sketched into the field notebook while performing the survey, to facilitate processing.

2.1.1.3 Survey Data processing

2.1.1.3.1 CAD Layers Naming
The definition of standardised CAD layers is crucial, as all graphic systems support and use the concept of layers. Standardised layer names identify content of the layers, and allow storage of topographic features of the same category in the same layer, thus improving processing of data, accelerating the outcome and categorising features in standardised groups. Use of standardised layer names enable to integrate and join several drawings in one, facilitating the creation of the Base Map from Surveys done at different time.
Each CAD layer corresponds to a unique Field Code to be used during Field Survey.

2.1.1.3.2 Applicable External Standards
Standard definitions for Survey and Mapping including the CAD Layer definitions are available on the following International Standards:
• ISO 13567-1:1998 Technical product documentation -- Organisation and naming of layers for CAD -- Part 1: Overview and principles
• ISO 13567-2:1998 Technical product documentation -- Organisation and naming of layers for CAD -- Part 2: Concepts, format and codes used in construction documentation
• United States National CAD Standard – V5ines, under NCS (United States National CAD Standards) version 6, – September 2014 CAD Layer naming standards.

2.1.1.3.2.1 ISO
The International Organization for Standardization (ISO) is the only recognized international body promulgating standards in the area of electronic building design data. The ISO Standard 13567, Organization and Naming of Layers for CAD, is in three parts, with the third part still under study by the ISO team for the time being and is not applicable.

2.1.1.3.2.2 US NCS
The US NCS allows selection from a number of format options for creating layer names.
2.1.1.3.3 **Selected CAD Layer Naming Standard**

*US NCS proposes a code, which is the best adaptable for Survey and Mapping needs and has been applied for the following reasons:*

- ISO refers to further standards like CI-SfB and Uniclass for the definition of one of its mandatory fields, the “Element”: they use hundreds of numeric codes to identify features or elements, rather than intuitive English abbreviations that are easy to remember;
- In US NCS there is already a Discipline coded for Survey and Mapping, with many needed codes already defined;
- US NCS allows creation of user-defined codes;
- US NCS allows combination of codes.

2.1.1.3.3.1 **CAD Layer Requirements**

*The layer name format is organized as a hierarchy. Layer names consist of distinct data fields separated from one another by dashes.*

A detailed list of abbreviations or field codes define the content of layers. Most field codes are mnemonic English abbreviations that are easy to remember.

*The US NCS proposes five defined layer name data fields: Discipline Designator, Major Group, two Minor Groups, and Status.*

The Discipline Designator and Major Group fields are mandatory. The Minor Groups and Status fields are optional.

Layer names that do not require a certain field shall use a dash to maintain the length of the layer name and the relative position of the fields.

*For conceptual conformance to ISO 13567 “Organization and Naming of Layers for CAD” the layer name format and length shall be the same for all layers.*

*CAD Layers shall then be composed as follows:*

- Discipline Designator Field
- Major Group
- Minor Group 1
- Minor Group 2
- Status

2.1.1.3.3.1.1 **Discipline Designator Requirements**

*The Discipline Designator denotes the subject matter contained on the specified layer. It indicates the creator, who has generated the CAD file. The Discipline Designator is a two-character field:*

- the first character is the discipline character
- the second character is a dash

2.1.1.3.3.1.2 **Major Group Requirements**

*The Major Group shall indicate the category of the physical items, which are going to be surveyed and mapped (e.g. building, road, vegetation, pipe). It is a five-character field:*

- the first 4 characters are the intuitive code for the category
- the fifth character is a dash

2.1.1.3.3.1.3 **Minor Groups**

2.1.1.3.3.1.3.1 **General Requirements for Minor Groups 1 + 2**

*These Minor Group fields further define the Major Groups. Two Minor Groups have been defined:*

- Minor Group 1, which shall indicate the physical item, which is going to be surveyed and marked (e.g. Neem tree, road curb, septic tank, building corner);
- Minor Group 2, which may hold annotations.

*Both Minor Group 1 and Minor Group 2 are five-character fields:*

- the first four characters are the intuitive code for the item
- the fifth character is a dash
2.1.1.3.3.1.3.2 Specific Requirements for Minor Group 2: Annotations

Minor Group 2 shall not use the field code “ANNO”.

Annotations consist of text, dimensions, notes, sheet borders, detail references, legends, symbols and other drawing elements on CAD drawings that do not represent physical aspects of a building or of a feature.

2.1.1.3.3.1.4 Status

The status field is a single-character field that distinguishes the data contained on the layer according to the status of the work or the construction phase.

All definitions of CAD layer naming, including list of Discipline Designators, Major and Minor Groups, Status, are in Annexure 08.

2.1.1.3.4 Field Survey Data processing

The survey processing software used is Autodesk AutoCAD Civil 3D, 2018 edition. Among others, the advantage provided by this particular software is its design purposely made for survey too: it has in fact several features to automatize the import of survey points, their assignment to specific layers, their representation through symbols predefined by the user, etc. This capability is achieved through definition of “Description Keys”: while importing points, their field code, corresponding to one and only one CAD layer, is detected, so all points having a certain Field Code are moved into respective layer. Moreover, a set of additional information is associated to Field Codes for points, in particular their symbology, and their labelling.

As for any CAD software, additional settings for each layer are defined:

- Visibility – Freezing – Locking
- Color – Linetype – Lineweight – Transparency
- Plot Style – Plotting
- Description

Creating a drawing template with definition of these parameters for each layer allows data to be consistently represented in the drawing, thus complying with chosen standards.

After completion of field work, survey data are downloaded from Controller and/or Total Station as text files (.txt) and CAD files (.dxf). A preliminary cross-check of all points data is conducted to ensure that all points have codes, and there are no inconsistencies in point serial-numbering. Given the high number of points surveyed daily (up to more than 1,000 points per day), these steps have been conducted on a daily basis.

Text files are imported into Survey processing software (Autodesk AutoCAD Civil 3D), all points are automatically assigned to their respective layers, related symbols and labels generated, through use of Description Keys.

After the import into CAD the following actions are required:

- ensure CAD file units are set on meters;
- ensure the drawing is georeferenced on selected projection (TM) with its defined CRS;
- confirm that points are in the correct layer; if not, assign them to the right layer, according to defined standards;
- from the “cloud of points”, connect all points which are on the same linear/polygonal features, so to draw the shapes;
- ensure shapes are into the right layer;
- export CAD data to GIS standardized format (shapefiles).
Figure 2—4 Example of Topographic Survey drawing in CAD – Residential Zone, Auroville

Figure 2—5 Detail of Topographic Survey drawing in CAD – Residential Zone, Auroville
2.2.1 Weather monitoring

Proposing an integrated water management plan means first of all assessing availability of water from all sources.

It is clear that the main, sometimes the only, available source is rain. It is then imperative to assess the quantity of rainfall over a time period.

Several devices are currently available for rainfall measurements: manual raingauges, as well as automatic raingauges and weather stations.

2.2.1.1 Raingauge

Precipitation is expressed in terms of the depth to which rainfall water would stand on an area if all the rain were collected on it (Subramanya, 2008). The precipitation can be collected and measured in a raingauge, consisting of a cylindrical-vessel assembly kept in the open to collect rain.

In particular, the nonrecording standard gauge (SRG) consists of a fibreglass reinforced polyester, circular collector funnel with a brass or gun metal rim and a collection area of 200 cm$^2$ (diameter 159.5 mm) leading to a base unit containing a polythene collector bottle. The base unit is designed to avoid possible losses due to overflow from the bottle. Details of standard raingauge are given by Indian Standard (IS 5225).

A calibrated measuring glass (rain measure) is provided with the rain collector, to enable measuring of the rain water collected. The rain measure is graduated for every 0.2 mm of rainfall. The gauge is read once daily and any rain held in the polythene collector is poured into the measuring glass to determine rainfall in millimetres.

For uniformity, the rainfall is measured at 8.30 AM (IST) (Subramanya, 2008) and it is recorded as the rain which fell in the previous 24 hours, from 8.31 AM on the previous day, till 8.30 AM on that day.

Though sixteen raingauges are installed in Auroville territory, not all of them are properly operated, for various reasons. Nevertheless, six raingauges operators are regularly collecting and storing data in a standardized format, and one of them in particular, started collecting rainfall data in April 1989 and has been consistent ever since.
Figure 2—Map of Manual rain gauges locations in Auroville territory

Table 2—1 Manual Raingauge data collection format

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<th>February</th>
<th>March</th>
<th>April</th>
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All records are preceding 24 hr’s from 8:30 AM each day.

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<th>Rain Days</th>
<th>Trace Days</th>
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</table>
2.2.1.2 Weather Station

Rain is only one of the parameters defining weather conditions: usually an automated Weather Station is the best tool to measure and record weather parameters.

A first attempt had been made in 2017 to assemble an automatic Weather Station: sensors for Humidity, Atmospheric Pressure, Solar Radiation, Temperature, Rainfall, Wind Direction, Wind Speed were acquired, calibrated and assembled with a datalogger recording readings every minute. The system was functional for few months, and later some hardware and software maintenance issues arose, unfortunately the service provider stepped back.

Figure 2—8 Assembled Weather Station and Automatic Raingauge

In 2018 a new, pre-assembled, fully automatic home Weather Station, brand Ambient Weather, (model WS-2902A) has been acquired, tested and installed on CSR building roof, in order to measure and record:

- wind speed, expressed in km/h
- wind direction, expressed in degrees from North
- rainfall, expressed in mm
- UV, expressed as numeric index
- solar radiation, expressed in W/m²
- barometric sea-level pressure, expressed in hectopascal
- temperature, expressed in °C degree
- humidity, expressed as percentage.
The weather station measures parameters every minute, and send the readings through encrypted radio waves to a console, placed within 100 meters from the station. The console is connected via Wi-Fi to the Internet, and sends all data to Ambient Weather dashboard website, from where data can be retrieved and stored in a convenient database. The setup works uninterrupted, provided power is constantly supplied to the console, and Internet connection is always available.
2.3.1 Groundwater monitoring

Auroville has developed more than 300 wells in its 52 years of history. Not being connected to any water distribution network, new settlements had no choice but access water through borewells. Parallelly, a large work of re-afforestation, through planting of more than 30 lakh trees, combined with land bunding, has been carried on to favour water percolation in order to increase groundwater recharge and limit surface runoff. These actions did improve the overall groundwater situation, water-table raised along with efficient management of water resource within Auroville territory. Unfortunately, the same did not happen in the surrounding areas: population increase, choice of water intensive crops and short-sighted political decisions (e.g. free electricity to farmers) have led to overexploitation of aquifers, with the unavoidable consequence of water table sinking at alarming rate.

Since aquifers are being shared between Auroville and surrounding region, all efforts towards a sustainable water management as envisioned by Auroville have been futile compared to the size of the over-extraction.

A monitoring campaign to record water levels in wells has been initiated on selected wells existing on Auroville territory, aiming to raise awareness of water situation, at the same time evaluating potential wells to be used as back-up in case of severe drought.

Between 50 and 60 wells are monitored on weekly basis, through an electric contact meter (brand Seba) long enough to measure up-to 100 meters, equipped with an optical and acoustic signal on contact with water. Reference for all measurements is always the top of well casing pipe, to keep consistency of readings. Knowing the height difference between top of casing and surrounding ground, and knowing the elevation of the ground with reference to the sea level, all readings are then referenced to sea level through simple calculation.

![Figure 2—10 Seba Electrical Contact meter used for water level monitoring in wells](image)

For well water levels readings to be considered as valid, in case of wells used for water extraction (in-use wells), the pump should not have functioned for at least 8 hours before taking the reading: people in charge of wells operations have been properly informed about this requirement, and requested not to pump before the monitoring. In few cases though, this
has been not complied with, and consequently the reading could not be done, or its value needed to be discarded.

Wells with automatic pumping systems (solar- or wind-powered, with automatic switch to turn the pump on) could not be monitored. If the pumping system of a well has been changed from manual to automatic, the monitoring of the well has been discontinued.

Wells without pump (not in use) do not pose this kind of problems, thus being preferred in case of multiple choice.

Monitoring of some wells might have been discontinued also due to other reasons, e.g. modified conditions of accessibility to well, presence of aggressive dogs, lack of cooperation from the person in charge of the well, sealing or covering of well head with heavy slabs.

Consequently, number of monitored wells has kept changing over time.

In order to conduct a preliminary analysis on the collected data, wells with readings spanning over a minimum period of two consecutive years, after 1st April, 2017 are considered: readings of wells where monitoring has been discontinued after less than two years from its inception, or where monitoring started less than two years ago, are not considered.

Out of 97 wells for which monitoring has been done as on date, only readings from 51 wells can be considered as valid, while 30 wells do not have enough readings, 4 wells have no casing reference, 12 have no data after the 1st of April, 2017. For details, see Annexure 01.
Considering only the valid readings, minimum water levels have been recorded in 10 wells (20%) in 2017, in 4 wells (8%) in 2018, and in 37 wells (73%) in 2019. On the other hand, maximum water levels have been recorded in 42 wells (82%) in 2017, in 6 wells (12%) in 2018, and in 3 wells (6%) in 2019.

![Minimum and Maximum Ground Water Levels Trends in Monitored Wells with data for at least 2 years](image)

*Figure 2—Minimum and Maximum water levels in monitored wells in the period from April 2017 till end of January 2020*

Data thus show that, during the monitoring period from April 2017 till end of January 2020, in most of the cases the lowest water level has been registered in the most recent year, while the highest level has been registered during past periods: water levels keep falling every year, highest levels are not reached any longer, while lower and lower levels have become the norm.

The water level monitoring as described above provides information for general awareness to public, and for basic management of resources in case of water scarcity. Nevertheless, to infer proper groundwater dynamics, monitoring of water level needs to be conducted on selected wells tapping into one single aquifer only: if a well taps into several aquifers, the resulting water level is subject to conditions pertaining to different groundwater systems, thus not representing any individual aquifer conditions.

To identify suitable wells for hydrogeological purpose, all information available on existing wells in Auroville have been collected, standardized, and then plotted to QGis software (Free and Open Source Geographic Information System)\(^\text{15}\) to conduct a suitability analysis.

Parameters considered for the analysis are:

- Status
- Presence of pump: yes, no
- Status of pump: functioning, not functioning
- Accessibility
- Stratigraphic information
- Interference from neighboring in-use wells:

Wells shall thus be not in use, shall have no pump, or no functioning pump, shall be accessible (absence of heavy slabs, fences, dogs, etc), shall have stratigraphic information to be sure that only one aquifer is tapped (if stratigraphic data are not available, the stratigraphic unit at the

\(^{15}\) For info, visit https://qgis.org/en/site/
bottom of the well shall be inferred from its depth and its distance from the nearest well with stratigraphy), shall not be interfered by other in-use wells. For the last points, criteria have been defined as:

- strong interference distance from the well less than 75 m
- medium interference distance from the well between 75 and 100 m
- light interference distance from the well between 100 and 150 m
- no interference distance from the well more than 150 m.

The evaluation of interfering wells can be conducted only on wells on Auroville land, for which GPS position data are available. In case wells are on land not owned by Auroville (private land) no data are available, thus interference from these wells toward Auroville ones cannot be excluded, but cannot be established as well.

As a result of the above selection, 14 wells have been identified as suitable for the purpose. In Annexure 09 all details for the evaluation are provided.

A metal clamped cover has been manufactured for each well, to ensure safety, and to prevent objects from falling into them. The cover is made in two sliding parts with a hole in between, so that a cable can be placed without being damaged.

Figure 2—13 Map of proposed monitoring wells on Auroville land
One monitoring well, not used for water extraction, having no pump installed, is located in Ami community, and it is stewarded by Mr. Rama; it has been equipped with automatic pressure sensors, connected to a LoRaWAN (LONg RAnge Wide Area Network)\textsuperscript{16} device transmitting data to a gateway installed in CSR compound, at a height of more than 20 meters from the ground level.

\textsuperscript{16} For info, visit https://lora-alliance.org/about-lorawan
The pressure sensor has been calibrated to read difference in water pressure and convert them into units of length, equivalent to the water level in the well where the sensor is installed, referenced to sea level.

The LoRaWAN device is kept in a dust- and water-proof IP 65\textsuperscript{17} plastic enclosure, inside a metal box specifically designed for the purpose of ensuring safety of the whole setup, at the same time preventing small animals (especially rodents) from damaging cables. The box is mounted on a pole fixed into the ground within 3 meters from the well, at a height which varies between 1 and 2 meters depending on local conditions, so that transmission of data and recharge of batteries through solar panels installed on top are guaranteed.

Readings are taken every 30 minutes, transmitted to the gateway, routed through internet to a storage facility from where they can easily be retrieved. Readings details are in Annexure 01, Well id 127.

![Figure 2—16 Graph of readings from LoRaWAN automatic monitoring of Ami-Rama well](image)

The graph shows very clearly the interference of a nearby well (the monitored well not having pump installed in it), and gives real-time information on water table fluctuations.

\textsuperscript{17} For info, visit https://en.wikipedia.org/wiki/IP_Code
3 Software development

The need of a dedicated software able to process and store the huge amount of resulting data has been clear right from the onset of the project. Existing software, including several Geographic Information System (GIS) software, meet certain demands, especially those regarding link of geographical information to a database.

Nonetheless, no single existing software could provide for all specific processing and calculations, as needed for the hydrologic modeling part (see below), and for building a platform hosting different data formats, at the same time able to allow online publication of all data and processing results in almost-real time.

In particular, proprietary software, also known as closed-source software, cannot be modified for these purposes, being its code usually under its publisher’s (or other person’s) intellectual property rights, copyright, patent rights and/or trade secret, with the result that “the owner can restrict use, inspection of source code, modification of source code, and redistribution. [...] Vendors typically distribute proprietary software in compiled form, usually the machine language understood by the computer’s central processing unit. They typically retain the source code, or human-readable version of the software, written in a higher level programming language. This scheme is often referred to as closed source. [...] most proprietary software is distributed without the source code [...]”18

On the other hand, “[...] The open-source model is a decentralized software development model that encourages open collaboration, meaning "any system of innovation or production that relies on goal-oriented yet loosely coordinated participants who interact to create a product (or service) of economic value, which they make available to contributors and noncontributors alike." (Levine et al., 2013). A main principle of open-source software development is peer production, with products such as source code, blueprints, and documentation freely available to the public."19

Hence, development of a dedicated software was necessary, in the Open Source model. As stated earlier, the software should be able to store and display:

- all topographic survey features, along with details about the project (area) they are part of, the Surveyor, the survey equipment used, the accuracy, the survey date, the status
- all rainfall data collected by different individuals
- all weather data collected by weather station(s)
- all water levels of selected wells measured either manually or automatically
- all information on existing wastewater treatment plants
- all existing geographical information (infrastructure, geology, topography, development planning, etc) collected by agencies and/or individuals in Auroville territory

At the same time, the software should allow, in the spirit of the Open Source model, for anyone to not only access the code and the information, but also download all data and encourage others to contribute to it in their capacities, complying with the standards and the principles in place.

To ensure consistency of processes and data, in compliance with the set standards, workflows have been set for each of above streams.

3.1.1 Information system and GISAF Software details

The newly developed software has been named GISAF (an acronym for Geographic Information System Auroville Front-end). It is designed to be a domain agnostic, extensible platform for

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18 For info, visit https://en.wikipedia.org/wiki/Proprietary_software
19 For info, visit https://en.wikipedia.org/wiki/Open_source
**Geomatics (topographic survey), GIS and data analytic integration.** While research on water resources is the main drive for its conception, this design facilitates the collaboration between teams working on many different domains to share data, resources, results: town planning, infrastructures, architecture, asset management, environment, etc.

### 3.1.1 Open source

The full source of the Gisaf software is available online at URL https://redmine.auvrole.org.in/projects/gisaf, free of cost under the GPL v3 license. It was presented at the “State of the Map Asia 2018” conference in the Indian Institute of Management, Bangalore, in November 2018.

### 3.1.2 Development

The requirements of the Gisaf software have evolved considerably during the project. The development makes use of well-known software development techniques and tools such as versioning system (git) and ticket tracking (redmine). The early versions concentrated on setting up the main lines of database structure and functions for importing of data in various formats such as geographical GIS shapefiles, Excel and CSV for measurement data samples. Concurrently to the data and software structures, robust business processes for data acquisition were defined in parallel. This ensures that the collected information is consistent, updated, traceable, and the integrity of the data is maintained.

### 3.1.3 Software stack

The core of the application is an asynchronous server written in Python. It drives a web application written with the Angular (version 9) framework. The software uses state of the art technologies and libraries, such as:

- Aiohttp, Asyncpg
- Pandas (data and statistical analysis)
- Mapbox-gl.js (maps)
- Plotly.js (interactive plots)
- GraphQL (APIs)
- Angular (web application framework) and Angular Material (web user interface).

### 3.1.4 Database

Building a consistent, reliable, updated database is a pivotal step, a crucial building block for the materialization of processes and models.

The database is a standard PostGres SQL database with PostGis extensions. This allows tools like QGis, AutoCAD, and many software and libraries to connect and have a direct access.

Two kinds of geographical enabled tables are defined:

- US NCS (ISO compliant) layers (surveyed features category): standardized schema matching the definition of the layers
- Custom definitions for layers imported from third party providers.

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20 For info, visit http://2018.stateofthemap.asia/
Features of some layers have temporal data associated to them. For example, wells have levels of water measured at different points in time, weather stations have a range of information such as temperature, rainfall, etc. For these layers, other tables are defined which store the time stamps and the different values, along with foreign keys which record these value points to the feature in the geographic table.

The import of data follows a workflow ensuring the consistency, traceability, and continuous improvement of the quality of the data, as shown in below figure.

- Data contributors (surveyors, operators of devices which provide samples of data such as wells, rain gauges, etc.) deposit files in dedicated “baskets”
- Each basket has its own workflow for importing the files in the database. For example, the basket for rain gauge levels receives Excel files, and the basket for rain falls includes a parser for this particular format of Excel files and processor for saving into the database
- A reviewer checks the data and eventually triggers the import into the database
- Users have many options to download the data, which can then be updated and fed back to the basket. This ensures that teams can get the latest data available, update and add information, which can then be shared to other collaborators.

This automated process takes care of re-projections, the association of metadata from the source and other metadata such as the equipment, accuracy, status and survey time stamp. The import of layers of points is fully automated from the CSV files given by the survey equipment to the map, whereas layers of line and polygons are uploaded as industry standard shapefile or geopackage formats.
A screen shot of the user interface for the routine management of the baskets, triggering the execution of the workflows, is shown in next Figure. Operators can easily upload files along with attributes used for the import in one of the baskets. Then the reviewer can import the files in the database after validation. After validation of the input, the Gisaf software applies the workflow of the basket and displays results: number of features in the file, added, updated, deleted, etc.

Default baskets are:

- Survey points
- Line work (with the survey category)
- Misc shapefiles (for customized layers, with associated table)
3.1.1.5 Tags
The Gisaf software has a feature to add pieces of information, called tags, to individual or
group of features, directly on the web user interface. These follow a (key, value) pair structure,
similar to the data structure used in the Open Street Map project. Tags can be used for simple
identification (name), references to other database (URL links), any kind of value necessary for
specific computations, etc.: since the tags are stored in the same database, they can be used to
identify and process features according to the information given in them.

3.1.1.6 Plugin architecture
The core of the Gisaf software can be extended easily with “plugins”, which use the standard
Python entry points module loading mechanisms. Plugins can define:

- Database models
- Custom tag types, with optional actions on geographical features
- Import baskets

Many plugins have been created for this project, such as:

- Rain gauges
- Waste water treatment plants
- Wells
- Weather stations

3.1.1.7 Data analysis: Pandas and Geopandas
Pandas is a popular Python library which has recently gained a lot of traction in the Open
Source communities; Geopandas provides geographical extensions. They are based on the
robust industry standard Numpy vector processing library, and add multidimensional data
structures called dataframes. As such, they bring optimized vector processing (operations are
executed on series of data) at a higher level, in opposition to traditional scalar processing
(operations executed on single values). This leads to massive savings in resources and
processing times; alternatively, a much larger amount of data can be processed on a given
hardware, sometimes by a factor 100. The Gisaf software makes use of them extensively, as the initial code was migrated from an ORM (Object Relation Mapper) paradigm.

3.1.1.8 Jupyter

Jupyter ([https://jupyter.org/](https://jupyter.org/)) as a software provides the ability to develop interactive computing through the creation of notebooks directly in a web browser. The notebooks are organized in cells of code, which can be run independently. They are user friendly, accept documentation, and are particularly well suited for research.

Jupyter has recently gained a lot of popularity in data analytic research, as it allows the experimentation on algorithms and data analysis techniques using languages and software libraries such as Python and Pandas, so far reserved to software development specialists. A screenshot of a practical application of Jupyter notebooks is provided below.

![Jupyter notebook for rain gauge levels analysis](image)

The Gisaf software provides a component to easily import and export data and Gisaf Python modules directly into Jupyter notebooks.

Although Jupyter normally executes the notebooks with user interaction only, the deployment of the Gisaf platform for this project includes the option of running the execution of notebooks automatically. Typically, they are run on a regular time interval, such as every night. This allows complex processing to be run without user intervention and get up-to-date results of these processing, for example in dashboard pages (see below).

3.1.1.9 Device interconnection, inputs and outputs

The Gisaf software is able to get data from, and provide data to different kind of network connected devices (sensors) and other applications through Application Programming Interfaces (APIs). See below Figure for an overview of these capabilities.
Modules have been developed to interface with:

- Ambient Weather (weather station data acquisition)
- Weather Underground (weather station data acquisition)
- The Things Network (devices/probes sending data through LoRaWan).

![Diagram showing inputs and outputs](image)

**Figure 3—5 Inputs/outputs**

### 3.1.1.10 Web front end

The Gisaf software provides a web user interface (a web site), which, for this project, is accessible at [https://gis.auroville.org.in/](https://gis.auroville.org.in/). It also increases the public visibility and recognition of the project, which is valuable in the current socioeconomic context. Public access to the raw data is a major feature in this project, as it allows the different stakeholders or the general public and the community to view and export relevant extracts, and even participate in return, in a virtuous circle.

The main features are listed below:

- **Home**
  - Introduction for the project, the web site, licenses and links
  - Dashboards

- **Map**
  - Left side panel:
    - Selection of a background (choice of satellite, Open Street Map, etc.) with a slider for choosing its opacity
    - Base map: predefined, domain-oriented set of layers (water management, infrastructure, town planning, vegetation, etc.)
    - Layers: individual selection of layers, organized by category
    - Filter and status: show only features on the map matching these criteria
    - Tags: display tags of the visible features on the map
  - Map:
    - Interactive, pseudo 3D map of the selected layers
    - Buttons:
      - Geographical navigation
      - Copy the URL link of that view (with layers, coordinates, angle of vision)
      - GPS tracking on/off, for devices offering location services to the browser
    - Coordinates of the mouse and identification of the feature under the cursor
    - Scale range
- Bottom panel (hidden when no feature is selected)
  - General information
    - Geographical information: coordinates in Longitude, Latitude, elevation, bounds, area and length for polygons and lines
    - Survey information: surveyor, equipment, date of survey, status, accuracy, details of the category
    - Layer specific information (e.g. geological description, characteristics of the well)
    - Attachments (file, picture)
  - Tags
    - View tags of the selected feature(s)
    - Add, edit, delete the tags of the selected feature(s)
    - Trigger tag specific action
  - Plots (for layers with series of value samples over time)
    - Interactive scales, ranges and zooms
    - Clear display of units
    - Re-sampling: hourly, daily, weekly, monthly, yearly
  - Tools
    - Download of all samples (for layers with series of value samples over time)
  - Schematic (for features having schematic details, like waste water treatment plants)

- Measures
  - Left panel (for layers with series of value samples over time)
    - Type (wells, rain gauges, weather stations)
  - List of features of the selected type
  - Information panel, identical to the bottom panel of the map

Figure 3—6 Screenshot of the actual web site: map of the Residential Zone with water management-related features, and the schematics of a waste water treatment plant
3.1.1.11 Mobile use

The web site is compatible with mobile devices, allowing on-site consultation and in some cases data acquisition. For example, the operator measuring the water level from a well can enter the
reading in the database on the spot. For modern mobile devices (smartphones), the position of the device can be tracked on the map.

![Screenshot of the actual web site: architectural features and mobile terminal location tracking](image1)

**Figure 3—9 Screenshot of the actual web site: architectural features and mobile terminal location tracking**

![Screenshot of a dashboard on the Gisaf software, generated automatically daily from a Jupyter notebook, showing the progression of the survey and its geographical coverage by zones](image2)

**Figure 3—10 Screenshot of a dashboard on the Gisaf software, generated automatically daily from a Jupyter notebook, showing the progression of the survey and its geographical coverage by zones**
3.1.1.12 **Dashboards**

The Gisaf software provides the option to display the result of Jupyter notebooks on dashboard pages. A dashboard is a space where the following components, whose data are typically generated by the execution of the Jupyter notebook, are shown to the user:

- Meta-data: name, description, notebook source, time stamp
- Visual (static picture, ex. map)
- Interactive plot (data provided to a Plotly component)
- Data (Pandas dataframe)

![Figure 3-11 Screenshot of a dashboard of the Gisaf software, generated daily automatically from a Jupyter notebook, showing a map of the actively monitored wells and a plot showing the top of the wells, the bottom (if known), and the water level, referenced to mean sea level](image-url)
4 Modelling

An in-depth research has been done on existing literature regarding regional geology, hydrogeology and climatic conditions; literature on surface water management, watershed analysis, hydrological parameters, runoff quantification models, have also been studied to establish a scientific framework. At the same time an extensive research on latest open source technologies on digital terrain modelling, vegetation classification from aerial or satellite imagery, point clouds analysis, treatment of complex geospatial datasets, has been conducted to find effective tools able to process the large amount of data collected and give tangible results.

4.1 Runoff computation model (RunCoMod)

4.1.1 Conceptual foundation of model

Harvesting the quantity of water falling during rain periods has always been indicated as a feasible and practical way to increase water availability. While this is true in concept, attempts in quantification of this additional source have been recently often done with geospatial computations through use of GIS (Geographical Information System), taking into consideration extension of impervious areas and amount of rainfall, and application of a correction factor to account for losses.

This concept is very much similar to the empirical equation used to calculate peak runoff, also known as Rational Method, widely used in many institutions around the world, when the area of interest is not exceeding 3,200 acres (about 13 square kilometres) (Frevert at al., 1955), or 50 square kilometres (Subramanya, 2008).

The Rational Method is used for predicting design peak runoff, mostly for engineering design of new infrastructures like bridges, culverts, or dams, in order to evaluate potential floods and related damages expected in a given period. The empirical equation at the base of the Method is

\[ Q_p = \frac{1}{3.6} C(i_{tc,p})A \]

where:

- \( Q_p \) = peak discharge (m\(^3\)/s)
- \( C \) = Runoff coefficient = runoff/rainfall, dimensionless
- \( (i_{tc,p}) \) = mean intensity of precipitation (mm/h) for a duration equal to \( tc \) and an exceedance probability \( p \)
- \( tc \) = time of concentration (h)
- \( A \) = drainage area in km\(^2\).

The equation is based on a few assumptions:

- rainfall intensity is uniform during the whole rain event;
- rainfall duration is at least equal to time of concentration.

Time of concentration (\( tc \)) of a watershed is the time required for water to flow from the hydrologically most distant point of the watershed, to the watershed outlet.
While evaluating rainwater harvesting potential, water is not negatively seen as reason for a damage, or a limitation to infrastructure development, but actually as a positive input, with the idea of “the more, the better”. Thus, the object of the computation is not the potential damage occurring because of a flood, and therefore design of solutions so to prevent it, rather the benefit generated by each and every drop of rain to increase available quantity.

In this perspective, instead of calculating the “peak runoff”, the focus is on the “whole runoff”, meant in terms of volume rather than flood. Similarly, instead of looking at the “intensity”, intended as the “rainfall intensity for the design recurrence interval and for a duration equal to the time of concentration of the watershed” (Frevert et al., 1955), the interest lies in the volume of water falling from the sky, basically the volume of rainfall, during a rain event, irrespective of its intensity (rate of rainfall per unit of time).

The equation can so be changed into

\[ V_e = C \cdot R_e \cdot A \]

where:

- \( V_e \): Volume of rainfall event \( e \), in cubic meters
- \( C \): Runoff coefficient = runoff/rainfall, dimensionless
- \( R_e \): depth of rainfall in the event \( e \), in meters
- \( A \): area receiving the rainfall event \( e \), in square meters.

To solve the equation, other than the obvious amount of rainfall and extension of the affected area, the value of \( C \) needs to be known. Various values of \( C \) are published in literature (e.g.: CPHEEO, 2013; Dinesh Kumar, 2004; Lindeburg, 1994; Subramanya, 2008; Thomas and Martinson, 2007), and many more online, all pointing to the same basic concept: value of \( C \) is the ratio between runoff generated, and rainfall which generates it. If ideally rain falls on an impervious surface, without any loss, the amount of runoff generated will be equal to its volume (depth of rain x surface area): in this case, ratio will be equal to 1.

In reality, \( C \) coefficient depends on several factors:

- vegetation cover: when rain starts, part of water volume is captured by vegetation existing on the rain-affected area; vegetated areas have lower runoff volumes compared to bare lands;
- ground surface slope: the higher the slope, the higher the runoff volume. Water, subject to gravity, will move faster on surface at high slope, and infiltration into the soil is reduced;
- soil infiltration rate: the higher the infiltration rate of a soil, the lower the runoff: in a coarse textured (sandy) soil, volume of water infiltrating into the soil (thus not anymore on the surface) is higher compared to a finely textured (clay) soil;
- depression/storage loss: if the surface of the area where the rain falls has topographic depressions, water tends to fill up the depression till it can overflow and start running off again.

These are the main parameters affecting the value of runoff coefficient \( C \). Looking at physical processes, there are other parameters which can be considered: one example is the degree of moisture already present in the soil due to antecedent rain events: if the soil is already wet, it will allow a lesser amount of water to infiltrate before reaching saturation, compared to a dry soil.

Built-up areas represent a variation of the infiltration parameter: the roof of a building made in concrete or any other impervious material actually has an infiltration rate value next to zero: in this case though, other physical processes are actively changing the previous statement: there is
the so-called “splash effect” which reduces the water able to runoff from that roof because it is actually lost due to it splashing on the roof while falling, and bouncing out of the roof itself; moreover, evaporation happens also during the rainfall, so another unquantifiable amount of water cannot runoff because it has evaporated; further on, some little quantity can infiltrate into cracks and/or lacunae of the roof; and other minor losses, all of them actually not quantifiable.

Considering all above points, other than having rainfall data and surface areas values, the challenge is to attribute a runoff coefficient based on ground realities, on the base of some objective parameters, rather than leaving the choice to the modeler.

In fact, even while comparing different published values of $C$, it can be noted that the value of the coefficient can vary from one author to another, for the same type of vegetation cover, or built-up areas, etc. The core of the problem is the level of subjectivity inbuilt in the Rational Method.

4.1.1.1 Runoff coefficient for rural and mixed-use watershed

Given the different values of runoff coefficient $C$ as suggested by several authors, and the consequent uncertainty on values to be adopted, a deeper research has been conducted on existing more objective criteria for its definition, looking also at publications focusing on rural areas. Interestingly, an online manual has been published by Texas Department of Transportation\(^2\), revised in September 2019, containing a systematic approach for developing the runoff coefficient.

In particular, a table has been proposed, which “applies to rural watersheds only, addressing the watershed as a series of aspects. For each of four aspects, the designer makes a systematic assignment of a runoff coefficient “component.” Using the following equation, the four assigned components are added to form an overall runoff coefficient for the specific watershed segment.”

The runoff coefficient for rural watersheds is given by:

$$C = C_r + C_i + C_v + C_s$$

where:

$C = $ runoff coefficient for rural watershed

$C_r = $ component of coefficient accounting for watershed relief

$C_i = $ component of coefficient accounting for soil infiltration

$C_v = $ component of coefficient accounting for vegetal cover

$C_s = $ component of coefficient accounting for surface type

Values of components can be derived from the table below:

Currently, the Rational Method is used mainly for design purposes, while evaluation of rainfall harvesting volumes is usually done on area of roofs and buildings only. Undeveloped land is usually considered as minor contributor to the overall runoff volume.

In model proposed here, every surface existing on the ground is evaluated: obviously roofs and buildings, but also roads (paved and unpaved), impervious surfaces like platforms, and undeveloped land. This might sound extreme, but the intent is to find a way to evaluate the entire potential of an area of interest, thus considering each and every fraction of the area in its parameters contributing to runoff generation. The purpose of the exercise is two folds:

- on one hand, given the actual water crisis, to see how much each and every surface can contribute as water source;
- on the other, to actually perform a proper cost/benefit assessment in terms of development of infrastructure to be built for rainwater harvesting.

This approach is usually not considered in literature, given the highly detailed information needed. However, technological innovations on hardware (equipment) and software (algorithms and analysis tools) are available for this approach: the main reason why it is not pursued resides in the long time needed for such a high-resolution investigation, the wide use of already known methodologies and impossibility sometime to explore the new ones (again, time and resources needed for it), and an overall bias in terms of cost-benefits while looking at the larger scenario, when water crisis is not so deeply perceived.

4.1.2 Area of Interest (AoI)

Within Auroville, the area falling into Sector 1 and 2 of the Residential Zone has been identified as the Area of Interest (AoI) for the concept, data acquisition and all computation of the proposed model.
The surface covers an area of about 5,90,000 square meters (about 0.59 square kilometres, or 145 acres), and it is all falling into the same watershed. The highest point is on the west of the AoI, at 54.5 meters above mean sea level (amsl), the lower on its Eastern side at 44.2 m amsl.

4.1.3 Proposed Model Type

Literature offers several types of models, oriented mainly on watershed analysis rather than focused only on rainfall-runoff potential evaluation.

The model proposed here can be defined as a “high resolution, distributed deterministic static (event-based), physically based model in ungauged catchment”.

Regarding the resolution of the model, it is recommended that when the peak runoff is the primary concern, the highest resolution is optimal (Daniel et al., 2011).

The so-called models of distributed parameters divide the watershed/AoI (editor’s note) in smaller units: these units are more homogeneous than the whole watershed/AoI, and the model is applied...
to them. The watershed/AoI response is a composite of the responses of the units. [...] These units may be subwatersheds or artificial units based on a preestablished criterion.

From Daniel et al, 2011:

"Distributed models account for the spatial variability of hydrologic processes, input, boundary conditions, and watershed characteristics. Spatial heterogeneity in distributed models is represented with a resolution typically defined by the modeller. Watershed-scale models can be further subdivided into event-based or continuous-process models. Event-based models simulate individual precipitation-runoff events with a focus on infiltration and surface runoff".

From Jørgensen and Fath B, 2009:

"Deterministic (mechanistic) models are generically a priori developed from an assembly of known processes, for example, hydrologic processes included in rainfall/runoff transformation, accumulation of pollutants in the watershed, vegetation growth and hydrological and pollution impact, etc. The model components are then tested by special field monitoring and in the final stage, the entire model is then calibrated and verified by field data for modeling a specific watershed.

A detailed deterministic or stochastic ecological model has five components (Jørgensen and Bendoricchio, 2001):  
1. Inputs or Forcing Functions,  
2. State Variables,  
3. Mathematical Equations,  
4. Parameters of the Models, and  
5. Constants.

Inputs can be controllable or uncontrollable. The model, like the real system, produces outputs to various inputs and the outputs also reflect the changes in the system itself. The variables describing the system are called state variables. The distinction between inputs and state variables is sometimes fuzzy but, typically, watershed size, soil composition and erodibility, land use distribution, watershed configuration with slope are examples of state variables while rainfall, atmospheric deposition, temperature, humidity and solar radiation are inputs. Most watershed models are driven by precipitation which is an uncontrollable input, while fertilizer application is a controllable, managerial input. The foundation of the model is an equation that describe the input to output transformation. The parameters of each equation may have ranges and the proper value of the parameter must be typically established by calibration and verification of the model. The equations also contain constants and thresholds. A threshold is a constant that activates or terminates a process described by a particular equation or a submodel. For example, many biodegradation processes cease when the temperature is near or below freezing or a priority pollutant is not toxic below a certain concentration.

There are two approaches to modeling watershed processes: lumped parameter and distributed parameter models. [...] Distributed parameter models are mostly deterministic. In the distributed parameter models the watershed is divided into computational subunits that are much smaller than those of the lumped parameter. The size of the subunits may range from 1 hectare to more than one km square. The subunit shapes are either rectangular (square) or triangular or they may follow some morphological or hydrological feature of the watershed. Each unit may receive external and internal (from surrounding units) input and is homogenous.

Models can be designed or run on an event or continuous basis. Event models simulate the response of a watershed to a single large rainfall or another major input (e.g., forest fire). [...]"

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4.1.4 Data acquisition
Several classes of data have been acquired using different technologies, in particular:

- Topographic data
- Infiltration data
- Vegetation cover data

4.1.4.1 Topographic data
An accurate topographic survey has been conducted in the area of interest, in particular paying attention to all ground level variations with height differences of at least 5 cm: compared to a standard survey, where usually ground levels are measured in a grid fashion (5 or 10 meters span) so resulting in lack of crucial information like presence of drains and/or bunds, this survey methodology resulted in more than 61,000 ground level points in the AoI only. Presence of micro-depressions and or micro-relief has been therefore accurately mapped, given their impact on surface water runoff paths: for instance, the presence in the field of an unmapped bund will result in erroneous evaluations on water flow direction. Survey data have been collected and processed following International Standards, as earlier specified.

Runoff coefficient for surveyed built-up features

<table>
<thead>
<tr>
<th>Short Code</th>
<th>Major Group</th>
<th>Minor Group</th>
<th>Status</th>
<th>Description</th>
<th>C</th>
<th>Infiltration Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>B7</td>
<td>BLDG</td>
<td>CTN</td>
<td>E</td>
<td>Container House</td>
<td>0.9</td>
<td>Though usually the material is metal, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.95)</td>
</tr>
<tr>
<td>B8</td>
<td>BLDG</td>
<td>CTNS</td>
<td>E</td>
<td>Container for Storage</td>
<td>0.9</td>
<td>Though usually the material is metal, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.95)</td>
</tr>
<tr>
<td>B18</td>
<td>BLDG</td>
<td>HUT~</td>
<td>E</td>
<td>Hut</td>
<td>0.2</td>
<td>Material usually is organic (thatch or palm)</td>
</tr>
<tr>
<td>B22</td>
<td>BLDG</td>
<td>METL</td>
<td>E</td>
<td>Metal</td>
<td>0.9</td>
<td>Though usually the material is metal, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.95)</td>
</tr>
<tr>
<td>B26</td>
<td>BLDG</td>
<td>OTLN</td>
<td>E</td>
<td>Building Outline</td>
<td>0.8</td>
<td>Though usually the material is concrete, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.9)</td>
</tr>
<tr>
<td>B27</td>
<td>BLDG</td>
<td>OVHD</td>
<td>E</td>
<td>Overhead</td>
<td>0.8</td>
<td>Though usually the material is concrete, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.9)</td>
</tr>
<tr>
<td>B29</td>
<td>BLDG</td>
<td>PLTF</td>
<td>E</td>
<td>Impervious Platform in bricks, stone or cement</td>
<td>0.5</td>
<td>Materials can be concrete, bricks or cement tiles, sometimes with gaps; moreover, water tends to infiltrate into the soil on platform sides; thus C value considered is lower than what is proposed in literature for concrete roads (0.9)</td>
</tr>
<tr>
<td>B30</td>
<td>BLDG</td>
<td>PRCH</td>
<td>E</td>
<td>Porch</td>
<td>0.8</td>
<td>Though usually the material is concrete, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.9)</td>
</tr>
<tr>
<td>B32</td>
<td>BLDG</td>
<td>RAMP</td>
<td>E</td>
<td>Accessible Ramp</td>
<td>0.4</td>
<td>Materials can be concrete, bricks or cement tiles, sometimes with gaps; moreover, water tends to infiltrate into the soil on platform sides, due also to ramp slope; thus C value considered is lower than what is proposed in literature for concrete roads (0.9)</td>
</tr>
<tr>
<td>B33</td>
<td>BLDG</td>
<td>RFDR</td>
<td>E</td>
<td>Roof Drains</td>
<td>0.8</td>
<td>Though usually the material is concrete, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.9)</td>
</tr>
<tr>
<td>B34</td>
<td>BLDG</td>
<td>ROOF</td>
<td>E</td>
<td>Roof</td>
<td>0.8</td>
<td>Though usually the material is concrete, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.9)</td>
</tr>
<tr>
<td>B35</td>
<td>BLDG</td>
<td>SHED</td>
<td>E</td>
<td>Shed</td>
<td>0.8</td>
<td>Though usually the material is concrete, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.9)</td>
</tr>
<tr>
<td>B37</td>
<td>BLDG</td>
<td>SPRT</td>
<td>E</td>
<td>Sports Fields</td>
<td>0.2</td>
<td>Though usually these are open areas, there is a slight compaction due to activities performed on its surface, thus C value taken into account is higher than what is proposed in literature for flat unimproved areas (0.1)</td>
</tr>
</tbody>
</table>

Table 4—2 Runoff coefficient for surveyed built-up features – part 1
Runoff coefficient for surveyed built-up features

<table>
<thead>
<tr>
<th>Short Code</th>
<th>Major Group</th>
<th>Minor Group 1</th>
<th>Status</th>
<th>Description</th>
<th>C</th>
<th>Infiltration Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>B39</td>
<td>BLDG</td>
<td>STRS</td>
<td>E</td>
<td>Stair Treads</td>
<td>0.8</td>
<td>Though usually the material is concrete, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.9)</td>
</tr>
<tr>
<td>B41</td>
<td>BLDG</td>
<td>TEMP</td>
<td>E</td>
<td>Temporary</td>
<td>0.8</td>
<td>Though usually the material is concrete, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.9)</td>
</tr>
<tr>
<td>B52</td>
<td>BLDG</td>
<td>MISL</td>
<td>F</td>
<td>Proposed Miscellaneous Building</td>
<td>0.8</td>
<td>Though usually the material is concrete, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.9)</td>
</tr>
<tr>
<td>E25</td>
<td>ELEC</td>
<td>OTLN</td>
<td>E</td>
<td>Outline</td>
<td>0.8</td>
<td>Though usually the material is concrete, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.9)</td>
</tr>
<tr>
<td>E45</td>
<td>ELEC</td>
<td>SOLR</td>
<td>E</td>
<td>Solar Panels</td>
<td>0.8</td>
<td>Though usually the material is metal and glass, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.95)</td>
</tr>
<tr>
<td>F18</td>
<td>FENC</td>
<td>STEP</td>
<td>E</td>
<td>Steps</td>
<td>0.4</td>
<td>Materials can be concrete, bricks or cement tiles, very often with large gaps where water tends to infiltrate into the soil; thus C value considered is lower than what is proposed in literature for concrete roads (0.9)</td>
</tr>
<tr>
<td>P20</td>
<td>WMNG</td>
<td>OTLN</td>
<td>E</td>
<td>Outline</td>
<td>0.8</td>
<td>Though usually the material is concrete, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.9)</td>
</tr>
<tr>
<td>P45</td>
<td>WMNG</td>
<td>DRTA</td>
<td>E</td>
<td>Drain Top Artificial</td>
<td>0.1</td>
<td>Materials can be prefabricated concrete parts assembled adjacent, very often with large gaps where water tends to infiltrate into the soil; in other cases the drains are simply dug into the soil; thus C value considered is lower than what is proposed in literature for concrete roads (0.9)</td>
</tr>
<tr>
<td>R3</td>
<td>ROAD</td>
<td>BKRS</td>
<td>E</td>
<td>Breakers</td>
<td>0.4</td>
<td>Material used is usually masonry brick / concrete tiles, with gaps in between, favouring infiltration into the soil</td>
</tr>
<tr>
<td>R7</td>
<td>ROAD</td>
<td>BRDG</td>
<td>E</td>
<td>Bridge</td>
<td>0.4</td>
<td>Material used is usually masonry brick / concrete tiles, with gaps in between, favouring infiltration into the soil</td>
</tr>
<tr>
<td>R10</td>
<td>ROAD</td>
<td>CURB</td>
<td>E</td>
<td>Curb</td>
<td>0.2</td>
<td>Materials can be prefabricated concrete parts assembled adjacent, very often with large gaps where water tends to infiltrate into the soil and the pavement; thus C value considered is lower than what is proposed in literature for concrete roads (0.9)</td>
</tr>
<tr>
<td>R29</td>
<td>ROAD</td>
<td>PAVD</td>
<td>E</td>
<td>Paved Surface</td>
<td>0.4</td>
<td>Material used is usually masonry brick / concrete tiles, with gaps in between, favouring infiltration into the soil</td>
</tr>
<tr>
<td>R31</td>
<td>ROAD</td>
<td>PRKG</td>
<td>E</td>
<td>Parking</td>
<td>0.2</td>
<td>Though usually these are unimproved open areas, there is a compaction due to passage and parking of vehicles on its surface, thus C value taken into account is higher than what is proposed in literature for flat unimproved areas (0.1)</td>
</tr>
<tr>
<td>R34</td>
<td>ROAD</td>
<td>RAMP</td>
<td>E</td>
<td>Accessible Ramp</td>
<td>0.4</td>
<td>Materials can be concrete, bricks or cement tiles, sometimes with gaps; moreover, water tends to infiltrate into the soil on platform sides, due also to ramp slope; thus C value considered is lower than what is proposed in literature for concrete roads (0.9)</td>
</tr>
<tr>
<td>R43</td>
<td>ROAD</td>
<td>UPVD</td>
<td>E</td>
<td>Unpaved Surface</td>
<td>0.3</td>
<td>Though usually these are unimproved open areas, there is a compaction due to traffic on its surface, thus C value taken into account is higher than what is proposed in literature for flat unimproved areas (0.1)</td>
</tr>
<tr>
<td>R45</td>
<td>ROAD</td>
<td>SPLI</td>
<td>E</td>
<td>Road Splitter</td>
<td>0.4</td>
<td>Material used is usually masonry brick / concrete tiles, with gaps in between, favouring infiltration into the soil</td>
</tr>
<tr>
<td>R46</td>
<td>ROAD</td>
<td>BUSA</td>
<td>E</td>
<td>Bus Area</td>
<td>0.4</td>
<td>Material used is usually masonry brick / concrete tiles, with gaps in between, favouring infiltration into the soil</td>
</tr>
<tr>
<td>T40</td>
<td>TOPO</td>
<td>ROCK</td>
<td>E</td>
<td>Large Rocks And Rock Outcroppings</td>
<td>0.5</td>
<td>Though rocks are considered almost fully impervious, there is a large quantity of water in filtrating into the soil on rocks sides</td>
</tr>
<tr>
<td>T42</td>
<td>TOPO</td>
<td>STEP</td>
<td>E</td>
<td>Steps</td>
<td>0.2</td>
<td>Though usually these are unimproved areas, there is a slight compaction due to walking passage on its surface, thus C value taken into account is higher than what is proposed in literature for flat unimproved areas (0.1)</td>
</tr>
<tr>
<td>V29</td>
<td>VEGE</td>
<td>TURF</td>
<td>E</td>
<td>Lawn Areas</td>
<td>0.1</td>
<td>The most conservative value of C is taken into account</td>
</tr>
<tr>
<td>W3</td>
<td>WATR</td>
<td>DAM**</td>
<td>E</td>
<td>Dam</td>
<td>0.8</td>
<td>Though usually the material is concrete, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.9)</td>
</tr>
<tr>
<td>W23</td>
<td>WATR</td>
<td>OTLN</td>
<td>E</td>
<td>Outline</td>
<td>0.8</td>
<td>Though usually the material is concrete, evaporation and splash losses are considered, thus C value taken into account is lower than what is proposed in literature (0.9)</td>
</tr>
</tbody>
</table>

Table 4—3 Runoff coefficient for surveyed built-up features – part 2
4.1.4.1.1  **Slope**
From topographic data, a raster has been generated and classified using QGis, to evaluate slopes in the AoI, classes being between 0, 5, 10 and 30%, according to the runoff coefficient components table seen earlier; raster classes have then been vectorized, with resulting vector polygons for each of the classes.

4.1.4.1.2  **Built-up features**
For each built-up feature, a value of runoff coefficient has been proposed: values have been derived from existing literature, or have been proposed considering the local conditions of the feature itself: for example, while published runoff coefficient values for different types of paved roads are usually on the high side (\( C > 0.7 \)), a conservative value of \( C = 0.4 \) has been proposed for Auroville paved roads, because these roads have been paved using tiles made of porous material, laid down with gaps of about 1 cm in between. As a general approach, while evaluating runoff coefficient, the most conservative value has been considered, so that the lowest volume of runoff for that particular situation is computed.

4.1.4.1.3  **Depressions/Surface storage**
The ground surface in the Area of Interest has many irregularities, with topographic depressions having minimal depth, in the order of 10 cm. While considering the influence of the component \( C_s \) of the runoff coefficient (component of coefficient accounting for surface type), a value of zero for it has been taken into account, thus opting for the most conservative value of it, impact of which, in terms of conceptual design, will reflect into a lower volume of runoff expected.

4.1.4.2  **Infiltration data**
Infiltration data have been collected from existing works conducted in the past by Auroville Water Harvest (AWH)\(^{23}\), which carried out standard infiltration tests on many locations in Auroville, thus allowing for the creation of an Infiltration map for the whole territory. Details of Infiltration tests are given in Annexure 10.

Infiltration rates in the map have been subdivided according to FAO classification (Brouwer, 1992): the AoI falls entirely in class 4 (infiltration rate higher than 3 cm/h), so it is quite uniform in respect to this parameter.

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\(^{23}\) Auroville Water Harvest (AWH) was a Public Service Unit with non-profit status, registered under the Auroville Foundation as a division of a Trust for the Centre of Scientific Research (CSR): it is no more existing but it has been an important and successful step in collaboration in the bio-region between Auroville and the nearby villages (from https://www.auroville.org/contents/1921).
4.1.4.3 Vegetation cover data

While trees have been mapped\(^1\) during the topographic survey, the obtained information cannot reflect the real vegetation cover of the land: small trees, but also bush and grass, not surveyed, are all elements contributing to runoff generation (or not) in the Rational Method.

An experiment has been conducted, through use of UAV (Unmanned Aerial Vehicle, also known as drone). A private company has been engaged to perform the drone survey, in the period between 28 and 30 January, 2019. The drone utilized for this survey is model Phantom 3 of DJI brand. The flying altitude was set at 200 feet (60 meters) from the ground, for each mission. The overlap between each photo had been set at 90\%, to ensure three-dimensional accuracy. Eighteen flight missions, each one lasting for about 20 minutes (being the duration of battery charge 25 minutes, including take-off and landing) have been carried on, with a total of 6,961 photographs taken. Image resolution had been set very high, each image having a width of 5472 pixels, a height of 3648 pixels, with a resulting GSD (Ground Sample Distance) of 2.5 cm per pixel.

---

\(^1\) Trees having a stem at least 10 cm diameter.
Ground Control Points (GCP) have been set on the ground, and their coordinates accurately measured through use of the DGNSS system (3D quality: 7 mm), in order to georeference the resulting orthophoto mosaic with an error of about 1 cm.

A comparison of ground level has also been done, to verify accuracy of ground levels as recorded by drone, versus the survey done using Total Station: x and y are impressively accurate, difference between the two methods in the range of 1 to 2 cm only. About z (elevation), results are quite different: in open areas the difference between the two systems is in the range of 5-10 cm, while in vegetated areas the difference is higher than 25 cm.

This comparison suggests that accurate survey in large areas without vegetation cover can be conducted through drones, with an expected error of 5-10 cm, quite acceptable when balanced with the large time saving allowed by this method, compared to traditional survey. The same cannot be done in vegetated areas.

One useful outcome of the drone survey is a 3D point cloud of the area: even if only partially explored, point cloud is yet another tool to be used for geospatial evaluations.

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25 The high difference in z is due to the methodology itself: the drone, flying at about 60 meters above the ground, can measure the elevation of the top of vegetation. So, to estimate the ground level at the bottom of the vegetation, algorithms (included in the software package used for drone imagery processing) are used to infer the ground level from trees height through use of interpolations, which do require data on the height of each tree: this is practically very difficult to obtain flying a drone in densely vegetated areas.
Once drone images were processed, the resulting georeferenced orthophoto mosaic has been further processed to generate a map of vegetation cover.

Once imported in QGIS\(^{26}\), the orthophoto mosaic has been classified using Dzetsaka plugin\(^{27}\): a very fast and easy to use, but also a powerful classification plugin based on Gaussian Mixture Model classifier. Samples of image raster texture have been classified as:

- Bare land Area
- Grass Area
- Tree Areas

The plugin then has found all areas having the same texture on the raster image, and automatically classified those areas into the classes earlier defined. Once raster has been classified, it has been vectorized, with resulting vector polygons for each of the classes.

All types of data have the same CRS (Coordinate Reference System), therefore they can be overlaid upon each other, and with any other dataset in the same CRS.

### 4.2 Model results

The model algorithm contains all the data, the parameters, the components and the formulas needed to automatically calculate the potential runoff. The algorithm processes all geometric intersections between all different layers of information, and in case of built-up features it attributes their runoff coefficient as defined earlier.

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\(^{26}\) For info, visit [https://qgis.org/en/site/](https://qgis.org/en/site/)

\(^{27}\) For info, visit [https://github.com/nkarasiak/dzetsaka](https://github.com/nkarasiak/dzetsaka)
The model requires two inputs from the user: the area on which the algorithm is applied, and the rainfall value for which the runoff will be computed.

The area in this specific project case, is the AoI, the Residential Zone of Auroville, Sector 1 and 2. About rainfall, it has to be noted that not all rainfall depths will physically generate runoff: in fact, given the high infiltration rate, and presence of vegetation on the land, in case of small rainfall events all rain water falling on pervious surfaces, apart that intercepted by vegetation, is infiltrating into the ground, and runoff from those areas is nil. On impervious surfaces, for safety reasons, it is recommended not to harvest rain falling at the onset of the rainy event, due to impurities present on the surface itself.

A minimum threshold has then to be considered in the concept, and there are no effective objective ways to determine this threshold: it is commonly stated that it depends on rain intensity (rate of rainfall per unit of time: the higher the quantity of rain falling in the unit of time, the lower the time for it to infiltrate), and on quantity of water content already in the soil, due to previous rains (so-called “antecedent conditions”).

Experience in the field has proven that with a minimum of 15 mm of rain, runoff is generated on most of the surfaces. In particular, during the intense rain event on October 30, 2019, in the time interval from 12:12 pm to 12:42 pm (exactly 30 minutes), a Weather Station installed by Cynergy in Maitreye community in the Residential Zone has recorded 16.75 mm of rain: a site visit during the event has been able to document the runoff on the ground surfaces.

<table>
<thead>
<tr>
<th>Date and Time</th>
<th>Cumulative Rainfall (mm)</th>
<th>Absolute Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-10-2019 12:10</td>
<td>5.25</td>
<td>0</td>
</tr>
<tr>
<td>30-10-2019 12:11</td>
<td>5.25</td>
<td>0</td>
</tr>
<tr>
<td>30-10-2019 12:12</td>
<td>5.5</td>
<td>0.25</td>
</tr>
<tr>
<td>30-10-2019 12:13</td>
<td>6</td>
<td>0.5</td>
</tr>
<tr>
<td>30-10-2019 12:14</td>
<td>6.25</td>
<td>0.25</td>
</tr>
<tr>
<td>30-10-2019 12:15</td>
<td>6.75</td>
<td>0.5</td>
</tr>
<tr>
<td>30-10-2019 12:16</td>
<td>7.25</td>
<td>1</td>
</tr>
<tr>
<td>30-10-2019 12:17</td>
<td>7.75</td>
<td>1</td>
</tr>
<tr>
<td>30-10-2019 12:18</td>
<td>8</td>
<td>0.75</td>
</tr>
<tr>
<td>30-10-2019 12:19</td>
<td>8</td>
<td>0.75</td>
</tr>
<tr>
<td>30-10-2019 12:20</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>30-10-2019 12:21</td>
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<td>0.5</td>
</tr>
<tr>
<td>30-10-2019 12:22</td>
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<td>1</td>
</tr>
<tr>
<td>30-10-2019 12:23</td>
<td>13.5</td>
<td>1</td>
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<tr>
<td>30-10-2019 12:42</td>
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<td>0</td>
</tr>
</tbody>
</table>

Total Event Rainfall (mm) 16.75

Figure 4—5 Rain event of October 30, 2019: 1-minute-interval rainfall data (left, courtesy Cynergy), pervious surface with visible runoff (right). Location: opposite Kalpana, Residential Zone, Auroville

In the model, opting for a conservative approach, a threshold limit has been set at 20 mm of minimum rainfall for generation of surface runoff.

To run the model, as mentioned earlier, the rainfall amount needs to be entered as input. Considering the threshold of 20 mm, to simulate the potential runoff generated all over the AoI, a thorough analysis of rainfall events has been performed, for the year 2019, on data collected by the raingauge\textsuperscript{29} located at Madhuca community, in the Residential Zone\textsuperscript{30}.

\textsuperscript{29} Dorle (Madhuca) is in charge of the raingauge, and she is regularly sharing all collected data since July 2017.

\textsuperscript{30} Invocation and Deepanam raingauges do not have data for the whole 2019 year.
In 2019, 86 rainfall events have been recorded in Madhuca, with a total annual rainfall of 1,136.55 mm. A total number of 66 events, each one with a rainfall lower than 20 mm in 24 hours, have been recorded, the total rainfall for all these events being 329.35 mm, amounting to 29% of the total annual rainfall. The number of rainfall events with a rainfall higher than 20 mm is 20, totalling 807.20 mm, which amounts to 71% of the total annual rainfall.
<table>
<thead>
<tr>
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<th>Date</th>
<th>Madhuca</th>
</tr>
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**2019 TOTAL RAINFALL**

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<th>Value</th>
</tr>
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<td>No. of rain events with rainfall lower than 20 mm</td>
<td>66</td>
</tr>
<tr>
<td>Total rainfall for all rain events with rainfall lower than 20 mm</td>
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</tr>
<tr>
<td>(in Percentage)</td>
<td>29.0</td>
</tr>
<tr>
<td>No. of rain events with rainfall higher than 20 mm</td>
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</tr>
<tr>
<td>Total rainfall for all rain events with rainfall higher than 20 mm</td>
<td>807.20</td>
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<tr>
<td>(in Percentage)</td>
<td>71.0</td>
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</table>

Table 4—Madhuca rainfall data for 2019
The same type of analysis can be done for Aurogreen rain data, over a period of 30 years. All Aurogreen rainfall data are in Annexure 11.

### Rainfall in Aurogreen (Green Belt)

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Annual Rainfall</th>
<th>Total Number of Rain events</th>
<th>Rainfall lower than 20 mm</th>
<th>Rainfall higher than 20 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total Number of events</td>
<td>Total rainfall</td>
</tr>
<tr>
<td>1990</td>
<td>1354.0</td>
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<td>37</td>
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<td>1992</td>
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<td>60</td>
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<td>275.0</td>
</tr>
<tr>
<td>1993</td>
<td>1548.0</td>
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<td>1994</td>
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<td>33</td>
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<td>54</td>
<td>32</td>
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<td>1998</td>
<td>1702.8</td>
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<td>21</td>
<td>145.4</td>
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<td>38</td>
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<td>43</td>
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<tr>
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<td>64</td>
<td>50</td>
<td>290.3</td>
</tr>
<tr>
<td>2019</td>
<td>1215.2</td>
<td>79</td>
<td>56</td>
<td>273.5</td>
</tr>
</tbody>
</table>

**Annual Average**

- Total Annual Rainfall: 40925.7
- Total Number of Rain events: 1881
- Rainfall lower than 20 mm: 1245
- Rainfall higher than 20 mm: 636
- Rainfall Percentage: 8423.6
- Rainfall Percentage: 32502.1
- Rainfall Percentage: 79.4

Table 4—5 Aurogreen: data analysis considering a threshold of minimum 20 mm rainfall
Comparing rain data from Aurogreen and Madhuca raingauges, it can be noted that the percentages of rainfall both lower and higher than 20 mm are in the same order of magnitude: Madhuca data, even if they refer to one single year, are in line with the average for the last 30 years, and thus can be used to estimate the total amount of rainfall fallen in the Residential Zone in one year during events with rainfall higher than the threshold.

Rounding off to 800 the 807 mm of Madhuca total rainfall in events with rainfall over the threshold, and entering this in the model as rainfall input, after less than one-hour computation the model has given the following overall results:

<table>
<thead>
<tr>
<th>Natural Ground Surface (terrain)</th>
<th>Area (square meters)</th>
<th>Runoff Volume (cubic meters)</th>
<th>Type of Area (%)</th>
<th>Runoff Volume (%)</th>
</tr>
</thead>
<tbody>
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<td>4,90,640.39</td>
<td>8,892.99</td>
<td>87.254</td>
<td>21.117</td>
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<tr>
<td>Built-up Features (features)</td>
<td>71,670.07</td>
<td>33,219.36</td>
<td>12.746</td>
<td>78.883</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5,62,310.46</strong></td>
<td><strong>42,112.35</strong></td>
<td><strong>100</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Table 4—6 Runoff computation model results with rainfall input = 800 mm

The model computes potential runoff on each portion of territory for which parameters are given: the geospatial intersection of all information is represented on a map generated by the model, showing the potential runoff volume for each of those portions.

### 4.2.1 Computational model main concepts

The Gisaf software and the related processes have provided a favourable environment to acquire consistent data in a reliable way in the domain of interest for this research. Combined with tools like Jupyter and Pandas, the resulting computational framework allowed to experiment and develop the models required for the completion of the project.

The computation of potential runoff during rain events is implemented in a Jupyter notebook. It is constituted by the following steps:

- **Initialization**: define the coefficient values, import of the polygon layer of definition of the AoI (clipping area) and other setup

- **Terrain**
  - Import the terrain polygon layers for each coefficient (slope, vegetation cover, soil infiltration, surface storage, the value of the coefficient being an attribute to each of the polygons), and clip them (see Figure 4-8)
  - Compute a geographical segmentation in smaller areas where all the coefficients are constant (intersection of all the coefficients polygons’ layers)
  - Compute the C factor as sum of the coefficients on all the constant coefficients areas (see Figure 4-9)

- **Built-up areas**
  - Import of all the built-up areas from the database, where a coefficient has been assigned, and clip them (Figure 4-10)

- Cut out the features from the terrain segmentation (spatial difference)
• Generate the final layer of the area of interest, as the union of the cut-out areas and the built-up areas (Figure 4-11)
• Compute the quantity of water for each area (attribute of each polygon) on the final layer
• Compute the quantity of water for the area of interest as the sums of the quantities of water for each area, and the percentage of water from the built-up areas compared to the terrain areas.

The polygons in the resulting layer covers the whole area with polygons. Each of these polygons represent an area with constant factors, and a q value (V – runoff volume is named q in the computation). The computation of the final $Gq$ value for the whole area is simply the sum of the $Lq$.

Figure 4—8 Screenshot of intermediate results of the Jupyter notebook for runoff computation on the AoI, showing maps of the coefficient layers (Cs, Cv, Cr, Ci)

Figure 4—9 Screenshot of intermediate results of the Jupyter notebook for runoff computation on the AoI, showing a map of the segmented terrain with constant coefficients
Figure 4—10 Screenshot of intermediate results of the Jupyter notebook for runoff computation on the AoI, showing a map of the surveyed built-up areas with assigned coefficients based on the features’ categories.

Figure 4—11 Screenshot of final results of the Jupyter notebook for runoff computation on the AoI, showing a map of all areas (built-up and terrain) with the coefficient factor.
Results of the computation highlight the obvious potential on built-up features; at the same time, they indicate that the runoff volume generated on undeveloped surface is not negligible in times of water crisis, and give an indication for town planning regarding the urgent need to build drains to direct this volume toward storage systems.

Parallely, it needs to be considered that Auroville is on top of a topographic ridge, it sits on the hydrologic top of the watershed: any choice taken on surface water management in this area will have an impact on lower parts of the watershed. Ideally, runoff should not be entirely captured at higher heights of watersheds, because this might deprive other areas of a valuable source of water. Issues like this need to be addressed with neighbouring planning authorities and stakeholders, since runoff is usually not considered as a potential water source at all, but most of the time discharged into the Bay of Bengal.

The scenario will naturally grow into larger built-up features while developing the evolving city, with higher runoff volumes generated. Even in this case, part of the runoff should be channelled to downstream areas to benefit local activities, keeping in mind that it should not be lost into the ocean.

The outcome of the model, in particular the map of runoff volumes, could emerge as a beneficial tool for town planning and priority-setting practices at decision-making level, for a real and effective water management strategy: it clearly identifies areas where interventions are most
effective in terms of cost/benefit. As an example, one of the biggest contributor to runoff volume is the paved road: the design of a drain along the road, and its realization along with construction of a storage tank and distribution of harvested water is to be considered as a priority by town planning team, and put in action at the earliest to start having excess water in crisis scenarios.

4.3 Complementary addendum to runoff computation model

4.3.1 Point cloud terrain analysis: TERGAL

This chapter introduces an experimental method, currently under development, that emerged during the research done for this project. It is an innovative approach which includes many fields of research: geomatics, water management, computer graphics, graph theory, data analysis. Combined with findings of the proposed runoff computation model, it is expected to provide a reliable tool for the estimation of rainwater runoff potential of terrains, generating valuable information for the determination of optimal surface rainwater storage locations at any scale.

The runoff computation model gives an estimation of the quantity of surface water runoff at a large scale. It needs to be completed by a geographical terrain analysis to determine the location of the water flows (drains, watersheds) in order to determine the possible locations for water harvesting.

4.3.1.1 Limitations of existing methods

Many tools publicly available (QGIS plugins, etc) and algorithms were evaluated for extracting drains and watersheds from topological data. They all use digital elevation models (DEM) as input, which are raster files by definition.31

A detailed topographical survey, such as the one done for this study, provides elevation points: a set of data points in space, also known in computer graphics geometry processing as “point cloud”32.

The use of DEM-based tools implies the conversion of the elevation survey points to a raster; at the end of these processes, the basins in turn need to be converted back from a raster format to a vector format (polygons). It was found that raster file-based processing models are not satisfactory due to the following reasons:

- Loss of valuable information in the conversion to a raster format, which is essentially a grid with a constant interval between cells
- Processing artifacts (ex. artificial pixelization)
- Need for extrapolations
- Determination of a various number of parameters to be set at many of the required steps of the process, influencing the final result
- Tediouos trial and errors process
- Reconstruction of meaningful vector-based layers from the resulting raster is not trivial and suffers also from interpolations, setting of parameters, etc.

4.3.1.2 Overview of a new methodology

The proposed methodology for terrain analysis makes direct use of the 3D elevation points/point cloud as input. A terrain data model is built directly from the elevation point cloud,

31 For info, visit https://en.wikipedia.org/wiki/Raster_graphics
32 For info, visit https://en.wikipedia.org/wiki/Point_cloud
based on a property of rainwater runoff: water flows following the steepest slope, subject to the action of gravity. At this stage, infiltration is not taken into account.

4.3.1.2.1 Data model
With nodes representing elevation points, and vertices representing drains of water flow, the result of this is a well-known structure of graph theory: forest of directed rooted trees. Each tree defines a basin and each root the lowest elevation point (sink) of the basin.

During the construction of this structure, the algorithm classifies points as:
- sources (leafs)
- way points
- confluents (branches)
- sinks (roots).

Reconstruction of the ridges which delimit the resulting basins (watersheds) is not a trivial problem. After experimenting with various shapes such as convex hulls and alpha shapes, tessellation with a Voronoi diagram gave satisfying practical results without compromising the model with extrapolations and debatable assumptions.

![Figure 4—13 Map of the results of Tergal order 1 computation. 1: the classified elevation points cloud with lowest points highlighted; 2: the drain system in each basin (trees rooted on the basins' lowest points); 3: the Voronoi tessellation coloured basins-wise](image)

It is worth mentioning that this solution implies that the ridge points (source nodes of 2 vertices, in 2 different trees in this case) are not points of the point cloud, and thus retain
the properties of trees in the graph theory, for example: unique path between 2 nodes, deterministic way of walking the graph up and down.

It might be useful to remind here that basins are intended as sub-watersheds, where all surface water will converge into one point (sink or catchment point).

The next step in the modeling consists in the identification of **overflow points**. After the soil is saturated during a storm event, basins start filling from their lowest elevation point until a certain level, after which water starts overflowing to a basin downhill. The point where the overflow takes place is determined as the point of lowest elevation located on the outline of the basin.

Using the outflow points as nodes, another graph can be constructed, which turns to be another forest tree, with roots being basins which do not have overflows. This construction is called **order 2 basins**. The shape of the order 2 basins are polygons, unions of the polygons of each basin in the same tree. Conceptually, it is a bit like a drain and basin system of smaller geographical scale (zooming out).

The generalization of this iterative process leads to the definition of **order n basins**, computed from the basins of order n-1. The iterative process stops when order n basins equals order n+1 basins. For example, for coastal areas, the process stops when all order n basins have their overflow point in the sea.

### 4.3.1.2.2 Status

A Python library called TERGAL (TERrain Graph AnaLyzer) is a prototype under development. It uses Pandas and Geopandas for vectorized operations, experiments are conducted in a Jupyter notebook.

The first and second order of basins and drains have been implemented, and the generalization to **order n** is under development.

Compared to traditional DEM based methods, and without optimizations, Tergal is very fast: a point cloud of 15,000 points is processed in less than 1 minutes on a consumer grade laptop, the results are arguably more accurate and informative.

Currently, **Tergal** uses a simple method of neighbouring points with the Euclidean distance for determining the slopes between points, and thus the steepest slopes. Although the results are already workable in the dataset of the Area of Interest of the project, other methods are also explored:

- Meshes, like the result of a Delaunay triangulation
- Ball pivoting
- Parametric functions.

---

33 For info, visit https://en.wikipedia.org/wiki/Delaunay_triangulation
Figure 4—Map of the results of Tergal order 2 computation.
1: a rectangle of the area shown in Figure 3-13; 2: order 2 drains (trees rooted on order 2 basins' lowest points), with arrows indicating the water flow direction; 3: areas covered by order 2 basins
5 Water Balance

In water management planning, the most important aspect is the final water balance, in a given area, between the entire human (and not only) water consumption, and actual water availability in the same area.

In this perspective, a tentative budget is proposed, considering the water consumption (as calculated from the available data) which defines the actual water needs, and the quantities of different water sources, already or potentially available, to meet the demand.

5.1.1 Water consumption in the Area of Interest

As seen previously, quantification of water consumption poses a big challenge: lack of systematic metering method, along with unconfirmed number of users, might discourage any such attempt. Nevertheless, some speculations can be attempted starting from available data.

5.1.1.1 Population

In the following table data on population of Area of Interest are shown.

To be noted: population data have been received from Auroville Residents Service on January 12, 2019.
Residents in AoI as on January 12, 2019

<table>
<thead>
<tr>
<th>Community</th>
<th>Children</th>
<th>Adult (\text{equivalent})</th>
<th>Teenagers</th>
<th>Adults</th>
<th>Total (adults, teenagers and adult equivalents)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arati</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Arati Iii</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Arka</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Creativity</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>Deepanam Staff Quarter</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Grace</td>
<td>15</td>
<td>7.5</td>
<td>7</td>
<td>52</td>
<td>66.5</td>
</tr>
<tr>
<td>Humanscapes</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Invocation</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>39</td>
<td>40</td>
</tr>
<tr>
<td>Invocation Iv</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Kalash</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Kalpana</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Madhuca</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>13</td>
<td>14.5</td>
</tr>
<tr>
<td>Maitreye</td>
<td>11</td>
<td>5.5</td>
<td>4</td>
<td>26</td>
<td>35.5</td>
</tr>
<tr>
<td>Maitreye Ii</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>32</td>
<td>38</td>
</tr>
<tr>
<td>Prayatna</td>
<td>1</td>
<td>0.5</td>
<td>2</td>
<td>31</td>
<td>33.5</td>
</tr>
<tr>
<td>Progress</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Realization</td>
<td>9</td>
<td>4.5</td>
<td>0</td>
<td>25</td>
<td>29.5</td>
</tr>
<tr>
<td>Sailam</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>Sanjana</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>28</td>
<td>29</td>
</tr>
<tr>
<td>Sukhavati</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>20</td>
<td>21</td>
</tr>
<tr>
<td>Surrender</td>
<td>3</td>
<td>1.5</td>
<td>1</td>
<td>63</td>
<td>65.5</td>
</tr>
<tr>
<td>Swayam</td>
<td>1</td>
<td>0.5</td>
<td>2</td>
<td>21</td>
<td>23.5</td>
</tr>
<tr>
<td>Vikas</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>28</td>
<td>32</td>
</tr>
<tr>
<td>TOTAL</td>
<td>59</td>
<td>26</td>
<td>493</td>
<td>667.5</td>
<td></td>
</tr>
</tbody>
</table>

NOTES
- Residents per Communities, whether or not they are present in Auroville.
- Children are individuals below 12 years old.
- Children consumption is assumed to be half the consumption of one Adult Equivalent
- Teenagers are individuals above 12 and below 18 years old.
- Adults are individuals above 18 years old.
- Population from Humanscapes and Kalpana have been given by those communities directly

Table 5—1 Population in AoI (courtesy Auroville Residents Service, 12.01.2019)

A cross check on total Auroville population has been done in order to evaluate the change in population between January 2019 and December 2019.

<table>
<thead>
<tr>
<th>AV population December 2019</th>
<th>3173</th>
</tr>
</thead>
<tbody>
<tr>
<td>AV population January 2019</td>
<td>3024</td>
</tr>
</tbody>
</table>

| Difference in population (Jan to Dec 2019) | 149  |
| Percentage                                  | 4.7% |

Table 5—2 Change in overall Auroville population between January and December 2019
Being the percentage of change rather low (less than 5%) over the whole population of Auroville, it is proposed to continue the speculation using the population data received in January 2019.

5.1.1.2 Population with metered water

The number of residents having metered water is cross checked against the total number of residents of Auroville.

<table>
<thead>
<tr>
<th>Network / Community</th>
<th>Total number of residents with metered water</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWS</td>
<td>623</td>
</tr>
<tr>
<td>Kalpana</td>
<td>88</td>
</tr>
<tr>
<td>Humanscapes</td>
<td>31</td>
</tr>
<tr>
<td>Courage</td>
<td>98</td>
</tr>
<tr>
<td>Transformation</td>
<td>24</td>
</tr>
<tr>
<td>Dana</td>
<td>74</td>
</tr>
<tr>
<td>Center Field</td>
<td>12</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>950</strong></td>
</tr>
</tbody>
</table>

AWS: Auroville Water Service Distribution Network

Table 5—3 Total number of residents with metered water

The number of Auroville residents is calculated including the “Adult equivalent”: consumption of one child (below 12 years of age) is considered as half the consumption of one “Adult equivalent”.

| Ratio metered/total population (december 2019) | 30%          |
| Children                                       | 412          |
| Adult equivalent                               | 206          |
| Population equivalent                          | 2818         |

Ratio metered/total population equivalent (december 2019) 34%

- Children consumption is assumed to be half the consumption of one Adult Equivalent

Table 5—4 Ratio residents with metered water / total Auroville residents

Being the ratio metered/not-metered population of 34%, it is here proposed to apply the average water consumption as calculated for metered residents, to all residents of Auroville.
5.1.1.3  Auroville average domestic water consumption

Considering all data collected from available meters, the average daily domestic consumption is calculated here.

Average water consumption

<table>
<thead>
<tr>
<th>Data from</th>
<th>Consumption (liters per capita per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWS</td>
<td>210</td>
</tr>
<tr>
<td>Kalpana</td>
<td>145</td>
</tr>
<tr>
<td>Humanscapes</td>
<td>120</td>
</tr>
<tr>
<td>Courage</td>
<td>181</td>
</tr>
<tr>
<td>Transformation</td>
<td>295</td>
</tr>
<tr>
<td>Dana</td>
<td>303</td>
</tr>
<tr>
<td>Center Field</td>
<td>287</td>
</tr>
<tr>
<td><strong>Average consumption (liters per capita per day)</strong></td>
<td><strong>220</strong></td>
</tr>
</tbody>
</table>

Table 5—5 Average daily domestic water consumption for all Auroville residents (liters per capita per day)

The average daily domestic water consumption for all Auroville residents can then be assumed to be 220 liters per capita per day. Eateries and other public places/institutions are not taken into account, due to lack of proper data.

5.1.1.4  Quantification of good-quality water use-wise

Distributed water can be defined as “good-quality” water, because it can be directly used for personal hygiene and home cleaning, for dishwashing and for laundry washing machines without need of filtration. Drinking water is also included in this computation, but it requires additional filtering to ensure safety.

Break-up of good-quality water quantity

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Uses of good-quality water</th>
<th>Liters per capita per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>drinking</td>
<td>4</td>
</tr>
<tr>
<td>b</td>
<td>hygiene: handwash, shower, house cleaning</td>
<td>60</td>
</tr>
<tr>
<td>c</td>
<td>clothes washing machine</td>
<td>50</td>
</tr>
<tr>
<td>d</td>
<td>dishwashing</td>
<td>25</td>
</tr>
<tr>
<td>e</td>
<td>other</td>
<td>4</td>
</tr>
<tr>
<td>f</td>
<td>Total (a + b + c + d + e)</td>
<td>143</td>
</tr>
<tr>
<td>g</td>
<td>Total average consumption</td>
<td>237</td>
</tr>
</tbody>
</table>

| Percentage of good-quality water consumption (f / g ) | 60% |

Table 5—6 Break-up of good-quality water quantity

The resulting percentage of 60% is to be noted for further considerations.
5.1.2  Wastewater treated in Residential Zone Wastewater Treatment Plant

Eight communities are connected to the newly realized Residential Zone Wastewater Treatment Plant (RZ-WWTP), and to the network of treated water distribution, to be used for irrigation in their compound gardens.

Wastewater treated in RZ-WWTP

<table>
<thead>
<tr>
<th>Community</th>
<th>Children</th>
<th>Adult equivalent</th>
<th>Teenagers</th>
<th>Adults</th>
<th>Population equivalent</th>
<th>Treated water used for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humanscapes</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>31</td>
<td>31</td>
<td>irrigation</td>
</tr>
<tr>
<td>Kalpana</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>88</td>
<td>88</td>
<td>irrigation</td>
</tr>
<tr>
<td>Maitreye 1, 3</td>
<td>19</td>
<td>9.5</td>
<td>8</td>
<td>38</td>
<td>55.5</td>
<td>irrigation</td>
</tr>
<tr>
<td>Maitreye 2</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>32</td>
<td>38</td>
<td>irrigation</td>
</tr>
<tr>
<td>Prayatna</td>
<td>1</td>
<td>0.5</td>
<td>2</td>
<td>31</td>
<td>33.5</td>
<td>irrigation</td>
</tr>
<tr>
<td>Realization</td>
<td>9</td>
<td>4.5</td>
<td>0</td>
<td>25</td>
<td>29.5</td>
<td>irrigation</td>
</tr>
<tr>
<td>Swayam</td>
<td>1</td>
<td>0.5</td>
<td>2</td>
<td>21</td>
<td>23.5</td>
<td>irrigation</td>
</tr>
<tr>
<td>TOTAL</td>
<td>38</td>
<td>19</td>
<td>14</td>
<td>266</td>
<td>299</td>
<td></td>
</tr>
</tbody>
</table>

Ref. Description

<table>
<thead>
<tr>
<th>Q.ty</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>c</td>
</tr>
<tr>
<td>d</td>
</tr>
<tr>
<td>e</td>
</tr>
<tr>
<td>f</td>
</tr>
<tr>
<td>g</td>
</tr>
<tr>
<td>h</td>
</tr>
</tbody>
</table>

(*) From CPHEEO, 2013: "... mean sewage flows [...] in well developed areas [...] may be as high as 90% ..."


Table 5—7 Wastewater quantity treated by RZ-WWTP

5.1.2.1 Ratio of treated wastewater used in communities

The percentage of treated wastewater used in communities for garden irrigation purposes needs to be estimated. Data from Kalpana community are used as reference here, having Kalpana a dedicated meter on the treated wastewater pipeline.
Kalpana - Good-quality and treated wastewater quantities in 2019

Total Average Population: 88 Person Equivalent (36 apartments, 7 offices and 1 guest house)
Summer Average Population: 55 Person Equivalent (APR - MAY - JUN)

<table>
<thead>
<tr>
<th>YEAR 2019</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water from AWS (cubic meters)</td>
<td>458</td>
<td>413</td>
<td>437</td>
<td>359</td>
<td>319</td>
<td>236</td>
<td>347</td>
<td>293</td>
<td>267</td>
<td>302</td>
<td>307</td>
<td>354</td>
</tr>
<tr>
<td>Treated wastewater received (cubic meters)</td>
<td>331.7</td>
<td>299.6</td>
<td>331.7</td>
<td>321</td>
<td>216.3</td>
<td>244.9</td>
<td>215.8</td>
<td>110</td>
<td>114</td>
<td>186</td>
<td>12</td>
<td>86</td>
</tr>
<tr>
<td>Ratio wastewater / water from AWS (%)</td>
<td>72%</td>
<td>73%</td>
<td>76%</td>
<td>89%</td>
<td>68%</td>
<td>104%</td>
<td>62%</td>
<td>38%</td>
<td>43%</td>
<td>62%</td>
<td>4%</td>
<td>24%</td>
</tr>
</tbody>
</table>

Average ratio wastewater / water from AWS (%) 60%

Courtesy: Margarita from MG Ecodies - Auroville

Table 5—8 Good-quality and treated wastewater quantities in 2019 in Kalpana community

The average ratio between quantity of wastewater received and total water received from Auroville Water Service distribution network, amounts to 60%.

5.1.3 Proposed water balance for AoI for 2019

Taking into account all previous speculations, and more importantly all the assumptions taken in each step, a tentative overall water budget for the Area of Interest is proposed. This budget does not consider the groundwater, but it is meant to indicate the order of magnitude of the different source’s potentials.

It takes into consideration the current water needs, intended as current water consumption, and the results of the runoff model in the AoI and the quantities of treated wastewater already available together with projected quantities for those communities not yet connected to the Residential Zone Wastewater Treatment Plant.
Water balance in Area of Interest for 2019

The final budget is largely positive, with 43,141 cubic meters of water potentially available per annum, both from runoff capture on built-up features, and from existing and projected quantities of treated wastewater: it amounts to an average of more than 118 cubic meters extra water available every day, to be used for irrigation also in other parts of Auroville, like the Matrimandir gardens compound, which is the highest water consumer in Auroville, but also for other uses like cement curing in construction projects, or wetting roads to prevent dust during the dry months, or to irrigate farms or gardens, or for flushing toilets (provided separate pipeline systems are considered already in the conceptual phase).

<table>
<thead>
<tr>
<th>Ref</th>
<th>Description</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Population Equivalent</td>
<td>667.5</td>
</tr>
<tr>
<td>b</td>
<td>Average consumption (liters per capita per day)</td>
<td>220</td>
</tr>
<tr>
<td>c</td>
<td>Average consumption (cubic meters per capita per day) (b / 1,000)</td>
<td>0.220</td>
</tr>
<tr>
<td>d</td>
<td>Total Consumption (cubic meters per day)</td>
<td>146.9</td>
</tr>
<tr>
<td>e</td>
<td>Annual consumption (cubic meters)</td>
<td>53,635.1</td>
</tr>
<tr>
<td>f</td>
<td>Good-quality water need (percentage)</td>
<td>60%</td>
</tr>
<tr>
<td>g</td>
<td>Annual good-quality water need (cubic meters) (e x f)</td>
<td>32,181.0</td>
</tr>
<tr>
<td>h</td>
<td>Annual lower-quality water need (cubic meters) (e - g)</td>
<td>21,454.0</td>
</tr>
<tr>
<td>i</td>
<td>Annual Wastewater generated (80%) (cubic meters) (e x 0.8)</td>
<td>42,908.04</td>
</tr>
<tr>
<td>j</td>
<td>Annual Wastewater treated by RZ WWTP</td>
<td>19,220.23</td>
</tr>
<tr>
<td>k</td>
<td>Annual Treated water received (percentage) (from Kalpana)</td>
<td>60%</td>
</tr>
<tr>
<td>l</td>
<td>Annual Treated water received (cubic meters) (j x k)</td>
<td>11,532.14</td>
</tr>
<tr>
<td>m</td>
<td>Excess wastewater in the system (cubic meters) (i - l)</td>
<td>31,375.90</td>
</tr>
<tr>
<td>n</td>
<td>Annual wastewater balance (cubic meters) (m - h)</td>
<td>9,921.88</td>
</tr>
<tr>
<td>o</td>
<td>Annual volume from runoff (cubic meters) (only built-up features from model results)</td>
<td>33219.36</td>
</tr>
<tr>
<td>p</td>
<td>Annual total low quality water potentially available (cubic meters) (n + o)</td>
<td>43,141.24</td>
</tr>
<tr>
<td>q</td>
<td>Daily potential lower-quality water balance (cubic meters)</td>
<td>118.20</td>
</tr>
</tbody>
</table>

Table 5—9 Water balance in Area of Interest for 2019
5.2 Final considerations

Looking at the conceptual foundation of the model, the so-called Rational Method, and at all steps considered during the computation of potential runoff, it is to be noted that the area limitation of the Rational Method (about 13 square kilometres (Frevert at al., 1955), or 50 square kilometres (Subramanya, 2008)) can be overcome: in fact, the geospatial computation is done for each and every area resulting from the intersection of all parameters, thus resulting in smaller areas, each having a particular combination of those parameters. It can then be said that the model can be applied to any area, provided that each intersection does not exceed those limitations: given the variability of territories in terms of infiltration rates and geological characteristics, vegetation cover, slope, presence of built-up features, it is very likely that those intersection areas are always smaller than the limitations.

Finally, when looking at the overall balance figures, it is quite clear that the overall scenario changes from scarcity to abundance: it is very much possible that, if proper measures are taken to harvest potential sources, the real problem becomes how to effectively use and/or store such large quantities of water: briefly, it is a complete overturn of the perspective at all levels, from town planning to single households.

After fifty years of existence, Auroville will not be able to rely on the strategy evolved since its inception: sourcing water only through extraction from borewell. Thousands of borewell are drilled within the surrounding bioregion, rates of extraction and absence of coordinated efforts to facilitate aquifers recharge in the bioregion, have contributed to the overall decline of groundwater levels in all water-bearing geological formations.

Evaluating different sources of water for different uses might help counteract this situation: envisioned steps consisting of identification of available sources, evaluation of their quantities and qualities, implementation of systems for collection, treatment and storage, efficient usage according to the sources quality, together with governance procedures would all contribute to achieve water security for the designated areas.

Creating a reliable water security management programme will need a multi-sourcing water strategy using rainwater, storm water, surface water, groundwater, and other available local water sources combined with water saving and recycling practices integrated within a human environment. Rain and storm water harvesting present huge potential as a water resource especially within cities, towns and peri-urban contexts.

As summarized by Custodio (2002), “[...] overexploitation, and even groundwater mining, are not necessarily bad from an ethical point of view when considered in a regional context. Some negative effects are necessarily linked to groundwater use as a means to produce an economic and social benefit to develop an area and to have better and more effective use of water in the future. The unethical side appears when no social benefit will be derived and applied in the area, and social and environmental damage and increased water costs are transferred to others and to future generations that lack economic resources to cope with them.
 [...] regulations are needed, as well as adequate water-management institutions and the effective participation, involvement and shared responsibility of stakeholders and developers. [...] “. 
6 Bibliography


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