# ABSTRACT

Deteriorating ambient air quality is a concern on account of its direct impact on day-to-day activities, human health and biodiversity. Air pollution issues are rising worldwide, especially in urban clusters of developing metro cities. Rapid fortuitous development of industrial and commercial activities coupled with exponential population surge, growth of transportation and infrastructure demand, biomass burning, and transboundary pollution transport are some major factors attributed to the deteriorating air quality. Periodic assessment of existing monitoring networks thus assumes significance for addressing the evolving and transient patterns of air pollution in developing urban clusters. The high installation and maintenance costs of a monitoring station demand the optimal design of an air quality monitoring network (AQMN).

Pollution issues in Delhi, India, making headlines in the recent past were majorly due to dominant pollutant $PM_{2.5}$ (particulate matter less than or equal to 2.5µm diameter) and shifting hotspots. $PM_{2.5}$ concentration in Delhi during most duration in the recent past had been about five to nine times greater than the twenty-four-hour guideline value specified by the World Health Organisation (WHO). The existing network of monitoring stations here, keeping track of air quality changes, may be redundant or may have become insufficient over time. The airshed boundary demarcation and its assessment for Delhi are at a very nascent stage. Airshed delineation (i.e. identifying larger surrounding regions that influence a region's air quality), and ambient air monitoring of airsheds, both play crucial roles in understanding and implementing strategic air quality management policies. Airshed can vary in size and pollution loads, and to a large extent is dependent on the meteorology, topography and the pollutant type. The provision of additional monitors under such a scenario is a challenge alongside budgetary constraints, thus requiring the

exploration of optimal solutions. The design of an air quality monitoring network must adhere to siting regulations and satisfy monitoring objectives together with optimality. The gravity of the problem is concerning though, but very limited studies in literature have engaged exclusively towards an integrated assessment approach or application of new techniques to find optimal locations of monitoring stations. With modern computational techniques available, this thesis proposes a GIS model in combination with an optimization model as a tool for effective air pollution management. The methodology is applied as a case study to explore the optimal expansion of the $PM_{2.5}$ monitoring network of 2018 for Delhi, India.

This research work executed is broadly directed to find solutions to the following objectives (a) adequacy assessment of monitoring stations of the existing network and (b) recommending an optimal configuration for expansion of the current monitoring network. To find the solution to these objectives foremost it was deemed necessary to define the intended purposes of monitoring. To fulfil this requirement, an extensive literature review was carried out to define significant monitoring objectives, prescribed air quality standards and siting criteria regulations. It was concluded that monitoring ambient emissions, safeguarding sensitive land use and mitigating health risks were the most important objectives that must be considered for the design of monitoring networks for urban clusters. The adequacy of existing $PM_{2.5}$ monitoring stations in Delhi, India was assessed for these attributes which defined the region's urban-specific characteristics. A framework was created in ArcGIS to assimilate the various data by generating map layers for:- existing $PM_{2.5}$ air quality monitoring stations, Thiessen polygon-based representative area delineation map (drawing its similarity to airshed boundary), gridded $PM_{2.5}$ emission inventory, gridded land use land cover (LULC) category, industrial locations, and gridded population density. Earlier works used conventional methods such as statistical and

geospatial analysis for adequacy assessment of monitoring networks but this thesis applies a novel approach for assessing the **heterogeneity** in the distribution of monitoring stations. The network adequacy for representation of the urban-specific characteristics (population,landuse, and emissions) and the coverage effectiveness is estimated and conveyed by two indices namely representative index and coverage index. The monitoring gaps in terms of attribute representation and coverage is estimating by the value of the indices. Additional monitoring stations could be added to cover these gaps for effective monitoring. Another contribution of this thesis is to explore the various approaches in the field of optimisation, in particular, for the design of AQMN and to recommend suitable alternative modern techniques for our study region. The optimisation involves allocating a limited number of monitoring stations to satisfy multiple and often conflicting or competing objectives. Most real-time combinatorial optimisation problems are NP-hard in nature, involving multiple combinations of the many objectives and constraints in a huge search space. Therefore, for such problems, metaheuristic approaches can be a suitable alternative to classical methods employed in literature so far. In literature, evolutionary computational (EC) methods:-evolutionary algorithms (EA) and swarm intelligence (SI) algorithms have been applied for solving various types of optimisation problems but found limited application for AQMN design. This thesis thus explores the application of these computational techniques for AQMN design for the area of study. Particle Swarm Optimisation (PSO) and non-dominated sorting genetic algorithm-II (NSGA-II) are the two EC techniques used to solve the multi-objective optimisation problem. The model takes inputs from a geospatial model comprising gridded attributes of the objectives considered for the AQMN design. The optimisation function examines the two objective functions: firstly maximizing the grid attribute demand for safeguarding population and sensitive land use, and secondly, maximising grid attribute demand for detection of emission

concentration and violations above the prescribed $PM_{2.5}$ limits. Further, to gain maximum information with limited monitoring stations, a few constraints are also set for the objectives such as threshold population density and land use category. The distances between two monitors are also evaluated as a constraint. The PSO algorithm analyses the maximisation of grid attribute demand for varying weights of the two objective functions. Several trials were run to investigate convergence to the global optimum by the PSO for varying sizes of initial swarm and number of iterations. The NSGA-II model used by this study offers the possibility of exploring several solutions based on the simultaneous maximisation of the competing objectives.

Thus, the present study illustrates the possibilities of an AQMN optimisation considering evolutionary computational methods as a suitable alternative. The adequacy assessment methodology adopted for representing urban attributes defining the monitoring purpose can be used in real-time to redesign airshed boundaries. It suggests the approaches to possible modifications of existing networks by assessment of representation and coverage gaps. The tabulated comprehensive summary of various design approaches applied so far, covered by this work will help all in having a glance and understanding the applicability of various methods. Finally, the thesis brings forth the challenges involved in the execution of the methodology which are briefly discussed in summary and conclusions. This thesis proposes a methodology that acts as a guide to overcome the shortfalls in terms of data adequacy by stakeholders and research aspirants. It recommends modifications and of other metro cities as well.

Keywords: Air quality, monitoring stations, urban cluster, design methods, monitoring network, standards, adequacy assessment, evolutionary algorithms