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Real-time dissemination of air quality information using data streams and Web technologies: linking air quality to health risks in urban areas

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This article presents a new, original application of modern information and communication technology to provide effective real-time dissemination of air quality information and related health risks to the general public. Our on-line subsystem for urban real-time air quality monitoring is a crucial component of a more comprehensive integrated information system, which has been developed by the Institute for Medical Research and Occupational Health. It relies on a StreamInsight data stream management system and service-oriented architecture to process data streamed from seven monitoring stations across Zagreb. Parameters that are monitored include gases (NO, NO_2, CO, O_3, H_2S, SO_2, benzene, NH_3), particulate matter (PM_{10} and $PM_{2.5}$), and meteorological data (wind speed and direction, temperature and pressure). Streamed data are processed in real-time using complex continuous queries. They first go through automated validation, then hourly air quality index is calculated for every station, and a report sent to the Croatian Environment Agency. If the parameter values exceed the corresponding regulation limits for three consecutive hours, the web service generates an alert for population groups at risk. Coupled with the Common Air Quality Index model, our web application brings air pollution information closer to the general population and raises awareness about environmental and health issues. Soon we intend to expand the service to a mobile application that is being developed.

KEY WORDS: *air pollution; air quality index; monitoring; integrated information system; public health; web services*

Urban air pollution is increasing in major world cities where there are continuous or large emissions of air pollutants. Currently, the most polluted cities are in developing countries such as China, India, and Pakistan with high population density, recent economic boost, and increased consumption (1, 2). The main sources of urban air pollution are transportation, commerce, and industry releasing criteria pollutants (CO, SO_2, NO_x, PM_{10}, $PM_{2.5}$, Pb, and O_3) and hazardous air pollutants (heavy metals, volatile organic compounds, etc.). Exposure to air pollutants, both short and long-term, has been associated with health effects in particularly vulnerable population groups such as children, the elderly or outdoor workers. High pollutant levels increase the risk of respiratory infections, heart disease, and even stroke and lung cancer (1, 3, 4).

In Croatia, local air quality monitoring networks have a 50-year-long tradition of basic pollutant monitoring and are organised across the country. Air quality data are delivered to the Croatian Environment Agency (CEA), which collects data and enters them into the Air Quality Information System (AQIS) as an integral part of the National Environmental Information System (5).

The Institute for Medical Research and Occupational Health (IMROH) is one of the collaborating institutions responsible for the local network of the City of Zagreb, which consists of seven monitoring stations. IMROH has a long tradition in multi-disciplinary research of environmental effects on human health as well as in providing reliable environmental monitoring services (including urban air quality) as an accredited national reference laboratory for particulate matter (6).

Effective urban air quality management requires an integrated approach, in line with the best practice and standards of environmental management and environmental informatics (7). In this sense, information and communication technology (ICT) is crucial for an effective air quality management information system (AQMIS), in line with the recommendations of the European Environment Agency (EEA), principles of the European Sharing Environmental Information System (SEIS) (8), and standards for geospatial information technology (EU INSPIRE Directive 2007/2/EC) (9).

In order to fulfil its roles at the national and local level, IMROH has developed Web applications that transfer air quality data to CEA's AQIS. Furthermore, IMROH has been working on a more comprehensive integrated information system and geo-portal with functionalities such as (10, 11):

- on-line subsystem for urban air quality monitoring in real time (data streams from automatic stations);

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- assessment of air quality (based on air quality index);
- prediction of air pollution and back-trajectory analyses of particulate matter (based on dispersion and statistical models);
- geographic information system (GIS) to integrate data and models and to estimate the contribution of pollution;
- dynamic spatial-temporal reporting and informing the public;
- decision-making support for authorised users.

This article presents our newly developed on-line subsystem for urban air quality monitoring and assessment as a crucial component of the integrated information system. Its architecture is based on Web services technology, which has been applied in many fields, but complex streaming and querying design and application in real-time air quality information reporting based on air quality indices are new.

Data stream management systems vs. *traditional Database management systems*

Traditional database management systems (DBMS) are designed to process datasets that do not change continuously with large data inputs. In addition, today's system databases are ill-equipped for the execution of any specialised data storage and management or data stream searches. Early data stream applications and systems completely ignored DBMSs or used them for offline data warehousing, but today they use queries that do not differ much from traditional database queries (12). There are two types of data stream queries: classic and continuous. Classic queries execute a dataset and return a response. Continuous queries execute data as they arrive and either save the response or convert it into a data stream (13). Queries can also be predefined or *ad hoc*. Predefined queries precede data input and are generally continuous, although in some situations they can be classic. *Ad hoc* queries are made online after the data have already started streaming. They can be classic or continuous (14-16).

Data streams differ from the conventional relational databases in as much as data are fed online; the system does not control the order in which data are fed or processed; data streams are not limited by data size; and once the data have been processed by a query, they can either be rejected or stored. Rejected data cannot be recovered.

Data stream management systems in air quality monitoring

Since it can handle large amounts of constantly changing data, data streaming seems to better fit the requirements of air quality monitoring than a DBMS, yet to the best of our knowledge none of the institutions monitoring air quality in Europe and the world use it. One of the reasons could be that data streams require complex programming, which has so far been mainly in the domain of open-source and limited to scientific research of stream semantics and data flows, stream processing languages, models, and architectures for data stream management databases (13-17). The other reason may be that most air quality monitoring applications are not fit for data transfer from a terminal or a device to the server/information system.

There are a number of stream databases and data stream management systems that enable real-time processing of multiple continuous queries over data streams, such as STREAM, AURORA, TelegraphCQ, StreamGlobe, StreamInsight, and InfoSphere Streams (16-18).

We opted for Microsoft StreamInsight (19, 20) as one of the most stable systems with strong customer support that can handle our SQL Server database. StreamInsight uses the programming language C# and Language-Integrated Query (LINQ). C# is an object-oriented language developed by Microsoft and is fully integrated into the .NET Framework. It has become popular among programmers and the scientific community because of support and

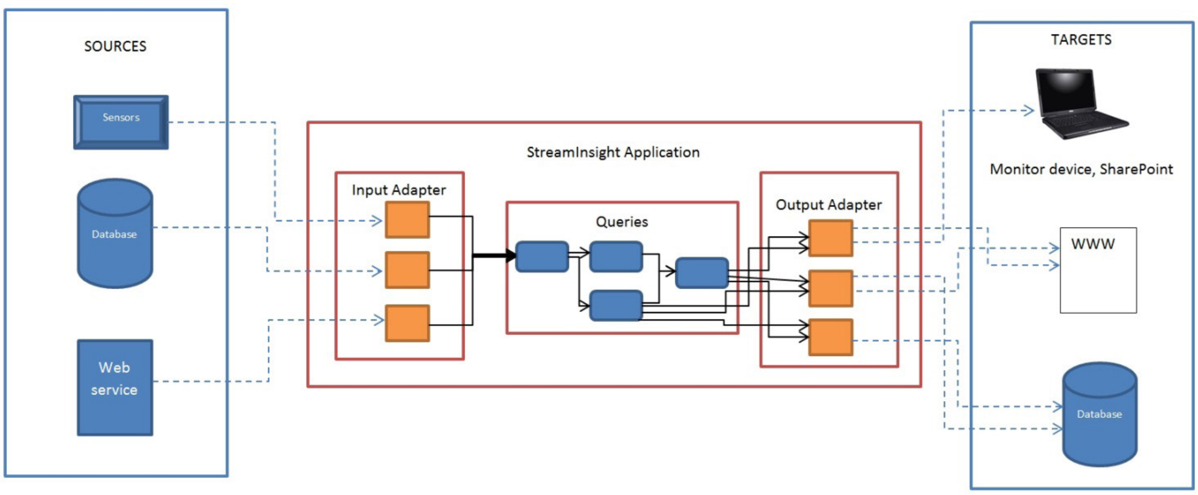

Figure 1 *Example of basic components in StreamInsight package according to (30)*

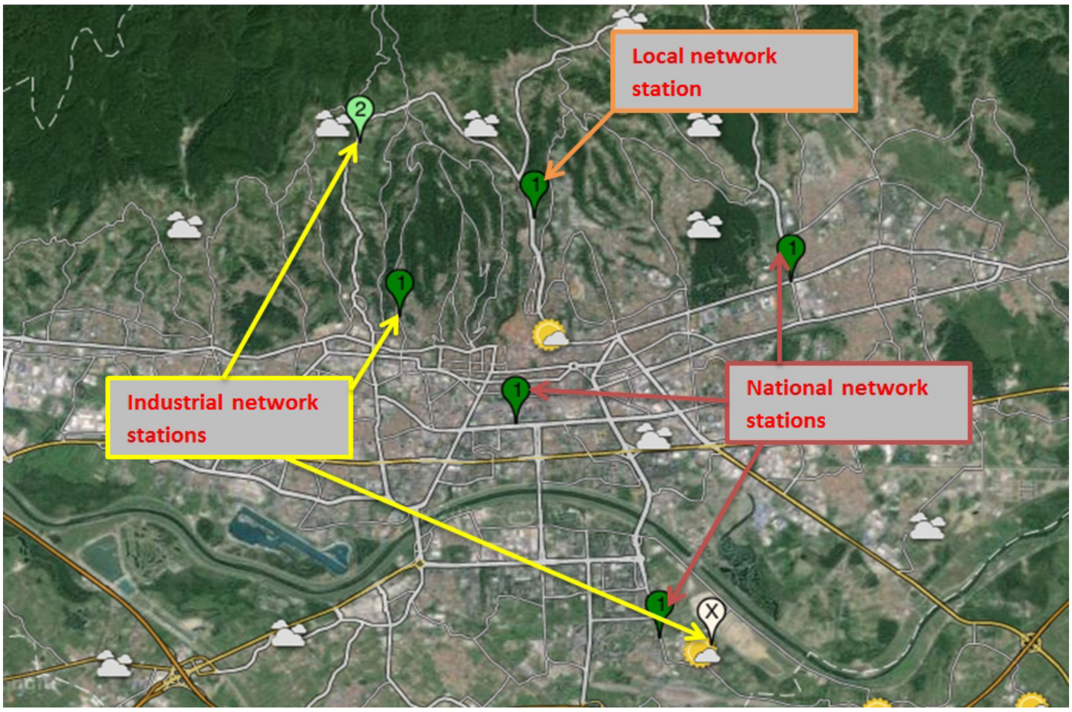

Figure 2 *Automatic measuring stations of Zagreb City*

development potential in terms of more advanced programming. LINQ is a set of features that adds querying capacities to C#. Its greatest advantage is the flexibility of use in any kind of database and form of data storage.

StreamInsight consists of three key components (Figure 1). The first is input adapter, which defines and decides where and at which rate data are collected (starting from 1 ms on). The second component is reserved for queries. The amount, type and course of executing queries solely depend on what we want to do with the flow of data collected on a data sheet. The third component is the output adapter, responsible for the way in which data will be stored, sent, or displayed.

Real-time air quality monitoring in the city of Zagreb

In order to enable real-time air quality monitoring in the City of Zagreb we combine several types of automatic monitoring stations to cover the whole city. For now, this includes three automatic stations within the national network monitoring traffic emissions, one local network station monitoring urban background pollution, and three private stations monitoring industrial emissions (Figure 2). With time we intend to increase the number of local network stations. The amount of streamed data ranges from 2,688 to 3,696 rows per day. Continuous data streams that keep arriving from each automatic monitoring station have a common structure: stream ID, station ID, date, time, parameter ID, and value.

Parameters that are monitored include gases (NO, NO_2, CO, O_3, H_2S, SO_2, benzene, NH_3), particulate matter (PM_{10} and $PM_{2.5}$), and meteorological data (wind speed and direction, temperature, and pressure).

Architecture of THE On-line subsystem

Our on-line subsystem for urban air quality monitoring and assessment relies on the so called Service Oriented Architecture (SOA), which is independent of specific technologies but can be implemented using a wide range of technologies (20). The benefit of implementing SOA with Web services is that it is platform-neutral.

Figure 3 shows the architecture of the on-line subsystem we developed for urban air quality monitoring and assessment. Automated stations feed the information system with data through a predefined query. They first go through automated validation, then air quality index (AQI) is calculated for every station, and a report sent to CEA for the local monitoring station. The last step is to save processed data in a database that shares data with our Web service application monitoring NO_2, O_3, and SO_2 emissions on all automatic stations in Zagreb. If their values exceed national regulatory limits (O_3 - 240 μg m^{-3}, SO_2 - 500 μg m^{-3}, and NO_2 - 400 μg m^{-3}) (21) for three consecutive hours, the web service generates an alert for population groups at risk (children, pregnant women, the elderly, the chronically ill, and people in poor health) not to leave their homes.

Continuous queries over data streams

Figure 4 shows sequential execution of multiple continuous queries over data streams coming from the automatic stations. The first complex continuous query validates concentration values in data streams with respect

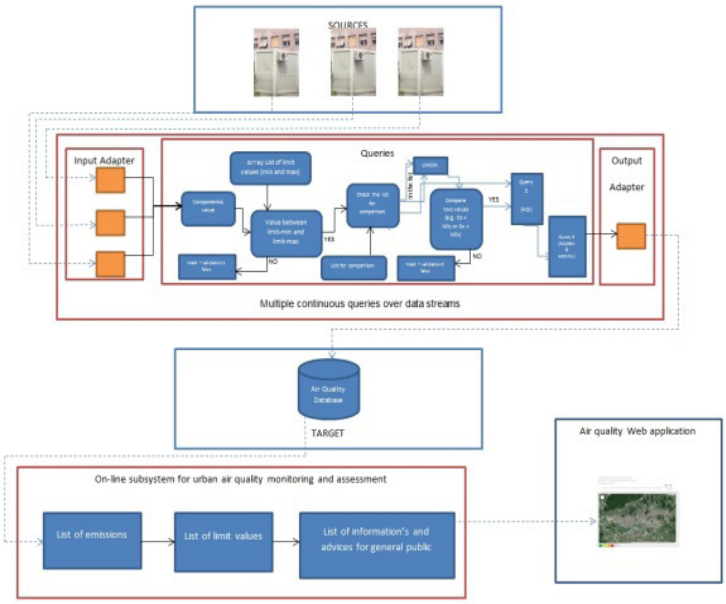

Figure 3 *UML component diagram of on-line subsystem for urban air quality monitoring and assessment*

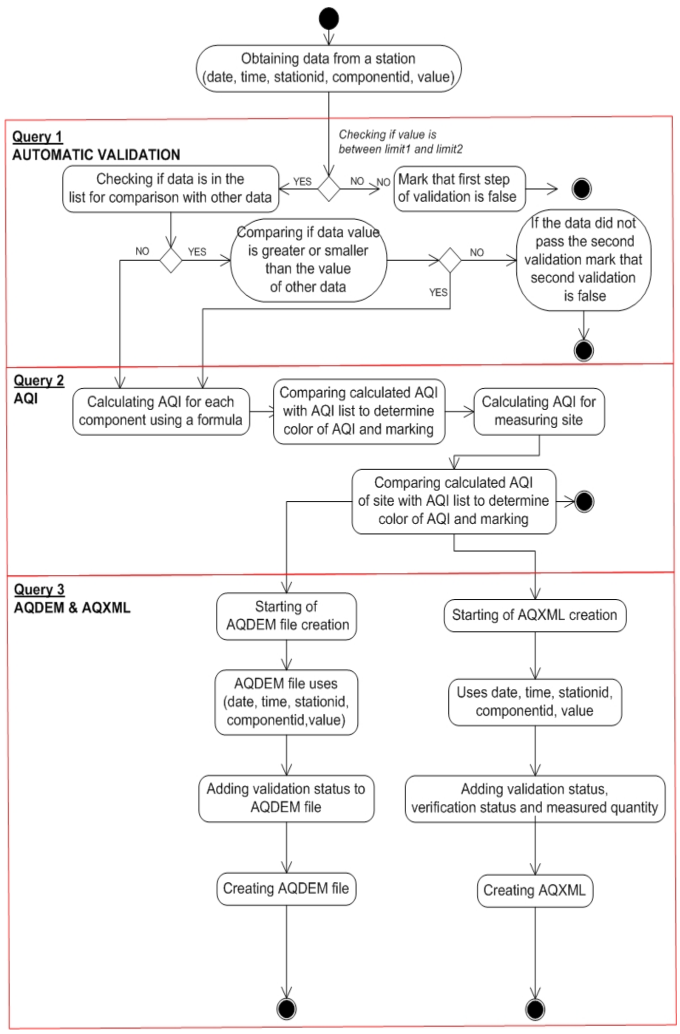

Figure 4 *Multiple continuous queries over data streams*

to a given set of criteria. The second query calculates air quality index, and the third query uploads an automatic hourly report to the CEA. The data obtained with each of the three queries are stored in the database and made accessible online by our web application. After 30 days, the data are archived.

Automatic data validation

Streamed data are validated in real-time using complex continuous queries (see Query 1 in Figure 4). In the first stage, the pollutant value is matched to criteria taking into account outliers and pollutant limits (21, 22). In this way, the query discards outliers caused by incorrect measurement. These values are not deleted but are marked not to have passed a specific criterion, so that missing data for a specific hour or parameter are all accounted for.

In the second stage, concentration values of pollutants that are known to be related (such as O_3 and NO) are re-checked and compared to remove errors due to a failure or faulty measurement (e.g., span and zero readings due to a non-sealing valve). Data that do not pass the second stage of validation are also marked and stored in the database.

Data that pass both validation stages are marked as validated and ready for further processing.

Air quality index calculations

Presently air quality information in Croatia (and the City of Zagreb) consists of raw monitoring data or corresponding categories of air quality for the past year. These categories are based on pollution levels, limit and target values, and long-term goals. According to the national Air Protection Act (22) the first category denotes clean or slightly polluted air and the second category polluted air. Such air quality information is more suitable for air quality experts rather than general public.

For the first time in Croatia, IMROH has introduced an air quality index based on the Common Air Quality Index (CAQI) model in accordance with the EU CAFE directive (23). The great advantage of AQI is that it allows comparison with a number of European cities in real time (24). The model uses a scale of 1 to 100, where 1 denotes best air quality and 100 the worst. The index is calculated from pollutant hourly mass concentrations, using a calculation grid (see Table 1) and the following formula (25, 26):

$$I = \frac{I_{high} - I_{low}}{C_{high} - C_{low}} (C - C_{low}) + I_{low} \quad (1)$$

where *I* is air quality index, *C* pollutant concentration, C_{low} concentration breakpoint is $\leq C$, C_{high} concentration breakpoint is $\geq C$, I_{low} air quality index corresponding to C_{low}, and I_{high} air quality index corresponding to C_{high}.

To adjust reporting to Croatian regulations (21, 22), air quality indices have been split at the AQI threshold of 75 to correspond to the two national air quality categories: I - clean to moderately polluted air and II - highly polluted air (see the grid in Table 1).

Table 2 shows the number of days in 2012 in which a prevailing pollutant (one with the highest index on a particular day at a particular station) exceeded its limit values. This calculation also relies on national legislation as well as CAQI methodology based on air quality indices. For example, PM_{10} exceeded its national limit value on 38 days at the IMROH station and was the prevailing pollutant on 301 days.

Assessment of air quality based on air quality indices

The second type of continuous query is used to assess air quality based on the AQIs (see Query 2 in Figure 4). It calculates the hourly index for each pollutant in real-time and the hourly index for the measuring site in real-time. The hourly index for Zagreb in real-time and the mean index for the whole city are calculated by the web service later, after the data are stored in the database. The formula shown in Equation 1 and the AQI calculation grid (Table 1) are directly integrated into the continuous query over data streams to avoid communication with the database, as it would slow down data stream processing by 15 %.

The hourly index for a measuring site is the highest index of a pollutant measured at the station for that hour. The first step is to set zero as the default index, which will change as pollutants are being measured and indices calculated for a measurement site. The calculated index for each pollutant is later stored in a database and displayed online on a digital map of Zagreb.

Once air quality has been indexed, the third continuous query generates an automatic report for the CEA (see Query 3 in Figure 4) in the format of Air Quality-DEM and XML files (as required by the EEA).

Air quality database

Streamed data are saved in a relational database. Figure 5 shows a segment of the database which is used to store information from automatic stations. AQ_DATA entity contains the basic attributes of the stream. In addition to the primary key, DataID, and foreign keys StationID, ComponentID, and AQIID, AQ_DATA has two binary-type attributes, AQDEM and AQXML, defining the format of the generated files. All other entities are related to AQ_DATA. The COMPONENT entity contains attributes related to pollutants and meteorological data measured at the automatic stations. The AQI entity contains attributes related to air quality index. The STATION entity contains attributes with information on the automatic stations.

Air quality Web application

Zagreb air quality monitoring information is displayed on the web page *http://kvaliteta-zraka.imi.hr/* thanks to the web application based on CAQI methodology and

Table 1 *Pollutants and calculation grid for the CAQI. Source: project CITEAIR II (35, 38)*

Pollution class	Index range (calculation grid)	Traffic				City background					
		Mandatory			Auxiliary	Mandatory				Auxiliary	
		NO_2	PM_{10} 1 h	PM_{10} 24 h	CO	NO_2	PM_{10} 1 h	PM_{10} 24 h	O_3	CO	SO_2
Very low	0-25	0-50	0-25	0-12.5	0-5000	0-50	0-25	0-12.5	0-60	0-5000	0-50
Low	25-50	50-100	25-50	12.5-25	5001-7500	50-100	25-50	12.5-25	60-120	5001-7500	50-100
Medium	50-75	100-200	50-90	25-50	7501-10000	100-200	50-90	25-50	120-180	7501-10000	100-300
High	**75-100**	200-400	90-180	50-100	10001-20000	200-400	90-180	50-100	180-240	10001-20000	300-500
Very high	>100	>400	>180	>100	>20000	>400	>180	>100	>240	>20000	>500

Table 2 *Number of days in 2012 when prevailing pollutants had the highest AQI and exceeded Croatian limit values (LV)*

	Station IMROH		Station Zagreb1		Station Zagreb2		Station Zagreb3	
	Highest AQI	≥LV	Highest AQI	≥LV	Highest AQI	≥LV	Highest AQI	≥LV
PM_{10}	301	38	353	28	364	28	294	31
SO_2	0	0	0	0	0	0	0	0
NO_2	4	0	6	0	1	0	0	0
CO	0	0	0	0	0	0	0	0
O_3	60	11	0		0		71	0

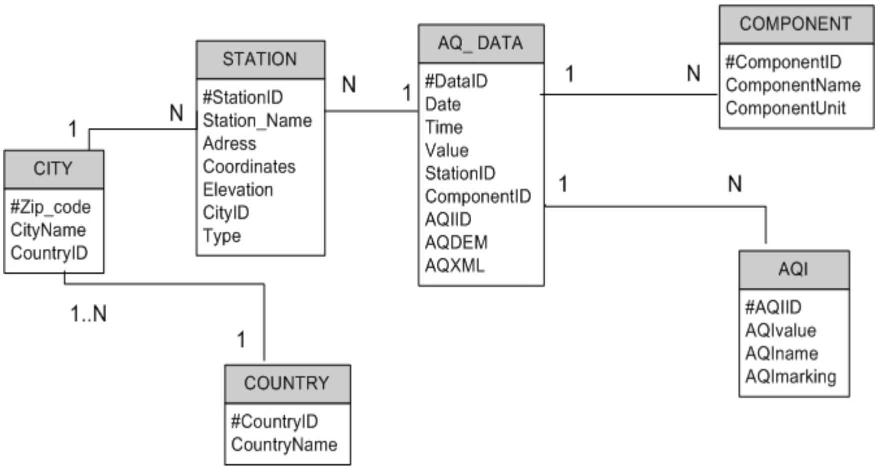

Figure 5 *UML diagram of relational database for storage of data from automated stations*

developed in accordance with European directives. Figure 6a and 6b shows the interactive dynamic map of the City of Zagreb with location markers of the automatic monitoring stations. Their colour changes with the air quality index. Placing a cursor or clicking on location marker selects a monitoring station and displays air quality index details. This allows a person who is not familiar with the Air Protection Act to understand the AQI in plain terms (11).

The application also associates AQIs with health risks for sensitive and general population and the corresponding notifications/alerts (Table 3). These notifications are reported for each station with the calculated index.

Every hour for each automated station our Web service application monitors whether pollutant levels have exceeded their limits. If the levels are exceeded for three hours in a row, the Web site displays an alert for the corresponding population group.

After a three-month trial, our web application was launched in the early 2014. Initially, it only processed the data obtained from the automatic station at the IMROH site. In the early September of 2014, our on-line information system at IMROH started receiving and processing data streams from all public automatic stations in Zagreb. Judging by the server CPU and RAM usage of only 2-5 %, it can support a much larger number of stations. Furthermore, the amount of data streamed to the server (250 MB per hour or 6 GB a day) does not constitute a burden on the Internet connection at IMROH, whose bandwidth is currently 100 Mbps but will soon increase to 1 Gbps.

CONCLUSION

Until now, data streaming has not been used in air quality monitoring. One of the reasons is that it requires complex streaming and querying designs that need to validate continuous measurements from automatic monitoring stations. Another reason could be that most research in the field of air quality ignores data transfer and communication from a terminal or device to the server or information system.

Our solution provides great benefits compared to traditional approaches to collecting, processing, and disseminating information. Continuous queries over data

Table 3 *Air quality index and health risk notifications for sensitive and general population groups*

Air quality index	Notifications for sensitive population groups (old, children, ill, pregnant women, asthmatic patients, outdoor workers)	Notifications for the general, healthy population
Very low	*Enjoy your daily outdoor activities.*	*Air quality is ideal for outdoor activities.*
Low	*Enjoy your daily outdoor activities.*	*Air quality is ideal for outdoor activities.*
Medium	*Consider reducing strenuous outdoor activities if symptoms occur.*	*No need to modify your usual outdoor activities unless you experience symptoms such as coughs and throat irritation.*
High	*Reduce or postpone strenuous outdoor activities. Children and the elderly should spend less time outdoors.*	*Consider reducing or postponing strenuous outdoor activities if you experience symptoms such as cough and throat irritation.*
Very high	*Avoid strenuous outdoor activities. Children and the elderly should also avoid strenuous outdoor activities.*	*Reduce or postpone strenuous outdoor activities, especially if you have symptoms such as coughing and throat irritation.*

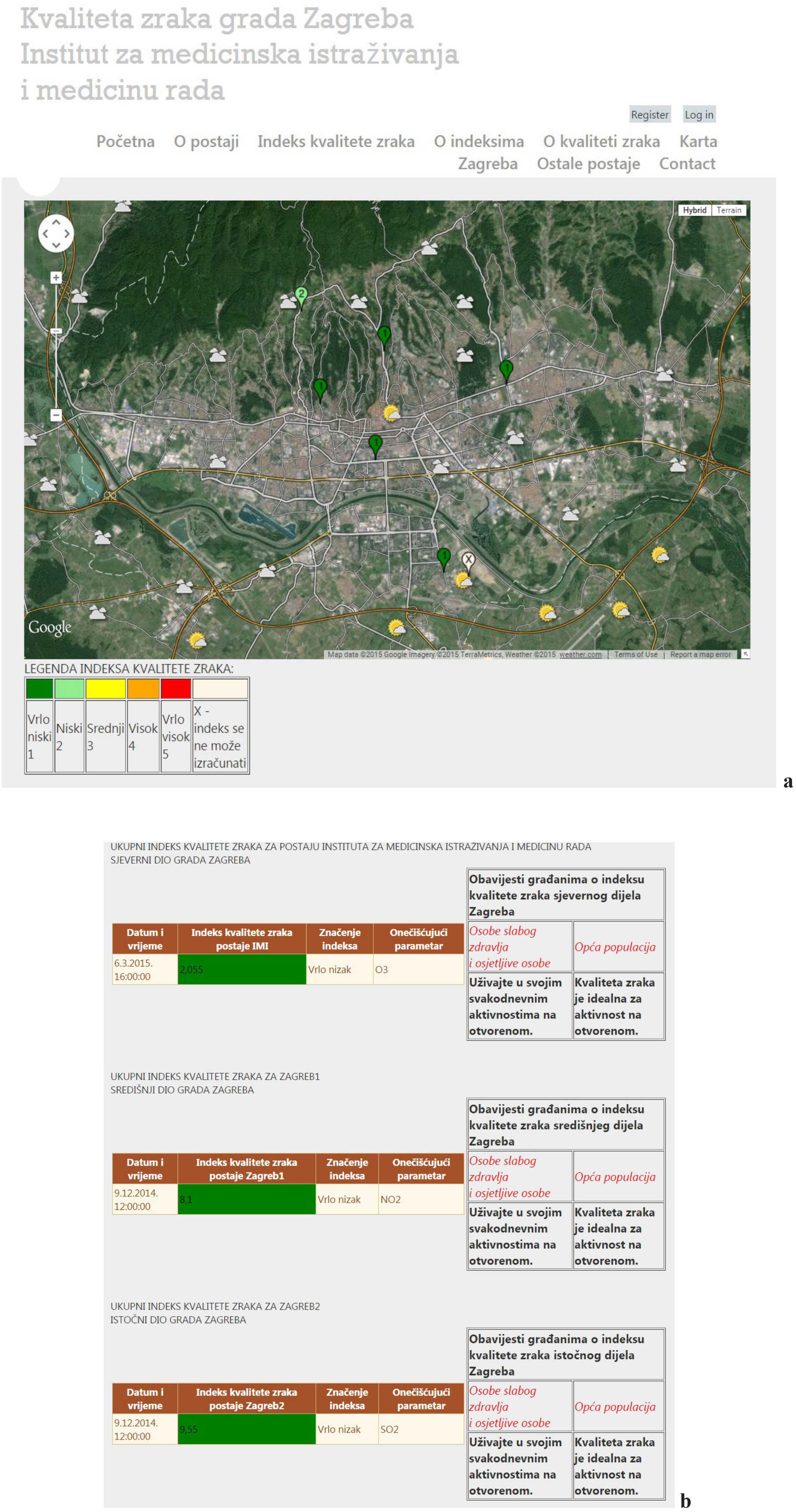

Figure 6 *Web application of air quality in Zagreb a) map of the city; b) details of monitoring stations and information for the general public on air quality*

streams enable high-speed processing of a large number of measurement data and easily connect to automatic stations. Furthermore it has proven to be stable and effective for streamed data collection and processing.

Coupled with the CAQI model, our web service application brings air pollution information closer to the general population and raises general awareness about environmental and health issues.

In the future we intend to develop a mobile application to expand the use of these web services. A future system could also use sound signals or messages for the benefit of the visually impaired or blind population. The system could also be extended to other air quality measuring stations across the country to get a better insight into the air quality in Croatia. With small adjustments, the system could also collect data from other non-air-quality measuring stations such as water quality stations, radiation stations, weather stations, and other automated stations.

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Izvješćivanje o kvaliteti zraka u stvarnom vremenu kontinuiranim prijenosom podataka i web tehnologijama - povezivanje kvalitete zraka sa zdravstvenim rizicima u urbanim sredinama

U ovom se članku predstavlja nova, originalna primjena suvremene informacijske i komunikacijske tehnologije radi učinkovitoga izvješćivanja opće populacije o kvaliteti zraka i s njom povezanih zdravstvenih rizika. Naš *online* podsustav praćenja kvalitete zraka u gradovima ključan je dio složenijega integriranoga informacijskoga sustava koji je razvio Institut za medicinska istraživanja i medicinu rada. Oslanja se na sustav upravljanja kontinuiranim prijenosom informacija (engl. *data stream management system*) razvijen pomoću StreamInsighta i SOA arhitekture radi obrade podataka koji neprekidno dolaze sa sedam automatskih postaja za praćenje kvalitete zraka diljem Zagreba. Prate se sljedeći parametri: NO, NO_2, CO, O_3, H_2S, SO_2, benzen, NH_3, čestice u zraku (PM_{10} i $PM_{2.5}$), brzina i smjer vjetra, temperatura i tlak zraka. Zbog stalnih složenih upita (engl. *continuous query*) podaci se obrađuju u stvarnom vremenu. Prvi je korak automatska validacija pristiglih podataka, zatim se izračunava indeks kvalitete zraka za svaki sat, a potom se izvještaj šalje Agenciji za zaštitu okoliša. Ako tri sata za redom vrijednosti pojedinih parametara nadilaze granične vrijednosti utvrđene zakonom, web usluga šalje upozorenje osjetljivim populacijskim skupinama (bolesnicima, trudnicama, djeci, radnicima na otvorenom i dr.). Oslanjajući se na model europskoga indeksa kvalitete zraka (Common Air Quality Index, CAQI), naša web aplikacija približava općoj populaciji aktualne podatke o onečišćenju zraka te podiže svijest o problemima vezanima uz okoliš i zdravlje. Uskoro namjeravamo proširiti ovu uslugu na mobilnu aplikaciju, koja je u izradi.

KLJUČNE RIJEČI: *indeks kvalitete zraka; integrirani informacijski sustav; javno zdravstvo; onečišćenje zraka; praćenje kvalitete zraka; web usluge*