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SIMULATING ENVIRONMENTAL IMPACTS BASED ON THE EXAMPLE OF ROŞIA MONTANĂ

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Abstract

One of the challenges of modern terrain modelling methods is to incorporate non-existing, planned features in the output. Remote sensing based solutions can only detect structures and shapes that are already present in the environment. In order to assess the impacts of a planned development on the surrounding landscape properly it is inevitable to solve this issue. In addition to the environmental, social and economic consequences, mining activities, especially open cast mining will also leave significant scars on the landscape. These can not only have a visual effect but also impact local weather conditions by changing winds, precipitation patterns. The current paper demonstrates a collection of methods and techniques able to cope with the various challenges that arise when modelling the landscape impacts of such developments. The experiments were performed in the area of Roşia Montană, where a Canadian company plans to create the largest open cast gold mine in Europe. The results of the terrain modelling process allow for the quantification of the estimated impacts on the terrain and the land cover of the area caused by the mining project. The presented methodology and visualisation tools can also facilitate the decision support mechanisms making the communication 'more understandable' amongst stakeholders; information meetings and public hearings involving organizing groups at any level. Obtaining the results required the development of several unconventional techniques especially in terrain modelling and visual landscape simulation, involving the combination of sometimes very different base methods.

Keywords: digital terrain modelling, visual impact assessment, landscape modelling, decision support, Roşia Montană

INTRODUCTION

Spatial decision support systems (SDSS) contain different components and can be used for planning, management and public communication purposes. Integrated structures of spatial data, numerical models and formulated expert knowledge are widely applied in environmental studies since computing, geodata collecting and processing technologies, such as database management tools, geographic information system (GIS) and remote sensing (RS), are available for researchers, analysts and policy makers (Goodchild et al., 1996; Bareth, 2009; Laudien et al., 2010).

The growing official and public demand of access to modern, realistic and user-friendly computer visualisation technologies suggests the new potentials of geo-visualization and navigable virtual landscape in decision and policy support and public relation, beyond digital cartography (Sheppard and Cizek, 2009; Pettit et al., 2011). The development of SDSS requires a harmonized dataset of spatial information. However, the necessary sources are not always available. Difficulties and elaborated solutions are also presented in the paper, in the case of the planned environmental intervention of the largest open cast gold mine in Europe.

Roşia Montană (Verespatak, Goldbach) and the surrounding region is known for its extensive resources of gold, silver and other minerals. The town has rich mining traditions dating back more than 2000 years (Téglás, 1888; Sîntimbrean and Bedelean, 2002; Géczi and Bódis, 2003; Paşca, 2010). The most significant remnants of the mining activities is the extensive network of shafts and tunnels built in the Roman era, some of which are open for visitors in the mining museum. The activities have been present almost constantly until 1996 when the Romanian State Mining Company decided to stop the extraction due to unsatisfactory yields (Géczi, 2011).

Canadian company Gabriel Resources formed a new business called Roşia Montană Gold Corporation (RMGC) in 1999, which planned to create the largest open, cast gold and silver mine in Europe. Their estimates say that 300 metric tons of gold and 1600 metric tons of silver can be extracted in a period of 20 years (Haiduc, 2003; Géczi et al., 2005; Paşca, 2010; RMGC, 2015). The project has raised vocal opposition from civil organisations (Buzoianu and Ţoc, 2013; MTI, 2013) because of the environmental risks posed by the cyanide-based technology that is planned to be used for ore processing (Földessy and Bőhm, 2012; Parasca and Butnaru, 2014). This will require the creation of a 2.7 km long tailings reservoir, covering 304 hectares while flooding a village. The pond will be held in place by a 180-metre-high dam (Bara, 2002, Haiduc, 2003).

In spite of the company's plans to start the project in 2006, the impacts of the Tisza cyanide pollution in 2000 (Prommer and Skwarek, 2001; WWF, 2002) and the breach of the alumina tailings dam near Kolontár in 2010 2010 (BBC, 2010, ICPDR, 2011) among other similar environmental disasters succeeded in thwarting the commencement of mining activities thus far.

The controversy surrounding the project does not stop at potential environmental risks though. According to the yield-estimates performed on behalf of RMGC, the actual gold and silver content of the rocks is so low that it borders on being economically unviable to extract. This means that the amount of profits and subsequent taxes toward the Romanian budget is highly unstable and difficult to estimate with high accuracy, especially when the fluctuation of gold prices is also taken into account. The low grade of ore content also requires enormous amounts of rocks to be processed and results in a very large volume of unusable waste material, some of which will be deliberately contaminated with cyanide and other dangerous chemicals (Haiduc, 2003). The subsequent storage, management and maintenance of these materials will invoke further costs as well as environmental risks for several years after the project is deemed complete.

The objective of the current study is to estimate the environmental impacts of the project as proposed by RMGC. The research focus is the terrain and the visual impacts on the landscape, as well as determining the changes in land cover. I will also demonstrate the results of a simulation about a dam failure on the planned tailings reservoir.

STUDY AREA

Roşia Montană is located in the NW part of Alba County in Romania. The actual township is made up of several smaller settlements in the Roşia valley with the centre being in the top half of the valley (Fig. 1). The population of the settlement cluster was 2656 in 2013, according to the Romanian Office of Statistics. The largest settlement in the study area is Abrud, in the SW corner with 5072 inhabitants in 2013.

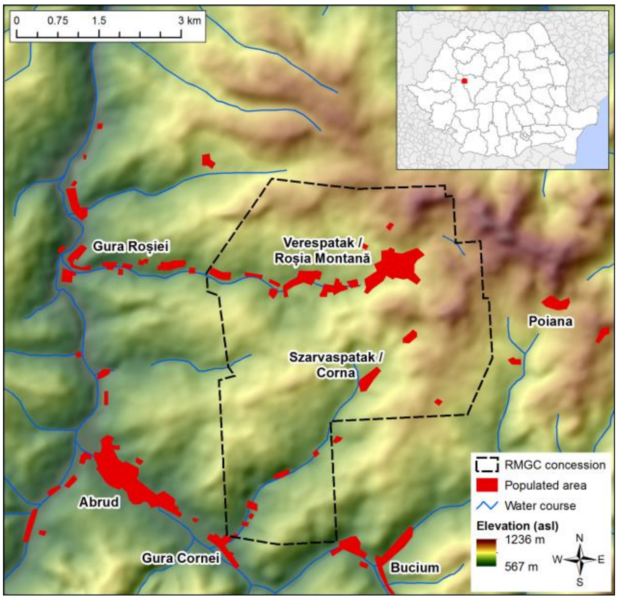

Fig. 1 Location of the study area

The concession zone is about 24 square kilometres, but for better context the full study area contains a 10 by 10 kilometre square. In terms of hydrology, the main watercourse in the study area is the River Abrud flowing to the North into River Arieş, a tributary of River Mureş (Maros) which in the end flows into River Tisza near Szeged, Hungary.

Since the main economic activity in the area is mining and associated processing industries, the waters have been heavily polluted, most significantly in the communist era, when little (if any) attention was paid toward the environment. The Roşia stream still contains relatively high levels of heavy metals and other pollutants, although the concentrations are decreasing since the cessation of active mining and processing activities.

The project plan proposed by RMGC intends to spend a considerable effort on improving the existing pollution sources as well as preventing future contaminations by diverting the natural water flows in the area. They also promise to respect the historical treasures of the area by avoiding the designated protection zones. Nevertheless, it is difficult to imagine that the high capacity vehicles, trucks and the explosions used in blasting out the mining pits will leave the surrounding buildings and historical landmarks unscathed.

The biggest environmental risk of the planned project would be the tailings reservoir located in the Corna valley (Géczi et al., 2006). This pond, in its final stage will be filled with 213 million m^3-s of waste material left behind from the ore processing. The sludge will contain high concentrations of cyanide and other harmful or toxic compounds (Haiduc, 2003). By comparison, the Tisza cyanide disaster in 2000 was caused by "only" 100,000 m^3 of water containing cyanide and heavy metals. Another significant risk factor is the location of the tailings pond, being just 1.78 km-s from the town of Abrud.

METHODS

In order to perform the necessary modelling and simulation tasks extensive preparations had to be done as well. These involved obtaining the source data and maps from various sources and collating them into a common database. The majority of the process used various GIS techniques, some of which have been developed and enhanced by the author.

The most difficult challenge was to incorporate the planned mining facilities and landforms into the existing surface in a seamless way. Artificial terrain elements tend to be more angular and to consist of more straight edges than those found in undisturbed areas. The main task was to resolve this conflict in a combined elevation model. To this end, it was decided to take advantage of the best characteristics of the two major surface modelling methodologies: vector and raster based algorithms.

Both approaches are using points of fixed elevation as base, but they estimate the elevation of in-between locations in different ways. The TIN (Triangulated Irregular Network) method in the first group generates triangles among the points with known elevation (Peucker et al., 1979; ESRI, 1994). This results in a surface with an angular, edgy appearance. One of the advantages of the TIN method is that it is computationally cheap, compared to the raster methods, delivering quicker results. However, the generated surface is visually quite different from the appearance of the most natural terrains, usually having much less edges and sharp breaks in them.

The majority of natural terrains can be modelled better using a raster approach. While there are many mathematical models to interpolate the unknown elevation value of the points based on the input data, most of these are aimed to generate statistical surfaces. Terrains have very specific features and characteristics, most of them formed by flowing water, which are beyond the capabilities of the generic interpolation methods like IDW (Inverse Distance Weighting), Kriging or spline based solutions. A more advanced algorithm was developed at the Australian National University (Hutchinson, 1988) which was able to respect the special requirements set by the effects of natural processes on the surface. The ANUDEM algorithm is now being used in ESRI's ArcGIS Spatial Analyst behind the '*Topo to Raster*' geoprocessing tool (Hutchinson and Dowling, 1991; Hutchinson, 1996; Hutchinson, 1997).

The tool is able to take advantage of the input data types commonly used to describe terrains, such as contour lines, elevation points. Water is the primary erosive force determining the general shape of most landscapes. For this reason, most landscapes have many hilltops (local maximums) and few sinks (local minimums), resulting in a connected drainage pattern. '*Topo to Raster*' uses this knowledge of surfaces and imposes constraints on the interpolation process that results in a connected drainage structure and correct representation of ridges and streams.

Using any of the two approaches above on their own would still not be able to produce an output surface that is sufficiently "smoothed" in the undisturbed areas while keeping the angular quality of the artificial structures. To achieve this, a combination of techniques had to be used. This means that a base surface was created using '*Topo to Raster*', and the rasterised TIN models of the artificial structures were merged into it later using raster arithmetics.

In the present study, the elevation data was based on the EU-DEM database available as a free download from the European Environment Agency (EEA) website. This was created using the latest versions of the ASTER-GDEM and SRTM (Shuttle Radar Topography Mission) surface models (Hensley et al., 2000; Hennig et al., 2001; Farr et al., 2007) with additional edits to improve the water surfaces. The final model is a 30-metre-resolution, medium scale raster surface, which is very usable for researches based on watershed basins (Tøttrup, 2014). The special requirements set by the modelling of artificial features required further processing of the raw EU-DEM data in order to improve its resolution and hydrological accuracy. Contours were derived from the surface at 10-metre intervals to serve as the base input for the new elevation model, which would be capable of storing the planned features as well. For better hydrological accuracy we used the water network layer in the Romanian National Cadastre Agency's INSPIRE View Service (ANCPI, 2014), which was digitised manually for the extent of the study area. Since '*Topo to Raster*' is using the stream network to build valleys and ridges into the resulting surface, the existing streams and rivers had to be extended upstream, until the shape of the contour lines made it necessary. This ensured that the valley's baseline was without obstructions and the water could flow freely as close to the natural conditions as possible. In the paper, this will be referred to as refined EU-DEM.

RMGC has published its Environmental Impact Assessment (EIA) reports as PDF documents in several versions. For this study the 2006 version was used (RMGC, 2015), which contained detailed maps of the planned mining facilities and other structures in the following time series:

- initial stage (year 0);
- operational stage (year 7);
- operational stage (year 14);
- operational stage (year 16);
- reclamation stage (year 19).

The PDF documents were converted into GIS compatible format and georeferenced into UTM34N projection to match the rest of the input datasets. The planned shapes were grouped into two categories, each requiring its own approach in modelling.

One group contained the planned quarries, mining pits and waste dumps. The most important part of modelling these structures was the creation of 3D line elements around them to define the boundary of the shapes. These 3D lines received their elevation values from the unaltered terrain (refined EU-DEM), while being digitised to follow the edges of the mining structure.

The planned structures also contained flat surfaces, which were modelled as simple polygon features with the elevation value read from the map labels stored as an attribute. In order to improve the accuracy of the TIN surface some additional contour lines and 3D lines were required in places where the algorithm would have otherwise produced incorrect results.

The digitised lines and polygons were then used to create TIN surfaces. To ensure that the resulting surface only covers the area of the artificial features, a boundary polygon was also added as the input data. This TIN model was then ready to be converted into a raster surface and to be mosaicked into the base refined EU-DEM. The 3D lines around them ensured the seamless integration, with the boundary polygon made sure that triangles were only formed within the structure.

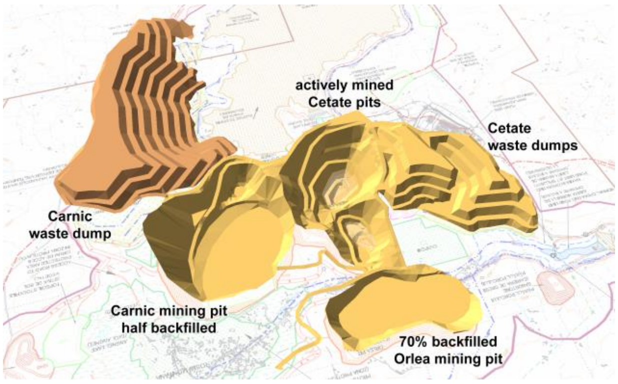

Fig. 2 TIN components of mining related features

The other main group consisted of the lakes and reservoirs planned in the project. These were digitised as polygon features, but it turned out that additional concerns had to be taken into account. The maps in the EIA were based on a terrain of unknown origins, as the map did not contain any information about the source of the used data. Therefore, it was possible (quite likely) that the refined EU-DEM would not match exactly to the shapes in the map which were based on a different elevation model. To overcome this problem the polygons representing the water (and similar) surfaces were digitised extending beyond the shapes in the map.

The TIN surface generated from the extended polygons was then converted into a raster surface based on the cell configuration of the base DEM (refined EU-DEM). The raster surface in its original state extended "below" the cells of the original DEM, i.e. where it was higher than the level of the tailings pond or lake. These cells had to be eliminated before mosaicking using simple raster comparison and arithmetic operations. The same approach was used in the case of modelling the dam structures as shown in Fig. 3.

Once the raster model only contained the cell that were higher than or equal to the corresponding cells in the original terrain, it could be merged into the surface. Using this method ensured that no gaps are formed and the "water" completely fills up the available space in the model. Taking the polygon digitised directly from the RMGC map may have caused such gaps, but this way the integration was seamless.

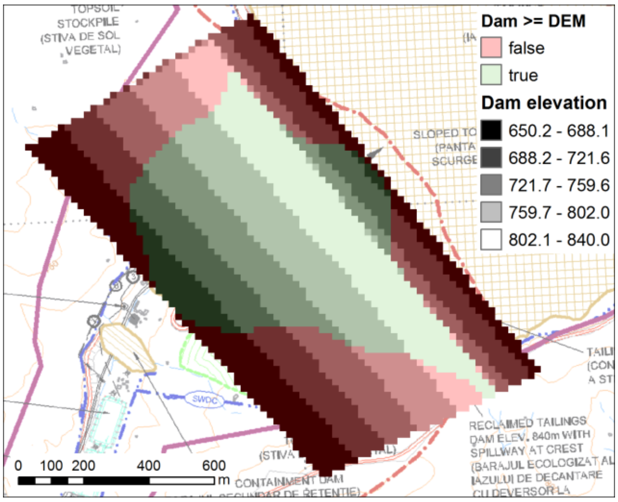

Fig. 3 Determining the cells to be discarded based on their elevation values

The modelling steps described above were performed for each of the project stages mapped in the EIA report, so in the end, five simulated terrains were created. Fig. 4 shows one of the maps draped on the built surface.

An additional, but very important part of the process was to simulate impact of the planned changes on the visual appearance of the landscape. This involved modifying SPOT satellite images of the area using standard graphics editing tools. The modifications were performed in the GiMP Open Source graphics software capable of every bit of functionality required in the editing.

The baseline SPOT image was captured in 2006, showing the existing Cetate mining pit and the surrounding area. Using texture and colour samples taken from

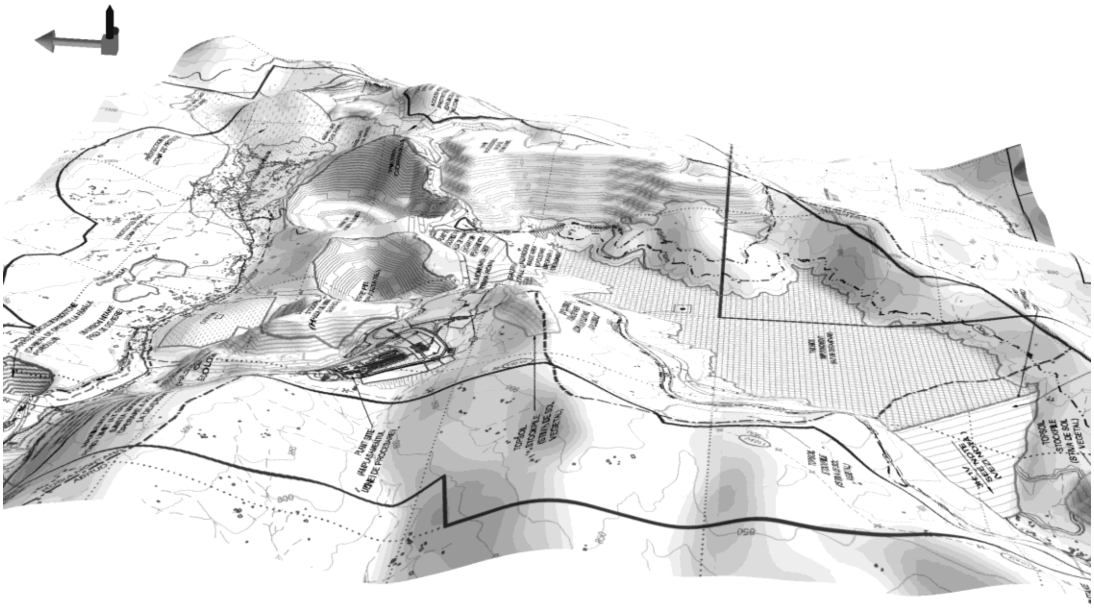

Fig. 4 RMGC map of year 14 draped over simulated terrain model

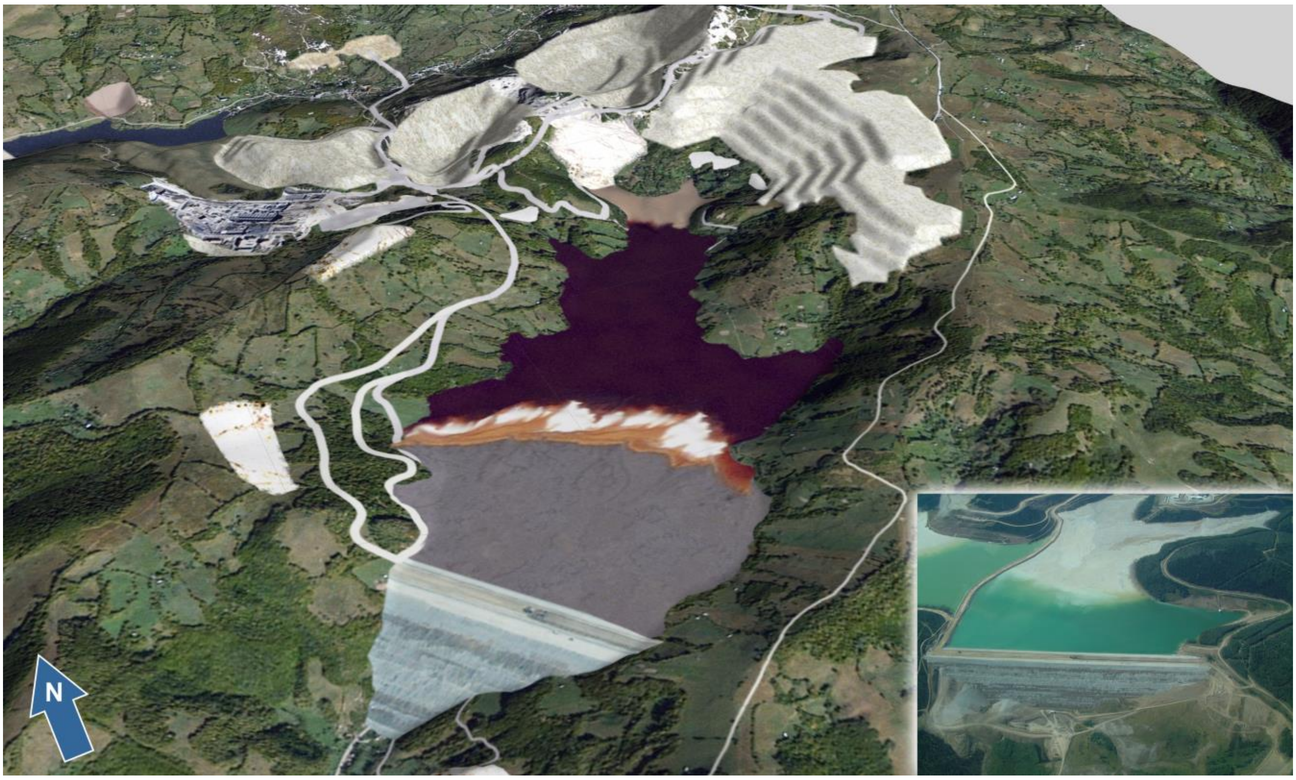

Fig.5 Simulated SPOT image of year 7 (photo in bottom right contains the texture sample for the tailings dam)

existing tailings ponds, mining pits, quarries and other features in the surrounding region (most notably the copper mine near Roşia Poieni) it was possible to generate hypothetical images of the planned changes. Textures could be obtained from other sources as well, for example, Fig. 5 shows the tailings pond in year 7 of the project, with the dam's texture copied from the photo in the bottom right corner.

Creating the visual appearance of roads was done by using the simple paintbrush tools and taking a colour similar to that found on the majority of existing roads in the image. The modifications were then subjected to various colouring and artistic effects to increase the level of similarity to the original satellite image. As with the terrains, the satellite images were also produced in five versions, which were later used in animations and time-series composite images.

RESULTS

The simulated terrain models are shown in Fig 6. Another aspect of the results was the estimation of land cover changes in the area. Based on the simulated SPOT satellite images and the original CORINE (EEA 2000) land cover 2006 (CLC2006) map of the study area it was possible to create a time series of the planned changes. The process involved removing any CLC2006 polygons from within the affected areas and repopulating these blanks with new polygons according to the modified SPOT image data. Analysing the relationship between current conditions on SPOT and CLC2006 it was quite possible to determine the changed land cover category. The simulated land cover of the reclaimed waste dumps takes into account the passage of time as well. This means that in project years 14 and 16 they are classified as scrub, while in year 20 they change into mixed forest, assuming the areas would be planted with fast growing trees. The time series maps of the simulated CLC data are shown in Fig. 7.

Using the source CLC2006 data and the boundary polygon encompassing all the planned mining features it was also possible to calculate the ratio of land cover types that will be impacted by the project. The boundary polygon was created by merging all the clipping polygons used in the TIN generation stage. Table 1 shows the results of this analysis. The percentage should be interpreted as the ratio of the land cover class within the area affected by mining.

Table 1 Distribution of different land cover types based on the CORINE land cover data for the year 2006

CLC2006 code	Land cover class	Area (%)	Area (ha)
311	Broad-leaved forest	40.56	379.22
231	Pasture	25.87	241.87
131	Mineral extraction site	11.54	107.92
112	Discontinuous urban fabric	9.91	92.63
242	Complex cultivation pattern	8.72	81.48
313	Mixed forest	2.89	27.02
324	Transitional forest-shrub	0.51	4.74
Total		100	934.88

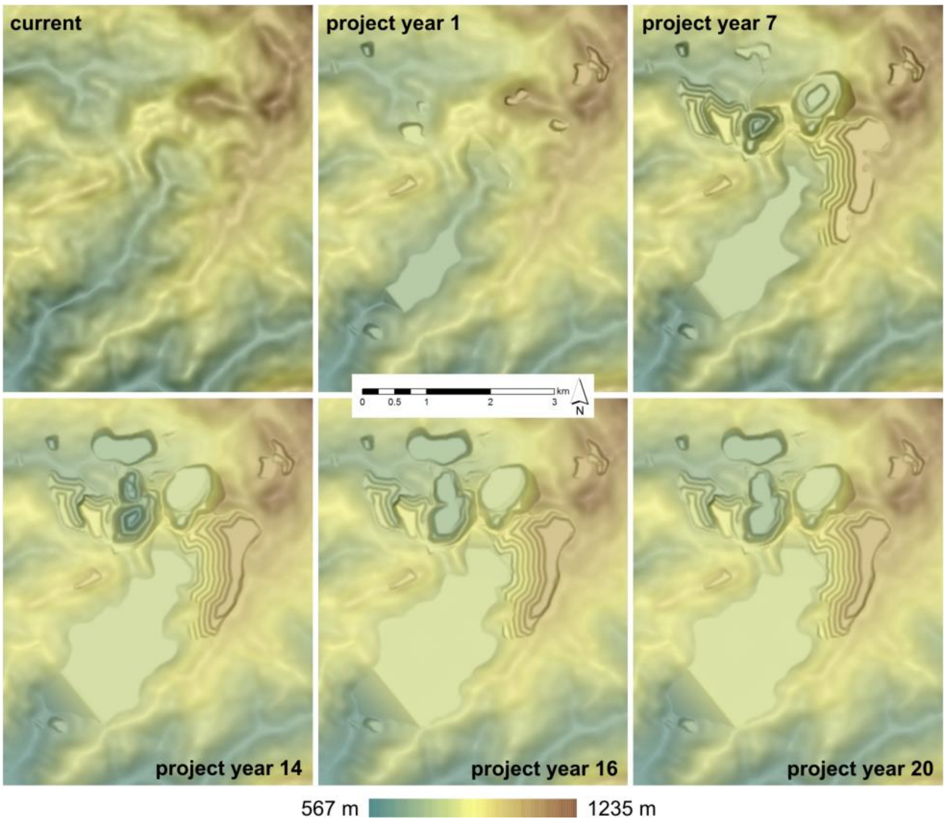

Fig. 6 Time-series maps of the simulated terrain changes

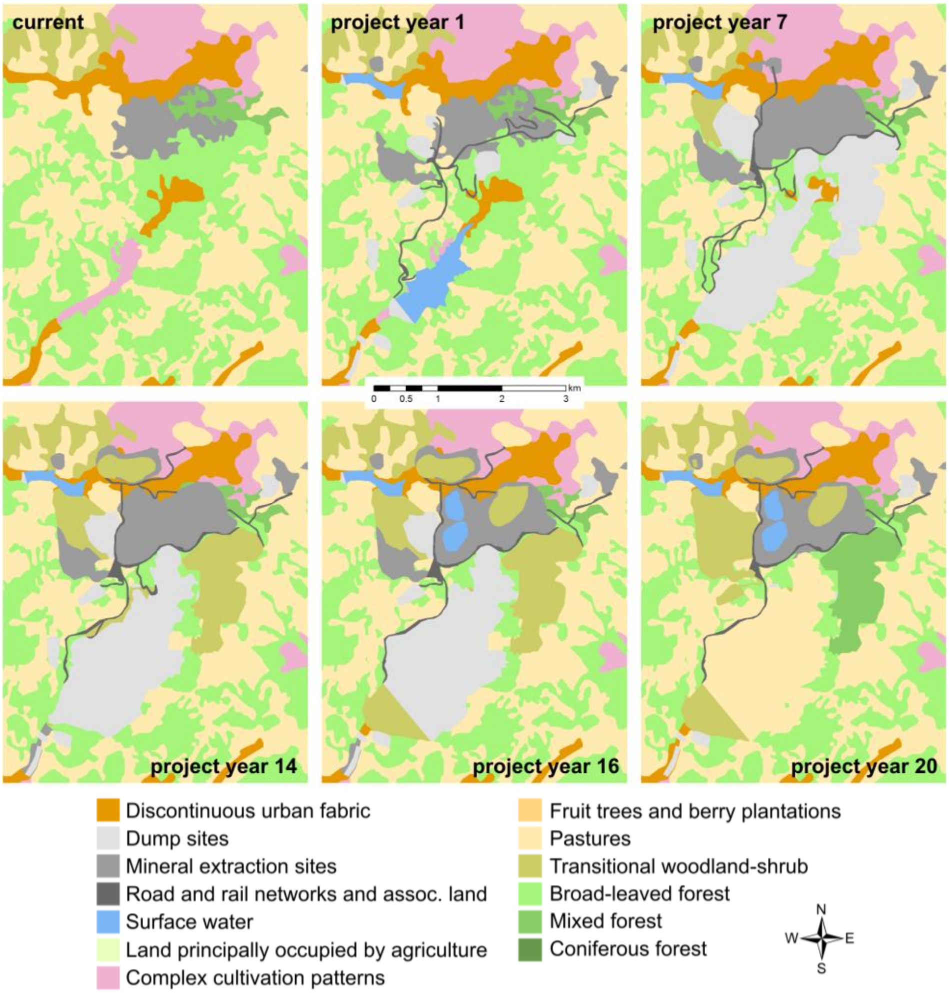

Fig. 7 Results of simulated CLC maps for each mapped project stage

One of the derivatives of the generated terrains was a time-series with the changes in elevation values during the project, shown in Fig. 8.

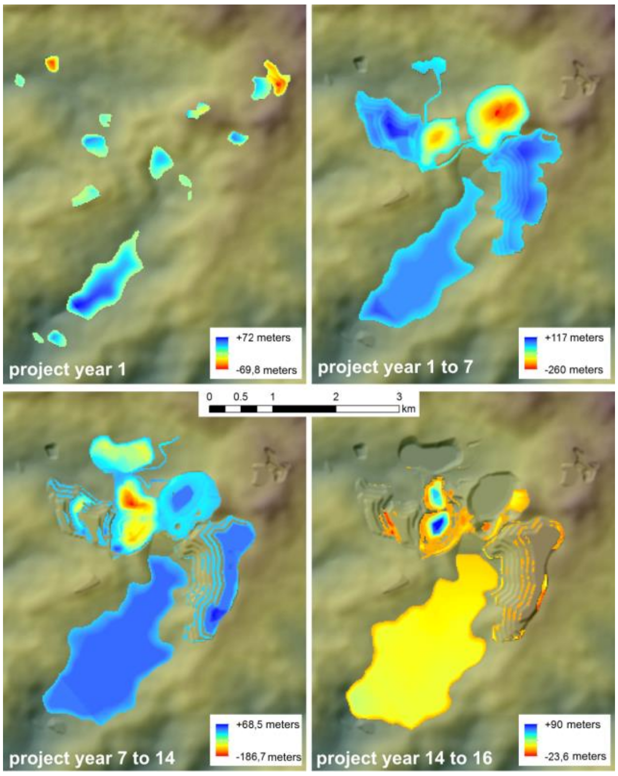

Fig. 8 Elevation changes in the study area

The generated terrain models allowed for the calculation of the volume of the relocated materials between each stage. The resulting figures are only estimates; their accuracy depended on the spatial resolution of the input surface models (20 metres) and the accuracy of the baseline, refined EU-DEM data.

One additional issue regarding the volume changes was that one of the four main mining pits (called Jig) did not appear in the RMGC maps in its excavated state. The plan for year 7 showed nothing in its area, while the one for year 14 showed that the pit has already been completely filled back with material. This meant that the volume of rock moved from and to Jig was left unknown. Table 2 lists the calculated amounts, with the limitations described above.

The calculations reveal that 529 million cubic metres of rocks and other materials are going to be relocated during the 16 years of active mining. The RMGC map after year 16 showed no changes in the terrain, mostly because the focus during those years is on reclamation of the disturbed areas. The two pit lakes in the Cetate pit and the extraction surfaces in neighbouring Carnic and Orlea pits will remain untreated as mining exhibits. The tailings pond is planned to be reclaimed as low value grazing land or managed grassland. The toxic compounds within the tailings material will require several decades to decompose properly into less dangerous chemicals, but the topsoil would be transported from stockpiles collected from other areas beforehand. The relocated materials were also visualised in a series of maps. The blue areas are those where material has been removed, the red patches cover the areas where material has been deposited (Fig. 9).

Table 2 Results of volume change calculations for each stage and the full project duration (thousand cubic metres)

Mining feature	Present – yr. 0	Year 0 – 7	Year 7 – 14	Year 14 – 16	Total
dump North of tailings pond	2,216.80	0	0	0	2,216.80
sandstone quarry	-1,256.82	0	0	0	1,256.82
andesite quarry	-3,313.85	0	0	0	3,313.85
andesite quarry waste dump	1,334.66	0	0	0	1,334.66
topsoil pile south of tailings dam	1,005.98	0	0	0	1,005.98
Carnic waste dump	1,029.49	45,551.14	14,778.60	0	61,359.23
Carnic pit	-127.53	-71,514.01	-47,862.92	-91.77	-119,596.23
Cetate pit	0	-23,955.94	-45,190.33	0	-69,146.27
Cetate waste dump	2,420.90	26,951.20	0	-297.72	29,074.38
Orlea pit	0	-274.69	-18,482.88	0	-18,757.57
Cetate lakes (water)	0	0	0	9,193.02	9,193.02
tailings reservoir	20,549.74	59,741.77	81,059.31	52,385.16	213,735.98
Total volume of relocated material (absolute value)					529,990.79

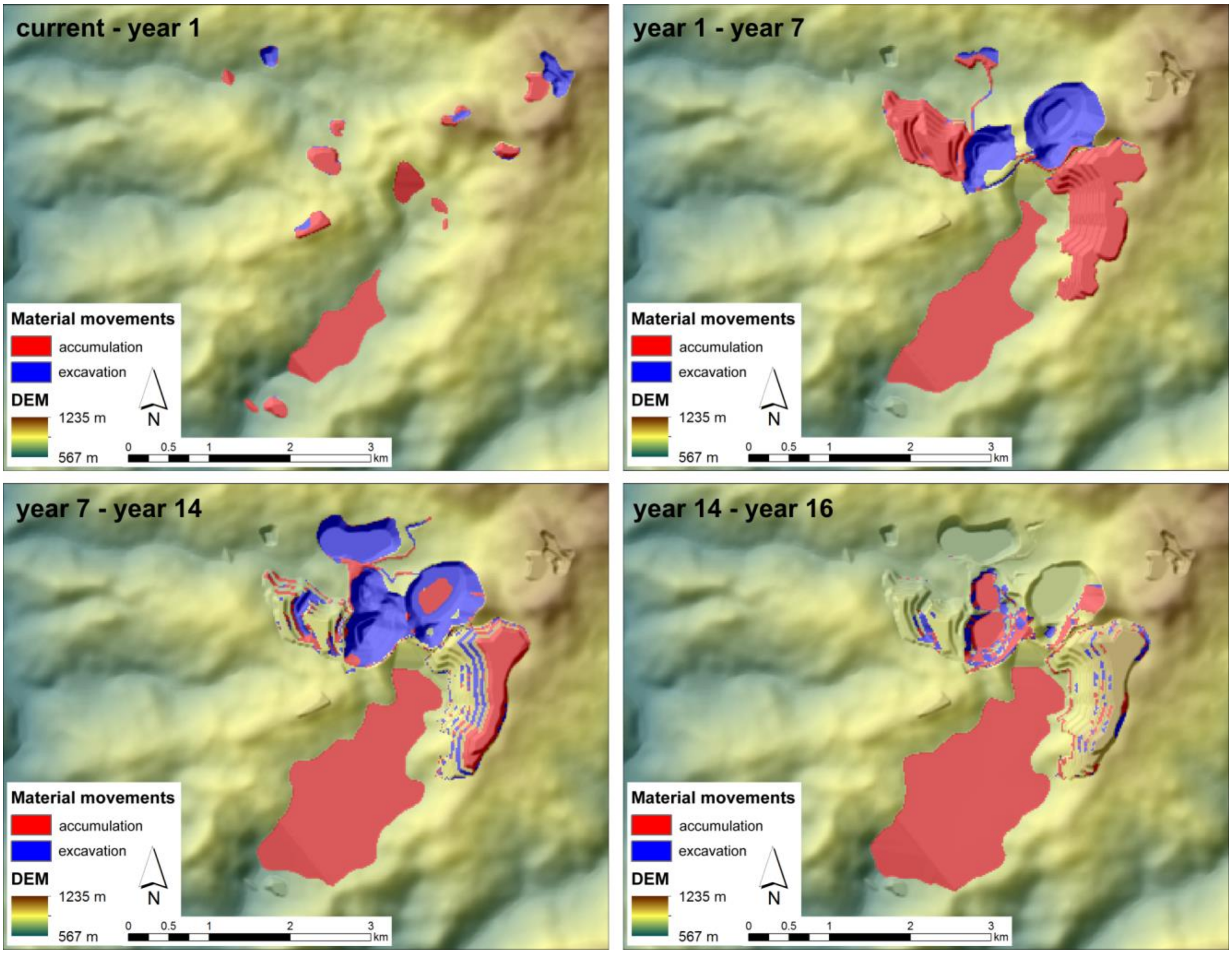

Fig. 9 Areas of material relocation during the stages of the project

DISCUSSION AND CONCLUSIONS

Environmental or infrastructural investments triggering significant changes require comprehensive impact assessment. Spatial decision support systems include tools enabling the creation of alternative scenarios. They also offer access to visual information and visual analytics functionality. These capabilities made such systems widely applied and an essential part of analyses of possible future geo-scenarios (Sheppard and Cizek, 2009; Pettit et al., 2011; Sheppard, 2012). The NIMBY syndrome ("not in my backyard" attitude expressing low public acceptance or opposition by residents to new proposals) is a frequently experienced situation (Wolsink, 2007). Landscape modelling extended by advanced visualisation methods for communication of landscape futures scenarios to stakeholders can enlighten hidden aspects of projects facilitating better understanding of pros and cons (Pettit et al., 2011).

The analyses performed on the simulated terrain data covering the area of the largest open cast gold mine in Europe have also revealed several results unforeseen without the presented unconventional, combined environmental and digital elevation modelling techniques (Barton et al., 2015). Some of these offer deeper insight into information already known from the RMGC EIA reports and studies (Haiduc, 2003; Paşca, 2010; RMGC, 2015), but some shed light on previously unknown consequences or details.

The terrain modelling processes developed during the research offer much more usable surfaces by combining the best characteristics of raster and vector methods, as the planned surface requires them. They allow the analyst to simulate terrain changes based on nothing more than the maps of the planned developments. The visual impact simulation process (performed by editing satellite images using standard graphics software) offers an inexpensive, efficient and creative way to visualise the changes in the landscape. The resulting terrain and image data can be displayed in 3D images and animations for better explaining the results to the community.

Area and volume calculations show that approximately 0.5 cubic kilometres of rock and other materials would be relocated during the planned mining project. When this amount is compared to the 300 metric tons of gold and 1600 tons of silver RMGC is expecting to extract we can see how disproportionate it is. The relatively low grade of the deposits in the area results in a very large impacted zone (934 hectares), 1/3 of which is taken up by the tailings pond in Corna Valley. This will contain more than 200 million cubic metres of waste material left behind from the cyanide leeching processes and will require close monitoring and management for several years after the project is closed.

The toxic compounds will make any meaningful land use very difficult in the future while it poses a potential threat to both the environment and the health and safety of the population downstream. Having a 180-metre high dam just 1700 metres from a town of 5000 people (Géczi et al., 2005), which is holding back thousands of tons of toxic sludge can easily be called irresponsible. Unless all the safety and building material requirements are strictly enforced, the dam will be liable to failure and this disaster would certainly have a severe impact on the River Maros. The river flows through densely populated regions of Central Western Romania, much of which relies on the river for irrigation and drinking water. Since there are already numerous mining operations in the region acting as additional pollution sources, it is very difficult to rationalise the introduction of such a high risk factor into the system. Thinking back on ecological and subsequent economic consequences of the Tisza cyanide disaster in 2000 (caused by a fraction of tailings material than what is planned in Roşia Montană) it is easy to imagine how severe an impact a dam breach would cause.

The modelling shows that the project would irrevocably turn the area into a highly industrial landscape. While it is true (if the company can live up to its word) that many of the currently observable pollution sources would be eliminated, we cannot forget about the new potential risks that would be introduced, especially the tailings reservoir. It is also very flexible whether the company can actually offer the amount of employment opportunities it is advocating in it campaign for the mine. Moreover, this amount will inevitably decrease with time as new and more efficient technologies are constantly being developed.

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DROUGHT MONITORING WITH SPECTRAL INDICES CALCULATED FROM MODIS SATELLITE IMAGES IN HUNGARY

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Abstract
In this study a new remote sensing drought index called Difference Drought Index (DDI) was introduced. DDI was calculated from the Terra satellite's MODIS sensor surface reflectance data using visible red, near-infrared and short-wave-infrared spectral bands. To characterize the biophysical state of vegetation, vegetation and water indices were used from which drought indices can be derived. The following spectral indices were examined: Difference Vegetation Index (DVI), Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Difference Water Index (DWI), Normalized Difference Water Index (NDWI), Difference Drought Index (DDI) and Normalized Difference Drought Index (NDDI). Regression analysis with the Pálfai Drought Index (PaDi) and average annual yield of different crops has proven that the Difference Drought Index is applicable in quantifying drought intensity. However, after comparison with reference data NDWI performed better than the other indices examined in this study. It was also confirmed that the water indices are more sensitive to changes in drought conditions than the vegetation ones. In the future we are planning to monitor drought during growing season using high temporal resolution MODIS data products.

Keywords: drought, remote sensing, MODIS, monitoring, spectral indices

INTRODUCTION

Climate change is one of the most significant issues facing the world because it is predicted to alter climate patterns and increase the frequency of extreme weather events. In recent years, the frequency of droughts that are due to global warming-related climate change has increased and is accompanied by a rise in the severity of these phenomena (IPCC, 2013; Trenberth et al., 2014). In our days – also in the Carpathian Basin – one of the environmental problems waiting for solution is water shortage, which is one of the biggest hazards, that causes serious damages especially in agriculture in drought-stricken years (Rakonczai, 2011). We are talking about water shortage if water supply falls short on human demand and wildlife needs. It can be caused by the limitations of available resources or the insufficient level of utilization of those or/and the increase of society's needs. According to the guide of the International Commission on Irrigation and Drainage (ICID), when precipitation cannot satisfy water needs, because there is a big deficit compared to normal or expected, which extends to growing season, or longer periods too, then there is drought.

It is hard to define the beginning and the end of droughts and quantifying its effects. Meteorological drought is characterized by the substantially less rainfall compared to multi-year average, this coupled with air temperatures exceeding the average and low relative humidity. This directly affects agricultural production (agricultural drought), which is most often visible on the physiological condition of plants to the naked eye, or can be seen from satellite above. Depending on the duration and the strength of meteorological drought, the soil moisture content decreases to the fraction of available water capacity (soil drought). If the catchment area is hit by meteorological drought, runoff and water level of reservoirs, lakes and rivers decreases which is called hydrological drought. The magnitude of drought is influenced by local conditions, e.g. more porous, thicker topsoil can absorb and store more usable water (Heim, 2002; Pálfai, 2004; Hao and Singh, 2015).

In addition to the economic damage caused by persistent drought, social damage can occur too (e.g. high prices, restrictions of water usage), as well as drought could amplify the existing vulnerability of the social classes (Wisner et al., 2004). There is socioeconomic drought when demand for economic goods, as the result of deficit connected to water supply, exceeds the human supply (Wilhite and Glantz, 1985). The Hungarian economy is frequently hit by droughts which are partly due to the unexploited water potential.

Drought is a relative rather than an absolute condition that needs to be interpreted separately in every region and on every group of organisms. Every drought differs from one another in intensity, duration and spatial extent. In agricultural point of view, drought is a substantial degree of water shortage of stand of croplands and forests which greatly limits the life processes of plants. Without a plant drought cannot be interpreted since different plant species react distinctly to the same level of drought (Anyamba and Tucker, 2012).

With the drought assessment in a quick and cost-effective way, with even the possibility of forecasting, it may become possible to increase adaptability of water retention. Optimization of the redistribution of water resources may become possible if location is known where greater need for them is. We could prepare for drought or at least moderate its damages by filling up reservoirs (partially) satisfying irrigation and ecological needs if necessary. Remote sensing methodology provides one of the ultimate tools that support the water management organizations' operational work

VULNERABILITY AND SOME INDICATORS OF DROUGHT

Risk is the combination of the probability of an event and its negative consequences which is the intersection of hazard, vulnerability and exposure. Vulnerability which is inversely related to coping capacity is the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard (UNISDR, 2009).

In drought monitoring there are many meteorological-statistical method and remote sensing based indices; more than a hundred of them is known (Faragó et al., 1993; Zargar, 2011). The one developed by Palmer (1965) in the US, which is calculated from precipitation, temperature and soil moisture content data, is the so-called Palmer Drought Sensitivity Index (PDSI) that has been used in Hungarian study areas too (Horváth, 2002). For the Standardized Precipitation Index (SPI) at least 30 years long precipitation dataset is needed. The gamma distribution fitted on the empirical probability distribution of the dataset has to be transformed to normal distribution; the probabilities are the SPI values (McKee et al., 1993). This analysis method is very popular (Hayes et al., 2012) in Hungary too (DMCSEE, 2010-14; Blanka et al., 2014).

Mu et al. (2013) used a drought index called Drought Severity Index (DSI), which can be generated from the ratio of evapotranspiration and potential evaporation (ET/PET), resp. Normalized Difference Vegetation Index (NDVI), for MODIS sensor data.

The basic version of Pálfai Drought Index (PAI), which is commonly applied in Hungary, is calculated from meteorological (daily temperature and precipitation) datasets and we get its actual value when we multiply its base value with empirical correction factors (Pálfai, 1989). Fiala et al. (2014) are analyzing the simplified version of PAI (PaDI) in Hungarian and Serbian areas with GIS processing; PaDI is calculated from monthly average temperature and monthly average precipitation dataset.

Spectral indices derived from measurements of multispectral sensors like the ones analyzed in our study could be a great addition to their method as well. Kovács (2007) and Ladányi et al. (2011) identified high drought risk areas based on time series of biomass productivity from Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI)

DATA AND STUDY AREA

Drought indices calculated from Terra MODIS satellite images may become suitable in monitoring short term spatiotemporal variations in drought intensity at regional scale. High temporal resolution allows analyzing environmental change processes. In the course of data processing, several pre-calibrated and evaluated products are manufactured which are available free of charge (e.g. GLOVIS database). MODIS-composites are compiled from the optimal selection of pixel values of satellite images recorded during the period of 8 or 16 days. Cell values of composites are always made of the best data quality pixels available (Huete et al., 2002; Vermote and Kotchenova, 2008). Selection covers the viewing and illumination geometry, the state of the atmosphere and the amount of cloud cover e.g. the first half of July is one of the most suitable dates, because precipitation in this month has the maximum weight since plants require a lot of water in July. In addition, the occurrence of a drought is the most likely in this month (Pálfai, 2004). However, after harvest it is inappropriate to choose a date, because harvested croplands can be classified as drought-stricken (e. g. time range of wheat

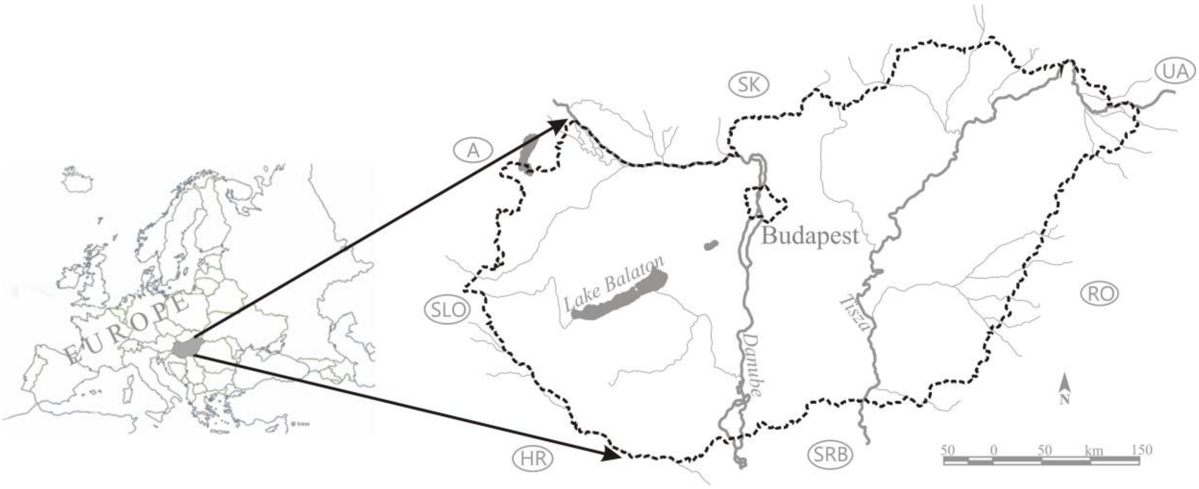

Fig. 1 Hungary, the study area

harvest in Hungary is from the end of June to middle of July). For our analysis we have chosen two dates: one from June and another one from July (Fig. 1).

For the calculation of spectral indices MOD09A1 (Collection 5) 500 m resolution 8-day surface reflectance composite images (Surface Reflectance 8-Day L3 Global 500m SIN Grid) between 2000 and 2014 were used (Table 1). Spectral band values are multiplied by a factor of 10,000. Images are from the 9-16th (resp. 10-17th) of June (resp. 10-17th) and the 12-19th (resp. 11-18th) of July. In some instances different periods were chosen because of high cloud cover. The 16-day 500 m resolution EVI composite images (MOD13A1 EVI, Vegetation Indices 16-Day L3 Global 500m SIN Grid) were obtained for the period of 9-24th (resp. 10-25th) of June and of 11-26th (resp. 12-27th) of July. Records from the MODIS catalog H/V 19/4 (Lat/Long 45/21.1) were downloaded from GLOVIS database [1]. The composites are not allowing observing changes on daily scale or less than 8 or 16 days long time periods, but they are still very good at monitoring changes for longer periods.

Table 1 Spectral bands of MOD09A1 surface reflectance 8-day composites (Vermote and Kotchenova 2008)

MOD09A1 bands	wavelength (nm)
1 (visible red)	620-670
2 (near infrared)	841-876
3 (visible blue)	459-479
4 (visible green)	545-565
5 (SWIR 1)	1230-1250
6 (SWIR 2)	1628-1652
7 (SWIR 3)	2105-2155

SWIR: short-wave infrared

Quality Control and State Flag created for the spectral bands provide information about each pixel's data quality, accuracy and consistency (e.g. cloud cover and cloud shadow, dead detector and data interpolated, value out of bounds, aerosol quantity of the air, zenith angle of sun). The quality control and state bands are storing metadata as decimal numbers which have to be converted into 16, resp. 32 bit binary series to extract information needed for pixel evaluation.

Before using MODIS data, incorrect, inaccurate or inconsistent pixel values have to be excluded from analysis. The processing tools (LDOPE Tools and MODIS Reprojection Tool) provided by the MODIS land quality assessment group (Roy et al., 2002) were applied at the extraction of quality, cloud cover and cloud shadow mask from the 16/32 bit binary quality and state bands. General rule is that the lower the value, the better the quality. Zero means that there are no quality issues. The pixel values defined as incorrect were overwritten by the pre-defined no data value of spectral bands (−28,672). For the execution of this operation a program was written in C language (named MODIS Quality Control Tool) which reads in data in ASCII grid file format. We have taken the following bits into consideration with the conditions for pixel evaluation shown in Table 2. The predefined no data value for MOD13A1 data is −3000. The strictness of specified conditions in case of MOD09A1 and MOD13A1 data are very much alike. Data accuracy is determined by inaccuracies of cloud filtering, variable viewing and illumination geometry, different amount of cloud filtered data for averaging, inaccuracy of atmospheric correction. Database can also be cleaned if we are not taking into consideration satellite passes with higher than 40° zenith angle or providing less than 25% data coverage (Huete et al., 2002).

Data processing and analysis was performed in open-source geospatial software environment, the following programs were used: SAGA GIS 2.1, QGIS 2.4-Chugiac (Python 2.7.5, GDAL 1.11.0 and GRASS GIS 6.4.3 integrated into QGIS), R for Windows 3.1.2, MODIS Reprojection Tool 4.1, LDOPE Tools 1.7, and own programs written in C language in Code::Blocks 10.05 environment. Processing was automatized by the use of scripts.

METHODS

Characterization of spectral indices

A new method for drought delineation using MODIS surface reflectance data was presented in the paper by Gu et al. (2007). It is called Normalized Difference Drought Index (NDDI). NDDI (Eq. 1) is derived from NDVI and NDWI (Normalized Difference Water Index):

$$\mathrm{NDDI} = (\mathrm{NDVI} - \mathrm{NDWI}) / (\mathrm{NDVI} + \mathrm{NDWI}) \qquad \text{(Eq.1)}$$

where:
$\mathrm{NDVI} = (\mathrm{NIR}_{858\,\mathrm{nm}} - \mathrm{red}_{645\,\mathrm{nm}}) / (\mathrm{NIR}_{858\,\mathrm{nm}} + \mathrm{red}_{645\,\mathrm{nm}})$,
$\mathrm{NDWI} = (\mathrm{NIR}_{858\,\mathrm{nm}} - \mathrm{SWIR}_{2130\,\mathrm{nm}}) / (\mathrm{NIR}_{858\,\mathrm{nm}} + \mathrm{SWIR}_{2130\,\mathrm{nm}})$,
NIR: near infrared, SWIR: short wave infrared.

Table 2 Pixel evaluation of MODIS satellite images using the quality assessment bands

MOD09A1	MOD13A1
State Flags: 0-1. bits: Cloud State (=0) 2. bit: Cloud Shadow (=0) Quality Control: 2-5. bits: 1st band's data quality (=0) 6-9. bits: 2nd band's data quality (=0) 26-29. bits: 7th band's data quality (=0)	VI Quality detailed QA: 0-1. bits: VI Quality (MODLAND QA bits) (<=1) 2-5. bits: VI Usefulness (<=4) 15. bit: Possible shadow (=0) Pixel reliability QA summary (<=1).

NDVI was developed by Rouse et al. (1973), and it has been in use for decades for monitoring vegetation cover, chlorophyll content and other properties of the plants. Absorption of healthy vegetation is very high in the visible wavelength range. On the other hand, the near infrared channel is located at the high reflectance plateau. Dry and unhealthy vegetation canopy has lower NDVI value because reflectance in the visible red channel is increased, simultaneously in the NIR channel decreased. If chlorophyll content is high, then it means that the plant is photosynthetically very active, which means high absorption in visible red and high reflectance in NIR channels.

NDWI represents the water content in vegetation canopies. Absorption by vegetation liquid water around 858 nm (NIR channel, at the high reflectance plateau of vegetation canopy) is negligible, while at around 2130 nm it is very high. If water content decreases, then in SWIR channels reflectance increases significantly, therefore the NDWI value decreases showing dry vegetation under drought stress.

Chen et al. (2005) used spectral indices calculated from $NIR_{858\ nm}$ and $SWIR_{1640\ nm}$, respectively $SWIR_{2130\ nm}$ bands of MODIS reflectance data for the estimation of moisture content of corn and soybeans. Both showed potential in estimating vegetation moisture content. This NDWI is the variation developed by Gao (1996). The study conducted by Gu et al. (2007) showed that NDWI has a stronger response to drought conditions than NDVI. The average of NDVI and NDWI were consistently lower ($NDVI<0.5$ and $NDWI<0.3$) under drought conditions than under non-drought conditions ($NDVI>0.6$ and $NDWI>0.4$)

At shallow, turbid waters the water-leaving reflectance at NIR is not negligible, and is not only related to phytoplankton abundance, but also to suspended sediment concentration. Atmospheric correction of MODIS (the “clear water” assumption) fails in the presence of even modest quantities of suspended particle matter, because NIR water-leaving reflectance is not negligible, and is not related to phytoplankton abundance (Chen et al., 2013; Wang et al., 2013). Because of that, some parts of water surfaces are being classified as drought-stricken in case of NDWI and the drought indices. It is the reason why the area of Lake Balaton was excluded from our analysis.

During calculation of NDDI, most of the values are transformed into an interval between −1 and +1, however in spite of quality control extreme out of range values are generated too that makes statistical analysis useless. With the use of difference drought index (DDI) the emerging of extreme out of range values was avoided. It is the reason we calculated simple difference index without normalization (Eq. 2):

$$DDI = DVI - DWI \qquad \text{(Eq. 2)}$$

where:
DVI (Difference Vegetation Index) = $NIR_{858\ nm} - red_{645\ nm}$,
DWI (Difference Water Index) = $NIR_{858\ nm} - SWIR_{2130\ nm}$.

The lack of normalization, which gets rid of the differences in spectral radiance resulting from different illumination angle and slope, is the only disadvantage DDI has, but the greater part of Hungary is lowlands with the dominant land use of croplands, therefore it is a small concern.

The Enhanced Vegetation Index (EVI), as an optimized hybrid index, combines the characteristics of the Atmospheric Resistant Index (ARVI) and the Soil Adjusted Vegetation Index (SAVI). EVI is an NDVI variant with correction factors for minimizing atmospheric effects and removing soil-brightness induced variations (Solano et al., 2010). The EVI formula is written as (Eq. 3):

$$EVI = G \cdot ((NIR_{858\ nm} - red_{645\ nm}) / (NIR_{858\ nm} + C_1 \cdot red_{645\ nm} + C_2 \cdot blue_{469\ nm} + L)) \qquad \text{(Eq. 3)}$$

where NIR, red and blue band values are atmospheric-corrected (for Rayleigh scattering and ozone absorption)

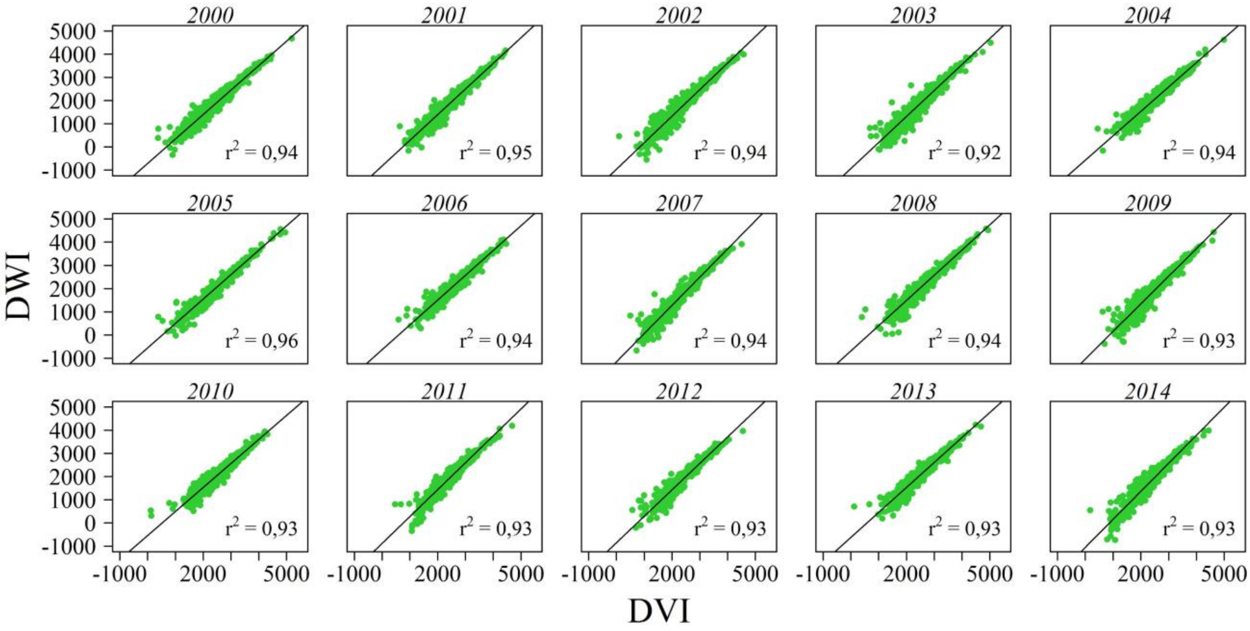

Fig. 2 The connection between DVI and DWI on the examined date in July

surface reflectance; L is the canopy background adjustment for correcting nonlinear, differential NIR and red radiant transfer through a canopy; C_1 and C_2 are the coefficients of the aerosol resistance term (which uses the blue band to correct for aerosol influences in the red band); and G is a gain or scaling factor. The coefficients adopted in the EVI algorithm are, L=1, C_1=6, C_2=7.5, and G=2.5.

Statistical connections between DWI-DVI and NDWI-NDVI

Relationships between DWI-DVI and NDWI-NDVI were unfolded using linear regression analysis which we run for a random sample of 500-600 pixels. We used the same random pixels for each date. There is a strong link between DWI and DVI; coefficients of determination vary from 0.88 to 0.95 in June, and 0.92-0.96 in July. Connection between NDWI and NDVI is weaker, coefficients of determination show greater variability (r^2 are 0.66-0.85 for June and 0.78-0.91 for July) (Fig. 2).

NDVI has been applied for decades in vegetation monitoring (Rouse et al., 1973). High correlation has proved water indices to be capable of quantification of droughts. There is a strong connection between chlorophyll and moisture content of vegetation canopy for which are vegetation and water indexes proxies that proves the usability of water indices.

RESULTS

Spatial extent of drought-stricken areas based on DDI and NDWI

When defining the value range of drought classes one huge advantage cluster analysis or other automatic classification algorithms have that we extract information from data without subjective interference. We used a cluster analysis method by Forgy (1965) called Iterative Minimum Distance for DDI data. Best results were obtained when setting eight outgoing clusters. Before the first iteration data was normalized with standard deviation. Separate classes were created, each containing pixels with similar drought intensity.

We calculated the DDI average for each date and the average of all June and July records between 2000 and 2014 (DDI_{June}=505.67 and DDI_{July}=520.95). If DDI mean exceeds these thresholds than the given time period is considered to be drought-stricken. Based on the rule June was drought-stricken in 2000, 2001, 2002, 2003 and 2009, and in case of July in 2000, 2001, 2002, 2003, 2007, 2009, 2012 and 2014. After that we averaged the DDI averages of drought years (DDI_{June}=578.86 and DDI_{July}=586.25) to get the drought threshold limits of DDI. The cluster mean of drought clusters exceeds these threshold limits. The difference between the average of drought and non-drought years referring to time series of the two months is 122 and 140 (June and July respectively). Based on class means we separated 4 drought intensity categories from the classes in the examined periods (Table 3). The DDI threshold of July (650) based on the cluster means between drought and non-drought is higher than the average of DDI (586) in drought years. The average of DWI, which is one of the factors influencing DDI values, is 1856 in drought years while it is 2197 in mild and wet years in July. In case of DVI, the other factor, these values are 2442 and 2639 respectively. By the differences DWI reacts more sensitively to drought condition than DVI. In case of the June values compared to the July ones DWI shows less, but still higher difference (189) between drought (2082) and non-drought (2271) average than DVI (difference is 107. Water indices are more sensitive to drought conditions than the vegetation ones. In order to utilize the high sensitivity of water indices we calculated the drought categories based on the vegetation liquid water content for NDWI too (Table 3).

Table 3 Created drought categories based on DDI and NDWI

DDI categories	Description
DDI <0	wet, water cover
0<= DDI <650	no drought
650<= DDI <812	weak drought
812<= DDI <1053	moderate drought
1053<= DDI <1319	strong drought
1319<= DDI	very strong drought

NDWI categories	Description
0.7<= NDWI	very high moisture content
0.6<= NDWI <0.7	high moisture content
0.6<= NDWI <0.5	moderate moisture content
0.4<= NDWI <0.5	low moisture content
0.3<= NDWI <0.4	weak drought
0.2<= NDWI <0.3	moderate drought
0<= NDWI <0.2	strong drought
NDWI <0	very strong drought

After defining drought categories for NDWI, we excluded the weak drought class because compared to DDI we would have overestimated the spatial extent of droughts. In case of NDWI pixels with value under 0.3 are considered to be drought-stricken. The results from DDI and NDWI coincide very well (r^2=0.91). Spatial extent of droughts for July is shown in Fig 3.

Average spatial extent of drought according to DDI was 22,778 km^2 in July. Average area was exceeded in 2000, 2001, 2002, 2003, 2007, 2009, 2012 and 2014. Spatial extent of drought was lowest (7,669 km^2) in 2005 according to DDI, but in case of NDWI in 2004 (7,454 km^2). The biggest drought was in 2007 which hit 42,452 square kilometers according to DDI. On the other hand NDWI showed that the spatial extent of drought was greatest in 2000 (35,846 km^2), however area hit by strong and very strong drought peaked in 2007 (in case of DDI the moderate drought areas culminated as well). In the ranking 2007 and 2000 are followed by 2003 and 2002 in July.

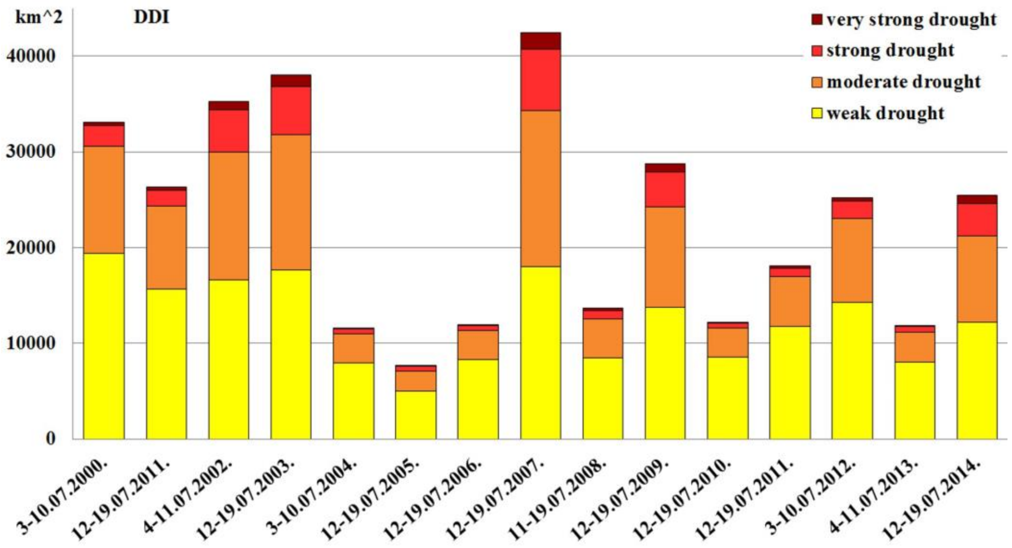

Fig. 3 Extent of drought affected areas in July according to DDI

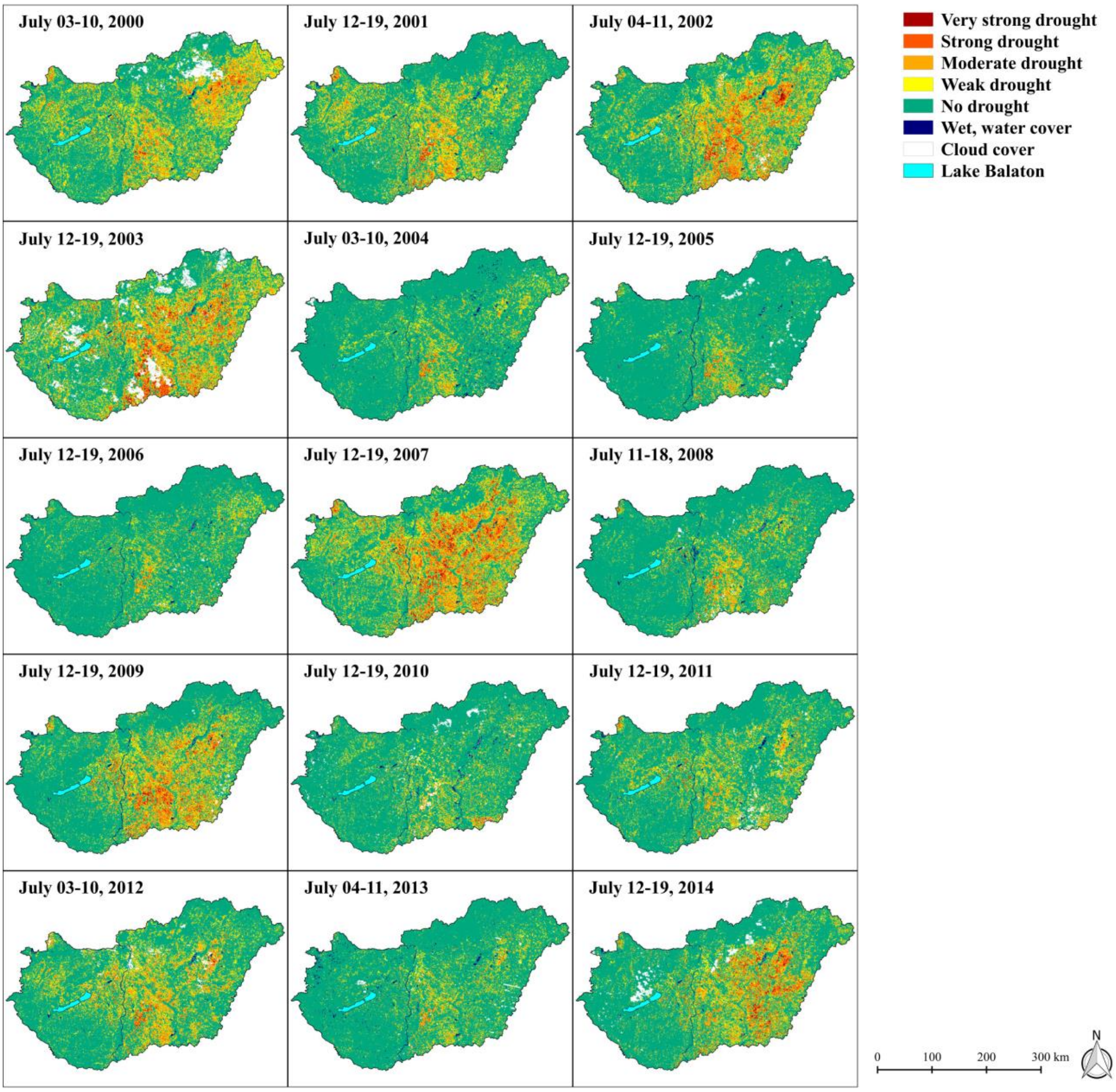

Fig. 4 Geographic distribution of drought areas according to DDI in July

DDI averages in June and in July show a great divergence in 2007 indicating that drought appeared first in July. In contrast, drought in 2003 was noticeable too. The difference between consecutive years stands out in 2003-2004 and in 2006-2007. In addition, higher annual variability between 2006 and 2010 is worth for mentioning. Geographical distribution of drought based on DDI and NDWI in July are shown on Fig. 4 and *5* where the high vulnerability of Danube–Tisza Interfluve stands out very well.

Comparison of results with reference data

To test the validity of spectral indices we analyzed their relationship with the Pálfai Drought Index (PAI) for the whole country and for the Great Plains only. Based on Pálfai (2011) the western border of the Great Plains was set to the midstream of River Danube. PAI data was obtained from the discussion paper of the National Drought Strategy (Hungarian Ministry of Rural Development 2012).

We compared the spectral index averages with the following reference data provided by CSO [2, 3]: crop yields of cereals (wheat, durum wheat, rye, barley, oat, triticale, corn, maslin (mixture of wheat and rye), rice, other cereals (indian rice, millet, canary seed, sorghum, buckwheat)) between 2000 and 2013, corn and wheat yields between 2000 and 2012 and irrigation water use of agriculture (labeled as „all sold water for irrigation, rice production included"). These data only applies to agricultural land, therefore we clipped DDI data with the area of the „non-irrigated arable land" category of the Corine Land Cover Database (CLC2012) [4]. In our current study we could only relate yields of different crops and irrigation data to the area of croplands based on CLC2012. Because of the lack of available data we could not differentiate between the fields of different cereals. Croplands can be identified in the knowledge of the dataset, since crops with similar growing cycle develop in a similar matter in a given year (Kern et al., 2014).

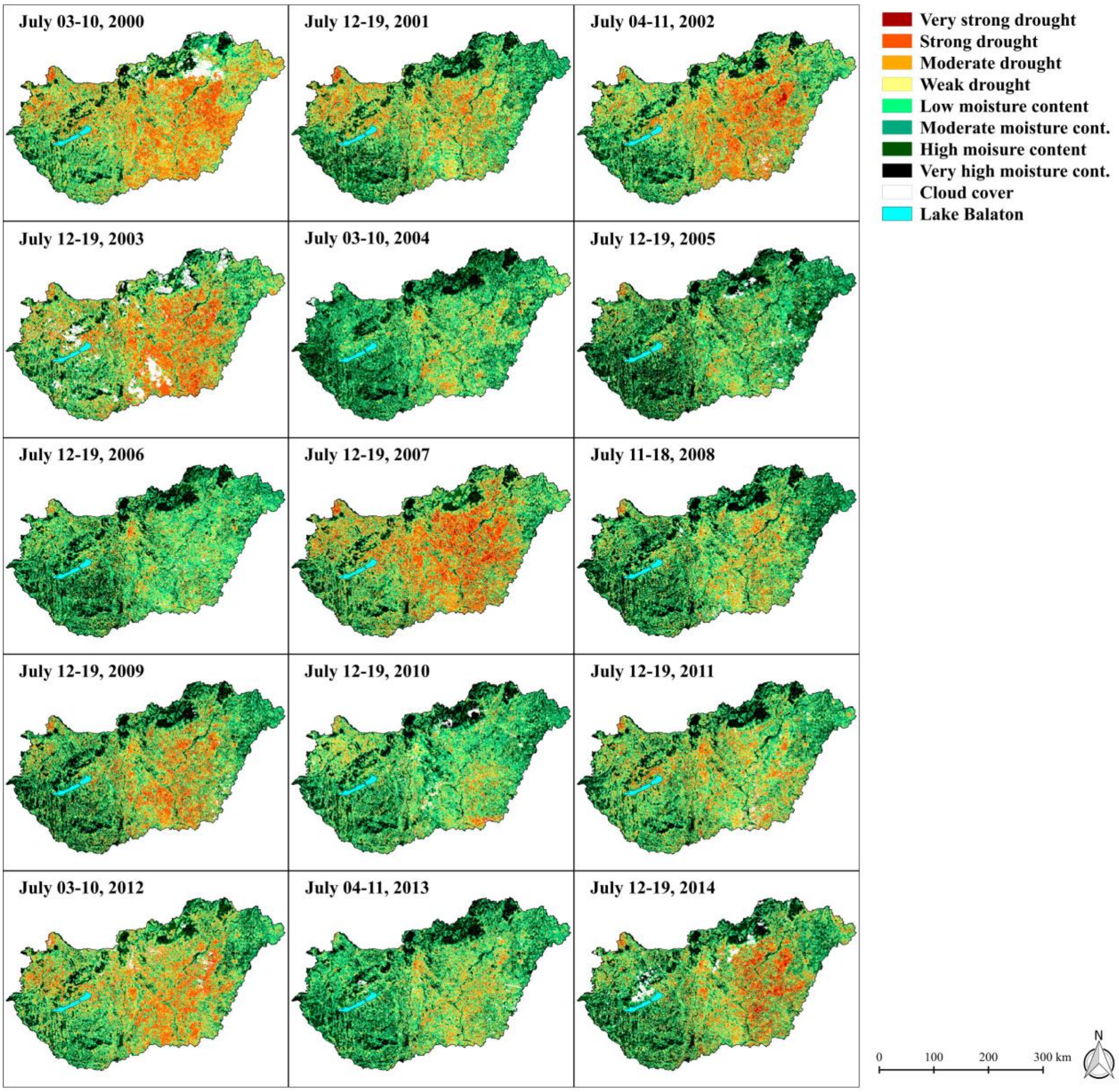

Fig. 5 Geographic distribution of drought areas according to NDWI in July

The spectral index values in June did not perform as well as the July ones. The spectral index-PAI relationships were weak and statistically insignificant except for DDI and NDDI, which performed slightly better (between DDI and countrywide PAI $r^2=0.54$, while between NDDI and PAI for the Hungarian Plain $r^2=0.52$). The correlations with yield data were very low, except for wheat-EVI ($r^2=0.62$) and wheat-DWI ($r^2=0.62$) correlations. No link was found with irrigation water use.

On the other hand, spectral indices performed well in July. The drought indices show positive trend with PAI; in contrast, vegetation and water indices a negative trend. Drought indices and crop yields are inversely related. Irrigation water use is directly proportional to DDI and NDDI. The opposite is true for vegetation and water indices: direct proportion to PAI and to crop yields and inverse proportion to water use. Normalized difference indices have a stronger link with reference data compared to simple difference indices, except for DDI which performed similar to NDDI (Table 4).

Based on the coefficients of determination in July, not the drought indices performed best, but NDWI. NDWI has the strongest link with PAI in case of the area of the Hungarian Plain, plus a strong one for the whole country as well. Strong statistical connections with all cereals' and corn yields were observed. In addition, NDWI has a moderate high correlation with agricultural water use. DWI is not far behind except for water use.

DDI has a strong link with PAI, but a weak one with agricultural water use; DDI shows moderate strong correlations with all cereals and corn yields.

PAI-DVI and PAI-EVI links were the weakest among the indexes, but EVI and DVI show a bit stronger link with corn yield data then DDI or NDDI. The NDVI-PAI relationship is stronger; in case of all cereal and corn yield data NDVI performed similar to DVI. Connections with irrigation water use were mostly weak; highest in case of NDVI and NDWI. In the harvesting period of wheat, we compared the spectral index averages of the harvested fields with the yields too, so the regression results for wheat which are statistically insignificant are not valid for July.

DISCUSSION

Although DDI performed adequately in drought detection, it may not be the best choice. On the whole, NDWI shows stronger links to reference data then the other spectral indices.

At the evaluation of results we have to take into consideration that crop yields are influenced by a number of environmental factors besides droughts: harvesting date is not constant it varies annually depending on how much precipitation there is, growing degree units plants get, coping capacity or tolerance of different crops, e.g. Besides drought, cold and wet weather, inland excess water, pest or an extreme weather event like rainstorm or hailstorm can also damage crop yields. Coping capacity of the plants is different; soil properties like fertility, water holding capacity, permeability have an influence on the yield too. Strength of the link between spectral indices and crop yields varies between months or years and between different areas as well.

The Difference Drought Index detects agricultural drought (via biophysical changes of the plants) whereas the Pálfai Drought Index rather detects meteorological drought (through precipitation and temperature time series). Moreover, the distance between meteorological stations is great (up to more than 10 kilometers) so the geometrical resolution of data is significantly less than 500 meters that MODIS reflectance data provides. Differences of spatial resolution may have influenced the tightness of linear fit. On the other hand, because of atmospheric effects some of the pixels had to be excluded from analysis may increase uncertainty of results. For our analysis we have chosen satellite images recorded in a relative cloud-free 8 day periods in order to keep errors originating from atmospheric effects at the lowest level possible.

CONCLUSIONS

The new remote sensing based difference drought index (DDI) performed above expectations during the analysis which is proven by the strong link between DDI and the PAI. Even though they combine water and vegetation

Table 4 Performance comparison of indices according to values of the coefficients of determination (r^2) in July

	Index	PAI (Hungarian Plain)	PAI (whole country)	All cereals [kg/ha]	Corn [kg/ha]	Wheat [kg/ha]	Irrigation water [million m^3]
MOD09A1	DDI	0.87	0.81	0.67	0.63	0.37	0.51
	NDDI	0.85	0.77	0.65	0.64	0.31	0.48
	DWI	0.81	0.75	0.79	0.77	0.47	0.52
	NDWI	0.90	0.80	0.80	0.78	0.48	0.64
	DVI	0.60	0.62	0.69	0.68	0.42	0.42
	NDVI	0.78	0.71	0.72	0.73	0.44	0.64
MOD13A1	EVI	0.63	0.67	0.81	0.76	0.41	0.35

indices, DDI and NDDI did not performed better compared to NDWI which is an ultimate vegetation moisture index. Our results imply that NDWI, which is a proxy for changes in moisture content of the canopy, reacts to drought conditions more sensitively than NDVI (or the other indices), because in case of a drought water loss occurs sooner than the reduction of chlorophyll content of vegetation. Because of its advantages, NDWI may become widespread in Hungary.

In the future we are planning to monitor drought during growing season using high temporal resolution MODIS data products in order to see how spectral indices react to seasonal variations of photosynthetic activity and moisture content of vegetation canopy in more detail.

Acknowledgments

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FACTORS RESPONSIBLE FOR RURAL RESIDENTIAL WATER SUPPLY SHORTAGE IN SOUTHEASTERN NIGERIA

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Abstract

Efficient water supply is very crucial to sustenance of socio-economic growth, poverty attenuation, and food security. In most rural areas of developing countries including Nigeria water supplies are not commensurate with demand leading to a shortfall in water use and many people suffer from this scenario. This research investigated the factors responsible for rural residential water supply shortage in Southeastern Nigeria. Data were collected through the use of four mixed but complimentary methods namely questionnaire survey, interviews, focus group discussions and secondary data sources. The data generated were analyzed through the use of descriptive and inferential statistical tools. Principal Component Analysis was employed to combine the variables accounting for water supply shortage into a few underlying dimensions. The results indicated that physical environment and inadequate water supply infrastructure; socio-economic and geographical location; management and socio-cultural problems are responsible for water supply shortage in the area. Residential water supply can be sustainable in the area by regulating the influence of these factors impacting on water supply as well as lessen the implications of water deficiency. The research concludes that the process of water supply development should be stepwise in accordance with the participatory and managerial capacity of communities.

Keywords: water supply constraints, sustainability, service delivery, community participation

INTRODUCTION

Clean, safe drinking water is scarce. Matter (1984) have recognized that water supply has been a primary logistical challenge since the beginning of civilization and balancing water demand and supply has been a major concern of all human society of all times. The objective of water supply is the provision of potable water on a constant basis which addresses security of supply across seasons, and between wet and dry years, and is also imperative if health and wider poverty mitigation benefits are to be met and sustained (Getis et al., 2008; Nwankwoala, 2011; Obeta and Chukwu, 2013). Worldwide, 663 million people lack access to safe water although there is regional variation. The populations without access to safe drinking water are mainly in Sub-Sahara Africa and Asia accounting for 84.33% of total. Of the 663 million people, 319 million people (51.88%) are in Sub-Saharan Africa while 260 million people (39.22%) are in Asia (WHO/UNICEF JMP, 2015; USBC, 2015). Sub-Sahara Africa has the largest population without access to safe water. Millions of people in rural communities and poor urban centers throughout this region suffer from lack of clean, safe water (The Water Project, 2015).

Safe drinking water provision in rural areas of Africa and Asia is a major challenge. Rural water supply is stalled by poor coordination, poor maintenance culture, poor technical institutional structure, multiple programs, lack of data for planning, overbearing bureaucratic control by various supervising ministries, lack of professional inputs in projects, lack of community participation, inadequate funding, irregular disbursements of subventions, inappropriate infrastructure as well as lack of clear policy direction, lack of focus in terms of goals and objectives which resulted in the country’s inability to achieve full coverage of the rural population with safe water supply (Katz and Sara 1997; Ajayi et al., 2003; Offodile, 2003; Oteze, 2006; Oyebande, 2006; Lockwood and Smits, 2011). In Africa, it is not easy to set up institutional arrangements that will ensure that drinking water facilities are provided, maintained, and managed in a well-organized, fair, and sustainable way (Bakalian and Wakeman, 2009; Sun et al., 2010). Providing safe drinking water in rural areas are mired by both market and government failures. The lack of incentives often shelve the private sector to invest in rural water supplies due to the high costs of infrastructure development and the high transaction costs of collecting fees for drinking water in such areas, especially if the awareness of the value of safe drinking water is limited and if people can easily opt for other water sources (Sun et al., 2010). Ensuring that government staff has sufficient funds and incentives to manage rural water facilities in a sustainable way are main challenges when government provide safe drinking water (Sun et al., 2010). To address these market and government failures, community-based approaches have been widely adopted yet, it is well-known that communities may also fall short of providing services effectively due to problems such as elite capture and limited capacity (Katz and Sara, 1997; Sun et al., 2010; Lockwood and Smits, 2011).

A fundamental shift from centralized ownership of water supply systems to local ownership and control has been experienced over the past decades (Harvey and Reed, 2003). Along with the shift comes a deviation from “supply-driven approaches” to demand based approaches”. The transition follows the market place economics principles: people pay for the upkeep of valued items while unvalued commodities are not paid for. Water systems deteriorate because they are installed in communities that do not value them. Katz and Sara (1997) analyzed the performance of water supply systems in six countries (Benin, Bolivia, Honduras, Indonesia, Pakistan and Uganda) and found that community participation significantly increased sustainability of water supply project.

However, despite the widespread application of community management of rural water supplies in Sub-Saharan Africa, the sustainability of such programs remains unsatisfactory (Harvey and Reed, 2007). Dewilde et al (2008) opined that the deep reliability of water systems and the capacity of communities to maintain and manage the systems need to be evaluated before you can make judgment on the effectiveness of safe water programs.

Analyzing the Economic Community of West African States (ECOWAS), Olokesusi (1990) noted that water supply situation in this region is unsatisfactory. The reasons for this have been the growing population and the water engineers’ shortfall in terms of scaling water projects in conformance with purpose. Most often water projects in this region are build beyond the capacity of the engineers to manage and maintain. Although the Millennium Development Goals (MGDs) target of reducing by half the population not having access to safe water supply have been achieved, figures are still high in Nigeria especially in rural areas (WHO/UNICEF JMP, 2015).

Policies to improve water supply in the country have been recommended. For instance, Obeta (2013) suggested that institutional reform, network rehabilitation, improved tariff, support by Local government authorities, human resource development, use of simple technology, setting up a rural development commission among other things are key actions to improve the water supply in rural areas. Nwankwoala (2011) emphasize the need to practice traditional approaches to water supply, the breakdown of sector boundaries and a search for new practical solutions. Uwazie et al. (2009) called on government to decentralize ownership and management of water supply systems to involve optimal community participation and support from the private sector. Onyenechere (2009) indicated that the participation of the private sector in water provision is necessary but needs strong regulations for public protection.

However, the implementation of recommended policies has been problematic. The reasons for this have been largely due to lack of political will and misappropriation of fund (Adewuyi, 2013). Despite the many agencies and programs for water supply in Nigeria, Nigerians still lack access to adequate water supply. In Southeastern Nigeria for instance, 80% of people in rural communities lack adequate access to potable water supply, they still depend on unprotected sources. The people trek long distances to fetch small quantity of water from the streams and springs (National Bureau of Statistics, 2008). Based on the foregoing, it is important to investigate the reasons why access to safe water supply remains inadequate in Southeastern Nigeria. This paper, based on principal research in six rural communities in Awgu local government area (ALGA) of Enugu State, Nigeria will attempt to access the nature of water demand and supply in the domestic sector, ascertain whether water demand is satisfied by supply, identify the factors responsible for water shortage and search for possible alternatives to the current water supply strategies.

STUDY AREA

This study was carried out in Awgu local government area of Enugu State, Southeastern Nigeria. Geographically, the area is located between latitudes 06^{o} 00’ and 06^{o} 19’ north of the equator and longitudes 07^{o} 23’ and 07^{o}35’ east of the Greenwich Meridian (Fig. 1). The area is bounded in the north by Udi and Nkanu west local government areas, in the west by Oji River local government area and share boarder with Isochi local government area of Abia State in the south. Currently, Awgu local government area is composed of 20 autonomous communities, namely, Agbogugu, Agbudu, Amoli, Awgu, Awgunta, Ezere, Ihe, Isu-Awaa, Ituku, Mbgidi, Mgbowo, Mmaku, Nenwenta, Nkwe, Obeagu, Ogbaku, Ogugu, Owelli, Ugbo and Ugwueme (Enugu State Government, 2014). Awgu local government area derived its name from Awgu town one of these autonomous communities which also serves as the headquarters. Awgu is a town in Awgu local government area.

The climate of the study area falls under the Tropical Wet and Dry Climate ‘Aw’ of Koppen climatic classification scheme (Anyadike, 2002; Lutgens and Tarbuck, 2004; Getis et al 2008; Mozie, 2011). The atmospheric condition of the study area depends on the position of the overhead sun and the Inter Tropical Discontinuity (ITD) (Anyadike, 2002). The average daily minimum and maximum temperature of the area are about 23.3^{o} C and 27^{o} C respectively while its average monthly maximum temperature is about 31.5^{o} C (Anyadike, 2002). Rainfall in ALGA is very high and intense. The average monthly rainfall ranges from 250mm in April to 380mm in October, with a mean annual total of 1500mm (Anyadike, 2002).

The geology of the area is marked by coal, shale and sandstone. The shale is bluish, grey, and well-bedded and is occasionally intercalated with calcareous sandstones and limestone (Ofomata, 2002). Also, fine to coarse grained, massive sandstone, locally cross-bedded with some pebble beds and subordinate bands of siltstone and carbonaceous shale are present. The Awgu formation is the youngest of the folded sequence in South-eastern

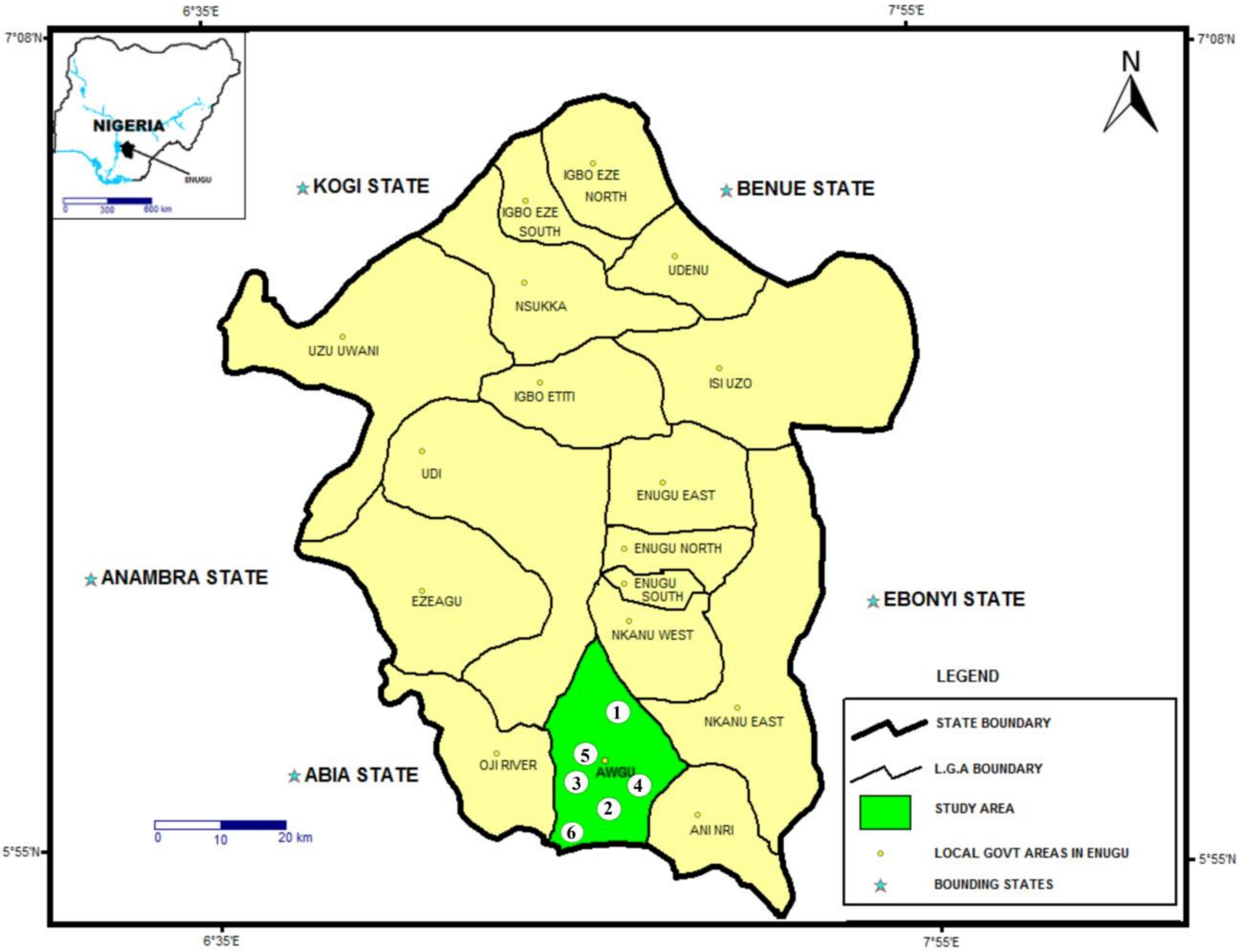

Fig. 1 Location of the study area and the investigated autonomous communities:
1: Agbogugu, 2: Awgu, 3: Mgbidi, 4: Mgbowo, 5: Mmaku, 6: Ugwueme

Nigeria (Ofomata, 2002). The area is also marked by long, broken hills especially in the western flank and lowland in the eastern side. These hills have steep slopes and could attain an altitude of about 350-400 meters above sea level with mean slope angle of 15^{o} and a modal class of 11^{o} (Mozie, 2011).

The study area is drained mainly by numerous finger-like springs and streams. Most of these streams are seasonal. They dry up during the dry season (November- March) and discharge large volume of water in the wet season.

Most of the streams have their source from top of the hills and flow downhill. The vegetation of the area varies with topography. Natural vegetation is denser at the valley and sparse at the top of the hills. Phil-Eze (2005) observed that graminoids cover the top of the hills while trees are dominant in the valley. The top and slope face of the hills are more covered by grasses such as *Andropogon gayanus*, *Ctenium spp*, *Hyparrhenia barteri* etc (Ofomata, 1997). The common tree species found are *Isoberlina doka*, *Anona senegalensis* etc. (National Resources Conservation Council, 1992). Awgu Local Government Area has a population of 198, 134 people as at 2006. Out this, 95, 421 are males while 102, 713 are females (Federal Government of Nigeria FGN, 2009). The distribution of population is uneven; a few areas are densely populated while many others areas are virtually uninhabitable. Majority of the population settle at the foot of the hills because of the difficulty posed by the rugged terrain and because the lowland have fertile soil that support high crop yield. The settlement pattern on the hills is clustered with a nearest neighbor index of 0.82 while settlement pattern on the lowland area is dispersed with a nearest neighbor index of 1.72 (Mozie, 2011).

METHODS

Six of the 20 autonomous communities in ALGA were randomly selected for this study namely *Agbogugu*, *Awgu*, *Mgbidi, Mgbowo, Mmaku and Ugwueme* (Fig. 1). A combination of instruments for data collection including questionnaire survey, field observation, key informant interviews and focus group discussions was used to generate data for this research.

Questionnaire Survey

A total of 300 questionnaires, 50 questionnaires in each of the six sampled communities were randomly distributed to households to acquire data on the factors affecting water supply in the area. Trained research assistances administered the questionnaires. The respondents (head of households) were asked to identify the factors that are responsible for water supply shortage in the study area. Of 300 questionnaires that were administered, we recovered 290 (96.67%). The indicators were predefined as shown in Table 1. The main question was “which of these factors affect water supply in your community”? Data on quantity of water demanded and supplied were obtained through household water budgeting using daily water need and water use based on household sizes.

Table 1 Water supply shortage indictors

Factors	**Label**
Rapid Population Growth	RPG
Seasonality of Water Sources	SWS
Absence of Water Infrastructure	ABWI
Long Distance to Stream/Spring Water Sources	LDSSWS
Non-protection of Stream/Spring Water Sources	NPSSWS
Inadequate Community Participation	ICP
Lack of Political Will	LPW
Politicizing Water Project	PWP
Limited Financial Capacity	LFC
Aging Water Infrastructure	AGWI
Misappropriation of Water Supply Projects Funds	MWSPF
Topographic Constraints	TC
Poor Maintenance of Water Supply Facilities	PMWSF
Tradition and Culture	TNC
Urbanization	URB
Vandalism and Damage of Water Facilities	VDWF
Geographical Location	GL
Absence or Inadequate Water Storage Facilities	AIWSF
Geological Factor	GF
Ownership of Water Supply Facilities	OWSF

Key Informant (Stakeholders) Interview

Interview as a tool of data collection is very important. This is because it allows us to interact with the people allowing them to express their thoughts about the water problems they are facing (Timmer et al., 2007). The following stakeholders were interviewed; traditional rulers (*Igwes*), the water department officials, community representatives, women leaders and youth leaders. A total of seven (7) interviews sections were done. In each of the six communities, one interview sections was held. Those interviewed were the traditional rulers, ward councillors, community representatives, women leaders and youth leaders. Meanwhile, another interview section was held at the local government secretariat. Those interviewed are the water department officials and Enugu State Rural Supply and Sanitation Agency (ENRUWASA) officials. The information gathered from these interviews was used to comprehend and confirm the responses from the questionnaires for better understanding of the problems.

Focus Group Discussions (FGDs)

Focus group discussion (FGD) is a good way to gather people from the same background or experience to talk about a particular topic of concern (Nzeadibe and Ajaero, 2010). A focus group allow participants to talk to one another and build on one other’s comments rather than continually responding directly to the moderator unlike interview (Krueger and Casey, 2002). Focus Group Discussions (FGDs) was conducted in each of the six randomly selected communities in the study area. The participants included the stakeholders and head of households. The research participants for the FDGs participated voluntarily and comprised between 6 - 10 participants in each community. The views expressed by the FGDs participants are incorporated into the findings of this research.

Analysis of Data Collected

The analysis of the factors responsible for water supply shortage in the study area was first done using descriptive statistics (frequency and percentage). Principal Component Analysis (PCA) of Statistical Packages for Social Sciences (SPSS) program version 20.0 was used to combine these factors affecting water supply into a few underlying dimensions.

PCA is statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of lineally uncorrelated variables called principal components (Anyadike, 2009; Vialle et al., 2011; Orakwe and Chukwuma, 2015). PCA combines large number of indicators into fewer, more analogous groups, each group defining the underlying dimension in the contributing variables forming the group (Anyadike, 2009). To do this, it is essential to estimate the number of significant factors present in the data. Specifically, a matrix of pair-wise correlations among indicators is collapsed into eigenvectors, which, in turn, are sorted in descending order of their corresponding eigenvalues (Vialle et al., 2011). The analysis is based on the correlation matrix, which is the covariance matrix of the synchronized indicators, to eliminate the scaling effect. The indicators have been computed as the sums of squares of deviations divided by N-1 (where N is the valid number of cases). Significant principal factors (PCs) with eigenvalues greater than unity (i.e., PCs explaining more than the variance of one indicator) were extracted (Orakwe and Chukwuma, 2015). Orthogonal rotation using variance maximisation varimax was used to maximise the variance of the squared component loadings for each component, repartitioning the loadings towards higher components, thus improving interpretation (Anyadike, 2009). The basic calculations were adequately and speedily done using the SPSS program as suggested by Anyadike (2009).

The responses were coded as 1= identified and 0 = not identified. The number of observation was N = 290 for all indicators. For example, ABWI was identified 189 times in 290 observations hence the column for ABWI in the SPSS data entry window will have 189 “1s” and 101

“0s”. The 0s will fill up the remaining rows after the 1s to sum to 290 observations. Significant component loadings are considered from an arbitrary threshold of 0.70, based on the size of the component loadings.

RESULTS

Characteristics of Respondents

95% of the respondents are male while 5% are female.1.4% of the respondents are between the ages 20 and 29, 2.4% are between 30 and 39 years, 58.9% are between 40 and 49 years, 12.8% 70 and 79 years and 0.69% are older than 80 years. 2.41% of the respondents have no education, 6.2% have primary school education, 65.5% have secondary school education, and 25.9% have post secondary education. Of this 25.9% of the total, 5.5% have National Certificate of Education (NCE), 7.24% have National Diploma (ND), 12.1% have Bachelor’s degree/Higher National Diploma (HND), 0.69% has Master’s Degree and 0.34% has PhD. 67% of the respondents are farmers, 12% are artisans, 8% work in the civil service, 9% are traders and 4% has other occupation.

Assessment of Water Demand and Supply in the Study Area

From our findings water supply is not commensurate with demand in ALGA. On average a gap of 28.52% of water demand is not satisfied by supply in the study area. The gap in quantity of residential water demand and supply is presented in Table 2. According to Table 2 the quantity of water demanded l/person/day is greater than the quantity of water supplied. Although water demand is low (48.85 liters) on average, it is not satisfied by supply (34.54 liters). The quantity of water consumed by an individual in the study area is very small and indicates inadequate access to water supply.

The gap between demand and supply is not the same for all communities sampled. Mgbidi recorded the highest water shortage followed by Mmaku because movement in these two communities is difficult such that people find it difficult to access the various sources of water. Mgbowo however, has the least water shortage because the people depend mainly on wells that are very accessible. Also as shown in Table 2, there is water supply shortage in all the sampled communities. A total of 71.48% of water demand was satisfied by supply leading to a gap of 28.52% in the study area.

Descriptive Analysis of Contributing Factors

Table 3 summarizes the various indicators and the frequency of how the respondents perceive them as factor affecting water supply in the study area. These indicators have been classified into three groups based on the percentage of respondents that identified them as influential. From 50% and above are classified as most important, 49% - 25% as important and less than 25% as less important.

Table 3 shows the percentage contribution of the six communities studied to the factors responsible for water supply deficiency in the study area. The three groups of indicators are discussed as follows.

Most Important Factors

Absence of water infrastructure is the most important factor affecting water supply in study area. 65.17% of respondents attest to this. In all the sampled communities, water supply infrastructures are lacking. Although some communities such as Awgu, Ugwueme and Mgbowo have mini water supply system none of them are functional as at the time of this research. Awgu water scheme was constructed about six decades ago but it has not been functioning regularly since Nigeria’s independence in 1960. The Ugwueme water scheme is as well not functional just two months after it was completed. Also, Mgbowo water scheme which is the largest water scheme in the study area has not been commissioned since 2003 when its construction started. Other communities lack water scheme but some communities such as Mgbowo, Mgbidi and Mmaku have been provided with boreholes although these boreholes are plagued by constant breakdown and some of them yield water of poor quality. The irregularity of the water schemes and boreholes is attributed to absence of personnel with the technical skill to maintain them in the area.

In the rainy season, rainfall is present and stream discharge is high while in the dry season, the opposite is the case. The consequence of this is that the people are short of water in the dry season and have more supply in the wet season. SWS is considered by the people as the one most important factor responsible for water shortage in the study area. 61.72% of the respondents attested to this condition. In severe conditions water shortage in dry seasons could pose great danger. For example, in Ethiopia, access to safe water in drought is always a major problem, and water-related disease resulting from re-

Table 2 Gap between daily household water demand and supply in the study area

Sampled Communities	No. of Sampled Households	Average Size of Household N=290	Water demand l/day/person	Water Supply l/day/person	Gap between Demand and Supply l/day/person	% of water demand satisfied by supply /day/person
Awgu	49	7	39.14	27.59	11.55	70.49
Mgbowo	48	6	45.89	40.21	5.68	87.62
Agbogugu	46	7	41.06	27.16	13.90	66.15
Ugwueme	49	6	47.04	37.86	9.18	80.48
Mgbidi	49	6	63.09	39.05	24.04	61.89
Mmaku	49	6	56.85	35.37	21.48	62.22
Mean		**6**	**48.85**	**34.54**	**14.31**	**71.48**

stricted water availability and access often causes fatalities (Coulter et al., 2010).

Awgu local government area groundwater resources have not drained even though boreholes are being sunk by ENRUWASA in partnership with the United Nations Children's Fund (UNICEF) in some communities. In three communities (Mgbowo, Agbogugu and Awgu) the people reported that the borehole water is not suitable for drinking because of its salty taste and odor. The Awgu local government area water department officials stated that the poor quality of the UNICEF-Assisted borehole water is due to the geology of the area. 59.65% of the respondents confirmed this situation. It was reported also that several attempts to sink boreholes in some villages was not successful due the underlying rocks (coal) that prevented them from reaching the water table. A comprehensive study of the geology of the area will reveal places to be explored for water and also help in data gathering (Fagoyinbo, 2015). The variation in groundwater quality in geologically complex area is caused by variation in mineralogy and rock chemistry (Fagoyinbo, 2015). In addition, water well yield and groundwater quality are determined by an intricate interplay between fractures in the aquifer, the local soils and saprolite which provide storage and recharge to the bedrock fractures (Toth, 1993).

Government efforts to supply water to the villages have yielded no laudable result. Although water schemes are provided, none of them is currently functional. They are poorly maintained. 58.96% of the respondents attested to this state of affairs. Water storage facilities are inadequate in the study area. 58.27%of the respondents agreed that the absence of storage facilities contributes to water supply shortage in the area. The tanks that were provided by the colonial masters are no longer in used. These tanks are connected to springs such as the *Ngeneofia* in Mmaku, *Nkwo* in Awgu but most of them are no longer available. Storage facilities are indispensable to store up water to be used in the dry season particularly in countries that experience protracted period of drought. FAO (2012) indicated that the level of infrastructure development that controls storage is one of the three main dimensions that typify water scarcity.

Non protection of stream/spring water sources have left most water sources polluted. 51.38% of the respondents confirmed this. Many streams are polluted by villagers who bathe inside the streams, wash their cloths and farm produce as well as defecating along and beside the streams channel which are washed into the stream by runoff rendering the stream water not safe for drinking. Open defecation is highly practiced in the area and this is one of the major pollutant of surface water bodies. FAO (2012) noted that protection and efficient management of freshwater resources (streams, rivers, lakes, and springs) would guarantee their long-term sustainability thus water supply sustainability. To achieve this, WHO (2006) and US EPA (2008) noted that stakeholders should be engaged in formulating and implementing source water protection policy.

Majority of the people in the study area are poor and economically weak. They have low adaptive capaci-

Table 3 Respondents Identified factors affecting water supply in the study area

		Percentage of households that perceived the factors as problem (%)						
Indicator Label	**Nr of households that perceived the factors as problem (N=290)**	**Awgu**	**Mgbowo**	**Agbogugu**	**Ugwueme**	**Mgbidi**	**Mmaku**	**Total**
Most Important								
ABWI	189	12.41	6.55	16.20	14.14	7.59	8.28	**65.17**
SWS	179	12.41	13.79	18.97	4.14	5.17	7.24	**61.72**
GF	173	12.41	14.48	12.07	6.20	6.89	7.59	**59.65**
LGW	171	7.59	7.24	12.07	14.48	8.28	9.31	**58.96**
AIWSF	169	7.24	11.38	14.83	10.00	7.93	6.89	**58.27**
NPSSWS	149	10.00	9.31	12.07	5.86	7.59	6.55	**51.38**
LFC	148	6.55	6.89	9.31	12.41	8.28	7.59	**51.03**
Important								
LDSSWS	140	10.69	9.66	7.93	4.48	5.86	9.66	**48.28**
RPG	139	11.72	8.97	9.66	5.17	6.20	6.20	**47.92**
TC	132	7.93	1.38	0.51	14.14	11.38	10.00	**45.34**
ICP	127	6.89	6.20	10.34	9.66	5.17	5.52	**43.78**
GL	123	9.66	8.96	10.00	3.45	4.83	5.52	**42.42**
AGWI	111	7.24	7.59	4.83	5.86	6.20	6.55	**38.27**
PWP	98	7.24	6.55	5.52	5.86	4.14	4.48	**33.79**
OWSF	96	6.20	8.62	3.10	7.93	3.45	3.79	**33.09**
PMWSF	85	7.24	4.48	4.14	3.45	3.79	6.20	**29.30**
Less Important								
MWSPF	72	5.86	3.79	4.14	5.17	2.76	3.10	**24.82**
VDWF	66	8.28	4.48	1.72	1.72	3.10	2.76	**22.06**
TNC	61	1.72	5.17	5.86	2.41	2.76	3.10	**21.02**
URB	54	6.55	3.10	5.86	0.34	0.51	1.03	**17.39**

ty to cope with water supply shortage consequences. They are also unable to participate in the water projects constructed in the area as a result of their low economic base thereby denying them the ownership of these projects. The people are also unable to buy vended water and self supply is practically limited because it is capital intensive. 51.03% of the respondents confirmed this situation. Financial instability causes a major setback to water development in developing countries (FAO, 2012). The National Bureau of Statistics (NBS, 2008) indicated that about 80% of Southeastern Nigeria rural population is poor as against 20% rich people. This means that most of the people may not be able to pay for water supply services.

Important Factors

Streams and springs are far from majority of the households. Most often they have to climb hills to fetch water from the springs. The long distance to these water sources makes it difficult for the villagers to fetch the quantity of water needed for their domestic activities. 48.28% of the respondents attested to this situation. Uwazie et al. (2009) remarked that reducing the distance to water supply source in rural areas will reduce the stress of women and children who can now devote more time to income generation and education, and will improve the health of community members being ravaged by water related diseases.

For decades even before the colonial period, people in the study area depend on springs and stream and till date, they still depend largely on these traditional sources of water. However, while population is growing rapidly, these sources are not increasing. As a result, the proportion of people depending on each spring and stream has increased by more than ten times. Consequently, there is pressure on these limited water resources and the resultant effect is water scarcity. The disproportionate level of population growth and water supply can be balanced if the available water projects and facilities in various communities in the study area are made functional and population growth checked. 47.29% of the respondents confirmed this situation. Similar situation abound in many parts of the world. Getis et al. (2008) observed that water is essential for development but its demand frequently exceeds supply in many parts of the world especially as population rapidly increases. As a result, regions with high population growth rate are expected to have water supply shortage if proper measures are not taken to equal demand and supply. For example, Glass (2010) noted that the water crisis in Yemen is caused by high population growth and exhaustion of water. The situation is severe and may cause mass fatalities due to dehydration of its people unless immediate action is taken.

The rugged terrain that occupies the study area's landscape hinders not just water development but other aspect of development. The topography of the study area hinders the distribution of water via pipe. In Ugwueme for example, the water scheme that was developed by the Anambra-Imo River Basin Development Authority was not successful in terms of distribution of water to villages because of the rugged nature of the area. Topography is a major challenge if large scale water scheme is developed to supply water to many communities in Awgu Local Government Area because piping will be difficult and expensive. 45.34% of the respondents confirmed this condition. In line with this, Bakalian and Jagannathan (1991) noted that the installation of conventional water infrastructure in complex topographic conditions is very costly. Furthermore, the study area is located where climatic condition does not favor water supply for all the months of the year. In the wet months (April-September) water is available in springs, wells and streams. Also, harvested rain water serves some purpose such washing, cleaning, bathing etc. However, in the dry months (October-March), streams are dry, springs become finger-like, some wells yield small quantity of water and there is no rain water to harvest. 42.42% of the respondents attested to this situation. This situation is typical of the Tropical Wet and Dry climate of the Humid Tropics (Wohl et al., 2012).

The level of community participation in water provision is low in the study area and has led to the abandonment of water facilities and projects. 43.78% of the respondents confirm this. The absence of water committee to manage the projects after they have been constructed has left most the water project dysfunctional. Similar scenario was discovered in Benin Republic, Bolivia, Honduras, Indonesia, Pakistan and Uganda (Katz and Sara, 1997). Also, because there is no regulation on the use of stream water which is supposed to be coordinated by village water committee to ensure the proper use of water e.g. preventing stream pollution by placing sanctions on washing, bathing inside the streams and defecating along the stream channel has left most of the streams polluted all seasons limiting available water especially to people living at the lower course of the streams. In addition, some water projects in the area are initiated no attention to the physical environment parameters of the area before sitting the projects. This is particularly so for the newly installed public boreholes. Water is a very pressing need of the people and can be used for political goals. However, the reverse has always been the case. 33.79% of the respondents attested to this situation. In developing countries especially in Africa, (Briscoe, 1999; Ünver et al., 2012) acknowledged politicizing of water projects as reflected in where to site the project. Water projects are sited based on political affiliations of community leaders.

The study area has some water facilities that are provided by the federal and state government however, most of these facilities are aging. They have been neglected by both the facilities providers and the local authorities while others under construction have been abandoned. Similar situation is obtainable in other developing regions (WWC, 2015). The problem of ownership of the water projects has led to the neglect of some water supply facilities. 33.09% of the respondents confirmed this. Most of the public boreholes are installed by state government in partnership with UNICEF while some are installed by the federal government. The federal government boreholes are beset with incessant breakdown. When they stop functioning, it takes about 1-2 years before they are repaired depending on the administration's priorities. The situation is such that some federal government's water facilities are not maintained by the state government. For instance, the water supply schemes in Ugwueme and Mgbowo are provided by the federal government and because their ownership has not been transferred to the state government, they are abandoned. As a result of the irregular maintenance of the facilities provided by the federal government, communities that have only federal water facilities such as Ugwueme are greatly affected. 29.30% of the respondents attested to this state of affair. As noted by (FAO, 2012; WWC, 2015) poor maintenance of water infrastructure is a growing concern for water supply sustainability in developing countries.

Less Important Factors

Misappropriation of water supply project funds might occurred according to the opinion of 24.82% of the respondents, however, there is no clear evidence to uphold this claim. Moreover, as FAO (2012) noted, a lack of transparency and poor accountability breeds fraud and are reasons for poor performance, resistance to change and unbalanced delivery of water services. Vandalism is a problem that beset water facilities in the area. For instance, in Umuhu village, Awgu autonomous community, the absence of village water guards gave room for some youths to vandalize the pipe connecting the *Ogbuma* stream and the Awgu Water Supply Scheme. They also extort money from villagers who come to fetch water from the stream. 22.06% of the respondents attest to this. This situation reflects the findings by Water and Sanitation for the Urban Poor (WSUP), a non-profit organization based in Zambia and Nkana Water and Sewerage Company (NWSC) in Zambia in 2014 which indicated that water and sanitation utilities often experience vandalism and theft of their property. The study showed that the acts of vandalism take a number of forms: they include water theft leading directly to a loss of revenue for the utility, and the vandalism and theft of valuable metal pipes, fittings and manhole covers leading to an increase in the utility's maintenance costs (WSUP and NWSC, 2014).

Tradition and cultural factors does not have much influence on water supply shortage in the area but it has helped some villages to protect their drinking water sources. For instance, in Awgu autonomous community, there is a tradition that the fishes in *Ogbuma* stream is not to be harvested and no any form of activity is allowed in the upper course of the stream. This tradition has helped preserved and protected the stream for centuries. *Ogbuma* stream is still the most relied source of water in the community. Another example is the *Ovi-angu* spring. As the tradition states, "there is no tourist activity in the vicinity of the spring" to avoid contamination. In communities such as Agbogugu where such tradition does not exist, their streams and springs are often polluted. 21.02% of the respondents attested to this. From an African perspective, water is of social, cultural, spiritual and economic importance (Zenani and Mistri, 2005). Against this background, Mathew and Le Quesne (2009) indicated aligning culture and tradition with institutional and legal water management strategies could solve water problems better in rural areas. In many rural settings in Africa, access, use and management of resources e.g. water is generally informed by customary rules that form part of a complex system of traditional governance (Kapfudzaruwa and Sowman, 2009).

Finally, urbanization has the least percentage (17.39%) of the respondents attesting to it. The influence of the factor in the study area is felt mostly in Awgu and Agbogugu autonomous communities where there is gradually urbanization. The result is that some households are now far from major springs and streams; they have to take very long distance to these water sources fetching small quantity of water because earliest settlements are found in areas close to streams in the eastern communities and areas close to springs in the western communities of the study area. Urbanization can put unparalleled pressure on a renewable but finite resource, principally water (FAO, 2012).

PCA Analysis of the Contributing Factors

From our analysis, we have been able to identify three unique factors which can be used to explain the causes of water scarcity in the study area. Thus, we have successfully transformed our 20 predictor variables to 3 underlying dimensions (Table 4), which, in order of importance are as stated below:

1. Physical Environment and Inadequate Water Supply Infrastructure
2. Socio-Economic and Geographical Location
3. Management and Socio-cultural Problems

Physical Environment and Inadequate Water Supply Infrastructure

With an Eigen value of 6.519 and 32.597% of variance explained, the first component loads heavily on SWS (seasonality of water sources), GF (geologic factor), LGW (lack of government will), AIWSF (absence/inadequate water storage facilities), and ABWI (absence of water infrastructure). There is positive relationship between this component and the variables. It is described as the effect of physical environment condition and inadequate water supply infrastructure. The study area is in a location that the geology has not favored water supply development. The area is underlain by coal, limestone, clay and shale which have made borehole sinking quite difficult. The boreholes sunk in areas underlain by coal do not yield water and those in limestone areas yield water of poor quality. In addition, the area is located where there is two marked climatic seasons. Springs and stream yield more water in the wet season than dry season. Furthermore, the water supply systems and some of the UNICEF assisted boreholes are not effective in supplying water to the people. This is as result of lack of will by government to provide and maintain water supply and storage facilities.

Table 4 Rotated Component matrix from the SPSS

Rotated Component Matrix[a]			
Investigated variables	Component		
	1	2	3
ABWI	*0.883	0.232	0.194
SWS	*0.910	0.280	0.206
GF	*0.904	0.325	0.212
LGW	*0.895	0.345	0.214
AIWSF	*0.879	0.368	0.217
NPSSWS	0.670	0.637	0.244
LFC	0.659	0.649	0.246
LDSSWS	0.568	*0.734	0.274
RPG	0.557	*0.742	0.279
TC	0.483	*0.779	0.321
ICP	0.435	*0.790	0.358
GL	0.401	*0.786	0.392
AGWI	0.318	*0.732	0.509
PWP	0.248	0.635	0.647
OWSF	0.241	0.615	0.667
PMWSF	0.217	0.484	*0.773
MWSPF	0.204	0.314	*0.885
VDWF	0.200	0.241	*0.919
TNC	0.195	0.194	*0.925
URB	0.186	0.152	*0.897
Eigen value	6.519	6.025	5.886
% variance	32.597	30.127	29.429
Cumulative %	32.597	62.724	92.153
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.			
a. Rotation converged in 5 iterations.			

Socio-Economic and Geographical Location

This second component has an Eigen value of 6.025 and explains 30.127% of the total variance. It loads heavily on ICP (inadequate community participation), GL (geographical location), TC (topography constraints), RPG (rapid population growth), LDSSWS (long distance to stream/spring water supply source) and AGWI (aging water infrastructure). All the variables show that there is positive relationship between the variables and the component. Generally, this component describes the problems caused by socio-economic and physical barriers in the study area. This is because majority of the people in the study area are poor coupled with rapid population growth that further push the dependency level higher leading to more socio-economic weakness (increase in poverty level). The teeming population becomes burden to the individual household, the community as a whole as well as the government such that investment in water infrastructure is limited due to high dependency rate on head of households which limit households' capacity to participate in water supply development. Also, the rugged nature of the area's landscape makes it difficult for water distribution through pipes because of the numerous jointed hills that will obstruct the laying of pipes. This component is therefore, described as the effect of socio-economic and physical barriers.

Management and Socio-cultural Problems

The third component has an Eigen value of 5.886 and explains 29.429% of variance. It loads heavily on VDWF (vandalism and damage of water facilities), TNC (tradition and culture), URB (urbanization), and MWSPF (misappropriation of water supply project funds). This factor is difficult to interpret but it could be described as management and socio-cultural problems. This is because proper management of water facilities is lacking in the area. Vandalism of water facilities could have been prevented if the water department of the local government employs guards to secure water facilities and ensure that damaged facilities are repaired or replaced by judiciously appropriating water funds. The level of education of a society reflect the social status the society accords, their level of thinking and to some extent their economic capability. The level of education in the study area is low with associated poverty of the mind which manifest as vandalism of government property (water facilities) by unemployed youths owing to their thinking that government has not done enough to elevate them from abject penury. In addition, communities that their tradition and culture does not provide for water protection have most of their water sources polluted. Furthermore, urbanization will increase the demand for water because there will be other demanding sectors such as industrial and commercial sector. Also as more buildings are erected, recreation centers built and other social amenities put in place, the natural hydrological system will be altered. Urbanization affects hydrological components such as precipitation, evaporation, infiltration, evapotranspiration (Ezenwaji, 2012; Obeta, 2013). Currently, this factor has less influence on water supply in the area but could be a major problem in the future.

DISCUSSION

Efficient water supply is very vital to achieving sustainable development in the area because water supply has link with rural livelihood system (Houweling et al., 2012). The shortage in water supply could have both direct and indirect impact in the area. Water supply shortage can affect directly some domestic activities such as bathing cooking, washing, basic sanitation and waste disposal. Insufficient water for these activities can result to poor hygiene which spreads water-related diseases such as diarrhoea, cholera, malaria, dysentery etc. (Basu et al., 2015). Consequently, households will have huge part of their income spent on health care leaving them with insufficient money for education, nutrition, better shelter etc. (Pearson et al., 2015).

Water supply shortage could also hinder economic progress of the area. Poverty reduction is linked to water development especially as the economy of the area is greatly dependent on agriculture. Agriculture is the primary prospect for rural economic growth and development and water is very vital to this. Adequate access to water supply can help lift many rural households out of poverty because water is crucial to large scale agriculture especially in dry seasons, crops and animals need water for their growth (Crow et al., 2012). Insufficient water for agriculture could arrest the food security of the area leading to poor nutrition. Poor nutrition could weaken the people that they die from illnesses and infections that are not usually severe (Lenton and Muller, 2012).

Generally, the main water supply problems in the study area are related to physical environmental barriers and anthropocentric factors. The physical barriers are geology, climate and relief while the anthropocentric factors are water infrastructure deficit, lack of community participation, population pressure, financial constraints, politics, vandalism, poor maintenance culture, urbanization, tradition and cultural factors. Based on our analysis of the factors responsible for water supply shortage in the study area, the following recommendations are made in the following paragraphs.

Public awareness campaigns have been recognized as effective sensitization program in water management (Butler and Memon, 2006; Willis et al., 2011). Rural people need to be informed that water is very important to their development and they should try to preserve and conserve the water resources they have to avoid further scarcity. The incessant pollution of streams and springs through washing of cloths, bathing and defecation in the stream could be attributed to lack of awareness of the consequences of such activities. Awareness can be done through the use of community town criers, cultural festivals, faith-based organization, school advocacy initiative, radio and television jingles (FAO, 2012), social media platforms and short message service (Nzeadibe and Ajaero, 2011).

The ownership of all the water projects including those installed by politicians should be specified. It will be better to transfer ownership to the state government because it is closer to rural communities than federal government and also, the funding of projects is done by the state government. However, the local government should be made to monitor their water facilities through community water committee. The committee will report any dysfunction, failure and maintenance need of the water facilities in their community to the local government. The water committee in each community should be appointed by the traditional rulers and approved by the local government chairman. In this way, the monitoring of water facilities will be the responsibility of the community it is servicing. Water guards should be employed as substantial staff of the local governments. The guards will have the responsibly of monitoring water facilities and sources of water to ensure that there is no vandalism and pollution of water sources. The water committee in each community will be made to supervise that guards and report to the local government.

The concerned state government institutions should commence the study, design and construction of new water supply systems using technologies that have been developed as appropriate responses to the physical environment conditions in the area. Provision of more boreholes and wells in villages would help reduce the trekking distance to where boreholes are sited as well as streams and spring. Proper study should be done before drilling new boreholes. Wells are quite easier to construct and relatively cheaper therefore, wells should be provided also as alternative to boreholes should they break down. Local craftsmen should be trained on how to drill and repair boreholes and other water facilities. Borehole drilling is still very difficult in the study area because the expertise is lacking. In the Nigerian energy sector, Ajao et al. (2009) advocated for the training of local craftsmen on how to install and maintain power facilities to enhance mass production and subsequent commercialization of power. In line with this, training local craftsmen will reduce costs of labor in the water supply facility installation and maintenance.

Restoration of all village tanks that were formally connected to springs should take effect immediately. These tanks such as the *Nkwo* Spring tank in Awgu autonomous community were provided by the colonial administration however, after independence they were all neglected. Also, addressing the problem of poor service coverage and aging water infrastructure should be targeted. Water supply infrastructures are essential to taping local capacities to contribute to social and economic development and crucial to delivering long-term water security. Sustained investment in water infrastructure is an essential pillar for developing countries (WWC, 2015).

Conserving water to reduce water waste is a first step in water management (Rahman et al. 2012). Thus the communities should adopt various water conservation measures such as installing concrete tanks in springs to avoid the waste of the spring water especially in dry seasons when water yield from these springs are low and to protect it from contamination (Khastagir and Jayasuriya, 2010). Harvested rainwater can be an alternative source in the dry season. Households should install large tank particularly underground tanks for collection of rain water in the wet season which can be used when springs and streams yield small quantity of water in the dry and also household water treatment should be encouraged (Vohland and Barry, 2009).

Private individuals, groups or organizations in the area should also partake in water supply development by placing taps where villagers can fetch water. In addition, government should encourage private water supply development by providing soft loans to those who will to develop the water resources in the area.

CONCLUSIONS

This research has shown that the factors affecting water supply in Southeastern Nigeria are mainly physical environment barriers, water infrastructural deficit, socio-economic problems geographic location and management bottlenecks. The research recommends that water development in rural communities should be a stepwise process; each stage should correlate with physical environment conditions and socio-economic realities. Sequel to the fact that majority of the people in the study area are engaged in subsistence farming and other extractive economic activities with very low economic and educational base, it will be more sustainable not to install multimillion high-tech water facilities that the community does not have the capacity to partake in their provision and management. No doubt community participation is a precondition for sustainability, i.e. to achieve efficiency, effectiveness, equity, and reliability (Harvey and Reed, 2007) however it requires ongoing motivation for continuing participation (Batchelor et al., 2000). Communities may have participated in the water supply planning process however this does not mean that they will sustain participation in service delivery or that they will successfully manage water supply. Community management is a development plan whereby community members assume control-managerial, operation, and maintenance responsibility for the water system (Doe and Khan, 2004). The beneficiaries of the water supply have full responsibility, authority, and control over it (Harvey and Reed, 2007). Studies in Sub-Saharan Africa showed that communities participated in the planning and provision of water projects when motivated but they are unwilling to manage them and also they lack the education and technical know-how to make an informed decision on management (Batchelor et al., 2000; Doe and Khan, 2004; Harvey and Reed, 2007).

As a first step, traditional sources sustenance intervention should be launched. About 80% of rural households in Sub-Saharan Africa depend on traditional sources (hand dug well, stream, river, pond, spring etc.) some of which they have discovered or occur naturally in their locality (Harvey and Reed, 2007; FAO, 2012), these sources can be developed and upgraded to provide sustainable access to safe water. Full information on all possible options should be provided to community members and private sector in order for them to decide on the most suitable technology and service level for them. Next, government should sponsor the training of the local people on installation and maintenance of mini water systems such as hand pump and borehole. Later, mini water supply system (borehole, hand pump) that can serve small area such as group of households can be introduced. As the community progress along a developmental path and the economic, educational and technical base of the people have improved considerably, high-tech facilities may be deployed. This stance does not infer that all people do not have equal right to water but that water supply in rural areas should be development in stages each stage corresponding with the community's participatory and management capacity so that the water supply facilities will be maintained after installation except if government, donor agencies or private bodies that install them are also willing and ready to make them work regularly.

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INVESTIGATION OF TREE STANDS OF PUBLIC SPACES IN SZEGED

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Abstract

In urban areas vegetation (especially woody vegetation) is of utmost importance, since it affects the ecological conditions of the city. Urban trees play an important role in improving urban climate both at the local (city, district) and the micro-level (e.g. in public squares). Establishing and maintaining advanced and detailed information systems necessary for the management of urban tree stands is an important task of environmental and climate-conscious city management. Despite that, few of the Hungarian municipalities have a regularly updated tree database. The city of Szeged started efficient green space management in autumn 2013, when we started the creation of a detailed and up-to-date tree register for the public areas, which has been continuously expanded ever since. The survey of the present study covers the period of the growing season, from late spring to early autumn of 2013. All the trees are included in the survey and quite a number of data are recorded for each individual (e.g. species, age, size parameters, exact location, health status, etc.). The recorded data are paper-based, however they are included in a GIS-based green space inventory software, Greenformatic, where coordinates are associated to each object, while information on the state of the tree, its location and handling can be found in the attribute table. The trees included are mostly concentrated in the inner city of Szeged, but the surveys will gradually cover ever larger areas of the city. The results highlight the fact that the structural attributes of the different species' populations are formed by the integrated effect of the species' urban tolerance and planting policies of the past decades. The current database already allows highly complex analysis, which contributes to the well-being of city residents.

Keywords: urban tree, green space management, tree database, Greenformatic

INTRODUCTION

Tree stands have many positive effects on the ecological status of a city, its population's health and well-being, making the urban built environment more liveable. One of the most noticeable direct effects is changing the microclimatic conditions (Andrade and Vieira, 2007; Bowler et al., 2010). During the active period of the growing season the daytime near-surface air temperature has been proved to be lower under the trees than above the free surface (Lin and Lin, 2010). This is primarily due to the canopy reducing the amount of radiation energy from the surface, as it reflects a part of it and absorbs another part - although the extent of this effect depends on the season and the time of day (Shashua-Bar et al., 2011; Konarska et al., 2013).

This directly causes a decrease in temperature, while on the other hand it has an even more significant impact on human comfort, because it results in further physiological (heat) stress reduction, which is well detectable using different human comfort indices (Égerházi et al., 2013). In areas planted with trees a much larger amount of water leaves to the air through evapotranspiration than either in grasslands or built-up areas. This increases humidity, which indirectly contributes to the development of lower temperatures under the trees and has a generally beneficial effect on human comfort, especially during heat waves (Zhang et al., 2013). Surface roughness increased by the presence of woody vegetation decreases the speed of near-surface air movement, which can have both positive and negative implications. In winter, it can lead to significant heating-related energy savings (Loehrlein, 2014).

An important element of improving air quality is the absorption of air pollutants (e.g. ozone, nitrogen, sulphur-dioxide, settling dust, etc.) - the actual quantity depending on the amount of leaf surface. During photosynthesis trees use a substantial amount of CO2 (extracting it from the air), one of the most important greenhouse gases (Nowak et al., 2006). Except for the latter, all those listed here have an indirect or direct impact on human health, either through human respiratory diseases or through otherwise affecting comfort.

A very important ecosystem service of urban tree stands is the massive interception of precipitation on the leaf surface, a part of which evaporates directly, while the rest is slowly conveyed towards the ground, making infiltration easier, and significantly reducing the size of flash floods following extreme precipitation events (to an extent depending on the size and state of the stand). The water trapped in this way does not burden the sewage system at the time, but seeps into the soil gradually and thus more efficiently. This in turn improves the quality of otherwise poor urban soils (Day and Dickinson, 2008).

Creating and maintaining a green surface property cadastre is a statutory obligation for municipalities in Hungary; woody vegetation represents a substantial part of this. However, the property value in this case is much more than just the value of wood. The pollutant and carbon sequestration, the reduction in runoff, the energy savings resulting from the shading of buildings are relatively easily expressible in monetary terms. Defining the monetary value of much more abstract concepts such as the reduction of thermal comfort, the aesthetic and / or cultural value, the mental and physical regeneration effect - the further benefits of well-maintained green areas and tree stands - is much more difficult, however without doubt these also should be given some consideration. It makes monetary evaluation particularly difficult that the idea of a property gaining value over time instead of losing it is quite foreign to traditional economic thinking (McPherson, 2003).

STUDY AREA

Szeged is situated in the south-eastern part of Hungary (46°N, 20°E; 78-85 m above sea level), in the Lower-Tisza-valley, at the confluence of the rivers Tisza and Maros. According to Péczely's climatic classification (Péczely, 1976) the Great Hungarian Plain is characterised with a dry-warm continental climate, therefore in summer heat is typical and drought susceptibility is high in the Szeged area. The annual sunshine duration is high and air humidity is typically low. Winter snow cover is rare and the amount of snow is also low. Szeged is the biggest city of the Southern Great Plain region with an area of 281 km^2 and a population of about 170 000 (Fig. 1).

Due to its size, the city of Szeged has easily detectable climatic effects on the local scale. The most apparent phenomenon is the formation of a so-called urban heat island as a result of artificial surfaces, which is most pronounced a few hours after sunset. In Szeged the added heat from the heat island is on average 2-3°C, but in calm, anticyclonic periods it may reach up to 6-8°C (Balázs et al., 2009). This (along with many other climatic effects) significantly affects the life chances of urban vegetation. It may therefore be useful if vegetation studies are supplemented with a climatological perspective, and vice versa, the climate-modifying effects of the vegetation are investigated.

METHODS

In order for a city to have an efficient green space management, which is also sustainable in the long term, a detailed, up-to-date database is necessary. To this end, in 2012 the Department of Climatology and Landscape Ecology of the University of Szeged (in collaboration with the Environmental Management Office of Szeged) started to set up such a detailed tree register which helps the performance of operational tasks and maintenance while also provides an opportunity for the scientific examination of the urban ecological role of trees (e.g. complex ecosystem services evaluation). The data-recording

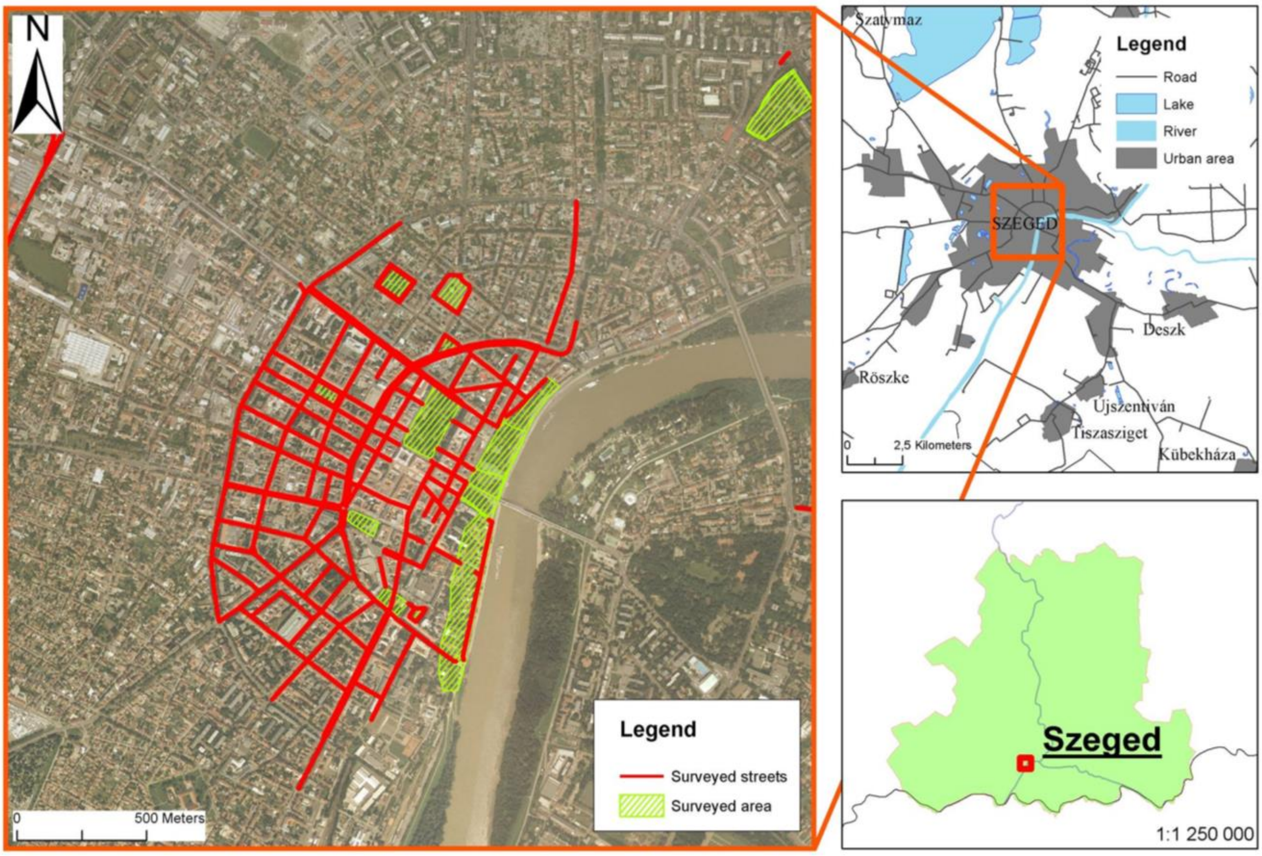


Fig. 1 Tree alleys and squares recorded by the end of November 2013

during the field surveys was paper-based, with a high demand on time and human resources; university students were heavily involved in the work.

The ideal period for the survey is from late spring to early autumn, namely the growing season, when the foliage has fully developed and autumn defoliation has not yet started. Some parameters, such as the exact extent of the canopy or the health status of individuals can only be established with reasonable accuracy in this period. All the trees or shrubs with a dbh (diameter at breast height) over 5 cm are included in the survey and quite a number of data are recorded for each individual (e.g. species, age, size parameters, exact location, health status, etc.). Photos are also taken of each tree and added to the database.

Additional data are related to the surroundings of the tree such as the size of the planting space, the nature of a protection measure or nearby damaging factors. Health data contain information on injury and lesions detected on the root system, the trunk or the canopy, as well as other anomalies included as comments. Based on the data recorded separately for the tree parts, an assessment of the whole tree’s health status is provided on a 5-point scale. The person recording the experienced damage can also make management proposals and include them in the database.

In order to get more accurate scientific analysis some extra parameters are also recorded for each individual, which so far have not featured in such registers. These include for example the proportion of dried-out crown parts, the proportion of missing or truncated parts (as a percentage) and the degree of light availability. These enable more realistic calculations of tree volume and leaf area serving as input for pollutant absorption and carbon-sequestration calculations. Thus regulatory ecosystem services can be evaluated more precisely (Takács et al., 2014).

In order to record and store spatial data a GIS is necessary, since visualization and spatial analysis are part of the complex requirements of users (both managers and scientific experts). The Greenformatic - Geospatial Information Software, is a targeted GIS-based green space inventory software developed in Hungary. Coordinates are associated to each object, while information on the state of the tree, its location and handling can be found in the attribute table. This primarily serves to directly make users' everyday work easier.

The results shown in the present work were derived from the data of over 5000 tree individuals recorded until November 2013 (see the extent of the area on Fig. 1.). As shown on the map in Figure 1, the database assembled by that date mostly represents the densely built-up areas of the inner city, within the Great Boulevard (Nagykörút).

RESULTS

The tree population in the register recorded by November 2013 contains 5197 objects, the tree individuals belong to 110 species and 4 categories: stumps, empty planting spaces, former planting spaces and dried-out trees. The city is quite species-rich, however approximately 60% of the individuals belong to the 10 dominant species (Table 1). There are 48 species with less than 5 individuals in the database.

Almost half of the recorded individuals belong to species non-native in Hungary (Fig. 2.). Of these, *Sophora japonica, Celtis occidentalis* and *Koelreuteria paniculata* are present in highest numbers (over 200 individuals each). Of native species, different species of linden trees (*Tilia sp.*) are most frequent (1321 individuals).

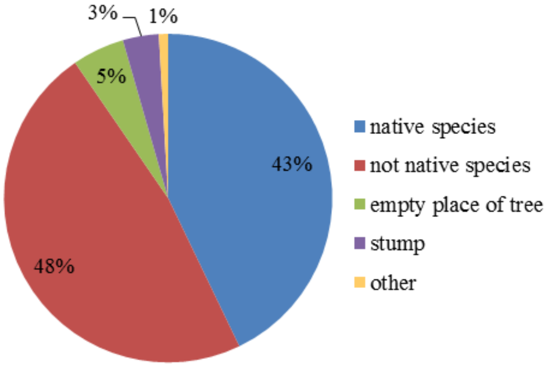


Fig. 2 The proportion of native and non-native species (miscellaneous: e.g. dried-out tree, removed planting space, unidentified species)

Table 1 The most common tree species in Szeged within the surveyed areas

Tree species		Number of individuals	%
Littleleaf linden	*Tilia cordata*	634	12.2%
Pagoda tree	*Sophora japonica*	542	10.4%
Common hackberry	*Celtis occidentalis*	472	9.1%
Silver linden	*Tilia tomentosa*	458	8.8%
Large-leaved Lime	*Tilia platyphyllos*	229	4.4%
Goldenrain	*Koelreuteria paniculata*	224	4.3%
Hore-chestnut	*Aesculus hippocastanum*	168	3.2 %
Manna or flowering ash	*Fraxinus ornus*	121	2.3%
Plane	*Platanus hispanica*	121	2.3%
Norway Maple	*Acer platanoides*	117	2.3%
dominant species	3086		59.38%
other species	1655		31.85%

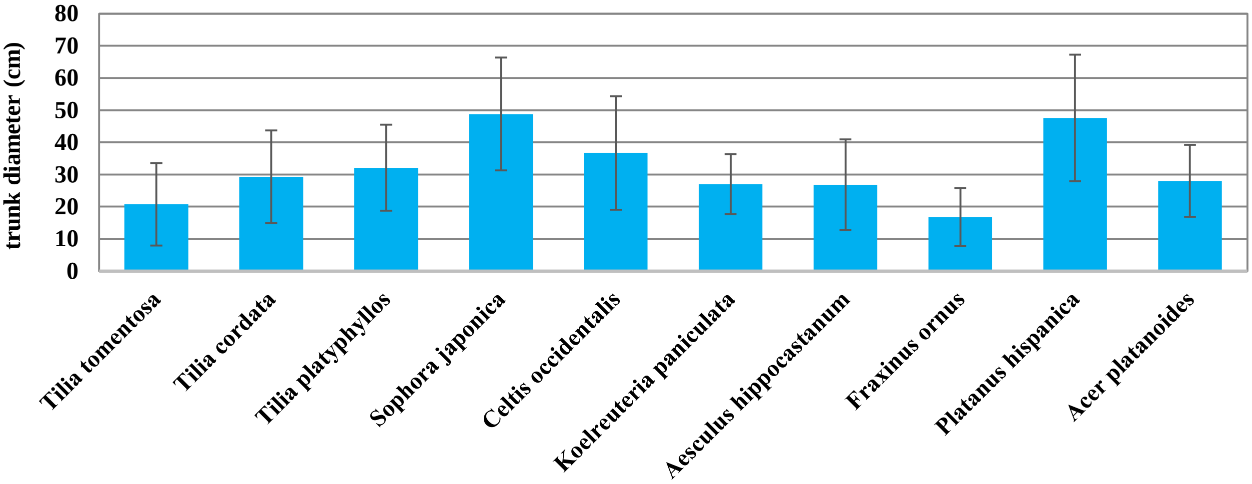


Fig. 3 The average dbh of the 10 most common tree species along with the standard deviation

It is noteworthy that empty planting spaces, tree stumps and other miscellaneous categories make up 8.6% of the whole database, which means 490 trees were waiting to be replanted. That number continued to increase in the winter of 2013, because in addition to the winter cuts a number of individuals had to be removed during the reconstruction of Kossuth Lajos Avenue. However, some trees were also planted in the autumn of 2013 and 2014. These changes are not included in the present analysis.

This also draws attention to the vital importance of an up-to-date database, which in addition to containing the existing trees, also includes the interventions, recorded in the shortest possible time. Only thus can the database facilitate effective green space management.

In addition to allowing the approximate estimation of tree volume value, the size parameters of the individuals serve as input to a number of other analyses. Although dbh depends on a number of parameters besides age, most importantly on species, light availability and other site conditions, the current distribution of stem diameter classes may be used to refer indirectly to the age of the stands. There is little information available in the literature concerning urban trees; there are more examples of such estimations from forest stands.

Sophora japonica and *Platanus hispanica* have the largest average dbh in the Szeged database, for both species it’s close to 50 cm. True, these species also have the largest standard deviation, therefore their dbh range (and probably the age as well) is higher than that of the others. Similarly, there is a large standard deviation in the case of *Celtis occidentalis*, but the average dbh is lower. *Tilia tomentosa*, *Koelreuteria paniculata* and *Fraxinus ornus* have the lowest average dbh. In case of the latter two species standard deviation is also the lowest therefore they show the most homogeneous age distribution of all the species in the database (Fig. 3) and are probably the youngest stands as well.

Looking at the age distribution of the total recorded tree population, the average estimated age is 36 years, while the software estimates the age of the oldest specimens as 103 years. The age group 15-45 makes up 66% of the total population (Fig. 4). The age distribution suggests that the last great tree planting campaign in this area was at the end of the 1980’s and the early 1990’s, but significant planting actions took place between the two world wars and in the 1970’s as well. (It should be noted that these results still only refer to areas of the city within Nagykörút. Since these events are intimately linked with the city's structural development, the extension of the database to the outer areas might significantly modify this picture). The number of the old trees (older than 90 years) is only 22. In the case of urban trees - with regard to the unfavourable ecological conditions and a fear of collapse damage – such high ages are very rare, especially in the light of Szeged having been destroyed by the great flood of 1879. As a result of the destruction, even the oldest trees can only be dated back to that time. Among the oldest trees are some of the planes in Széchenyi square, and a few old oak trees in Korányi Alley.

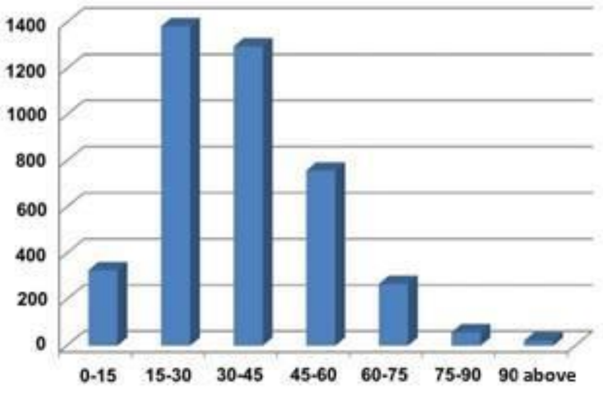


Fig. 4 Age distribution of the whole recorded tree population

Examining in detail the age distribution of the 10 most common species, the planting practices of the last hundred years are neatly outlined. It can be seen that Tilia plathyphyllos, Sophora japonica and Platanus hispanica have the most diverse age structure, which suggests that these species enjoyed an almost unbroken popularity over the last hundred years; they were favoured throughout the last century in plantations (Fig. 5).

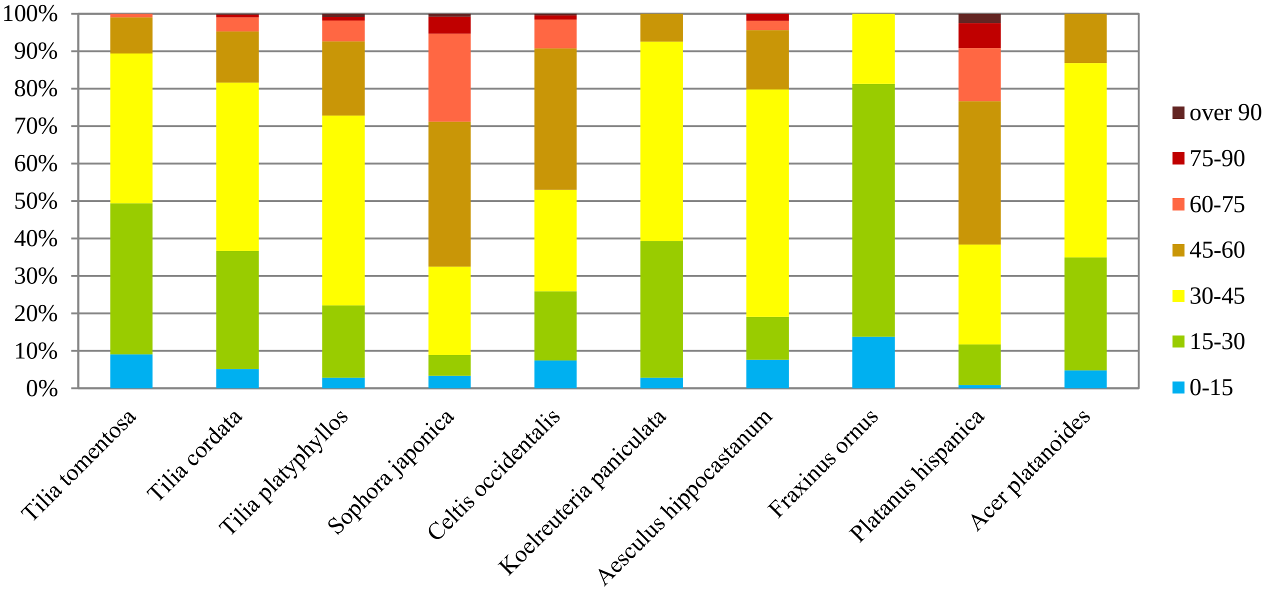


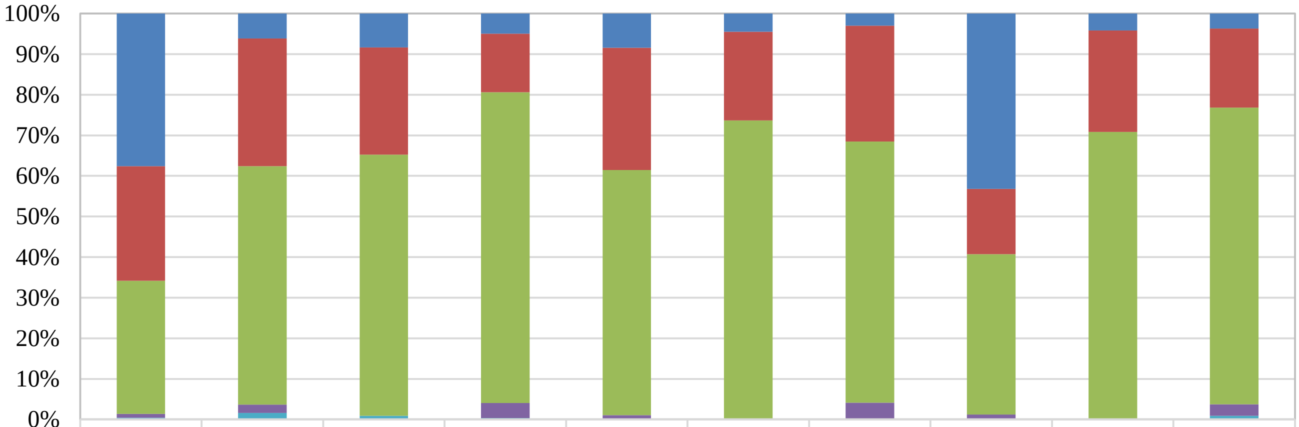
Fig. 5 Age distribution of the 10 most common species

Aesculus hippocastanum was clearly a favourite of the 1970's, the vast majority of today's white-flowered population belongs to the age group 30-45. The species is in many ways an ideal park tree; it has a very significant microclimate-improving effect since it allows only a small percentage of the direct radiation through the canopy, and it is also very decorative through almost the whole year. The species was very popular until the late 1980's (until the massive invasion of horse chestnut leaf miner - *Cameraria ohridella*) but by now the population is in a critical condition.

The proportion of older individuals is the highest in the case of *Sophora japonica* and *Platanus hispanica*. However, it seems that these species have lost some of their popularity over the last 20 years, since there are very few young individuals in the database.

Celtis occidentalis (with an average age of 42) shows the most uniform age distribution in the observed population. This is due to the fact it is one of most urban-tolerant species; much more tolerant to the unfavourable urban conditions (air and soil pollution, drought) than other species, so it was commonly used in the past as well as in today's urban tree planting.

In the last 20-30 years, however, the focus has clearly shifted towards *Tilia cordata* and *tomentosa*, *Fraxinus ornus* and *Koelreuteria paniculata*. The age distribution of lindens shows that from 1965 to the present day they are the fashion trees of the city of Szeged



	Tilia tomentosa	Tilia cordata	Tilia platyphyllos	Sophora japonica	Celtis occidentalis	Koelreuteria paniculata	Aesculus hippocastanum	Fraxinus ornus	Platanus hispanica	Acer platanoides
🟦 1	163	39	19	27	40	10	5	35	5	4
🟥 2	122	199	60	78	142	49	48	13	30	21
🟩 3	142	372	146	414	285	165	108	32	85	79
🟪 4	4	13	0	20	4	0	7	1	0	3
🟦 5	2	10	2	2	1	0	0	0	0	1

Fig. 6 Health status of the 10 most common species
(1: Optimal 2: Well-cared for, 3: Deficiencies, 4: Serious deficiencies 5: Neglected)

(Gaskó 2008), and in recent decades a rejuvenation process can be observed. However, *Tilia tomentosa* plays a more important role among younger individuals (about 50%). This is due to the fact that in recent years many perished *Tilia platyphyllos* trees were replaced with *Tilia tomentosa* individuals, more tolerant of the harsh urban environment.

In the inner, more built-up areas of the city, it is no wonder that in the last 20 years species with relatively smaller proportions have been favoured, which would not outgrow the confined space very fast – such as *Fraxinus ornus*.

The assessment of the health status of the population was carried out according to the standards presented in the methods section. In terms of the whole observed population it is pleasing that 40% of the trees are in a relatively good state, so only minor changes of the trunk and canopy are observed. The other end of the spectrum represents individuals with severe deficiencies, i.e. where serious trunk and/or foliage damage was observed, such as deep-penetrating trunk decay, rot of the root collar or the crown - which represents an imminent risk of an accident - or withering of the treetop, which warns of major root damage. These symptoms require immediate and significant intervention, and in some cases make it impossible to save the tree. The database contains 60 such individuals, which makes up only 3% of the total observed population, but since the most densely populated inner city areas are affected, they require increased attention.

The health status data of the 10 most common species draw attention to a number of interesting facts. The highest proportion of significant deficiencies (i.e. more than slight deterioration of health status), can be observed in the case of Sophora japonica (77%), *Platanus hispanica* (71%), *Koelreuteria paniculata* (74%) and Acer platanoides (73 %) (Fig. 6). The first two species can be characterized with higher average ages, including a relatively high proportion of older trees. Of course, this may explain the health status being worse than average.

The second place of *Koelreuteria paniculata* in these rankings is an interesting phenomenon since the age distribution suggests these trees to be relatively young, so poor health is not expected. It may be a reminder of the fact that the environmental circumstances in Szeged are probably not well tolerated by this species. The same applies to the case of Acer platanoides. The "serious deficiencies" or "neglected" category contain individuals with severe crown-base or root collar rot, or a strong deep-reaching parent branch decay.

These two categories appear in major proportions in the case of four species, *Tilia cordata, Sophora japonica, Celtis occidentalis* and *Aesculus hippocastanum,* which seem to be the most threatened of the observed tree population of Szeged. In Hungary the horse chestnut leaf miner (*Cameraria ohridella*) spread at a very fast rate in the early 1990's and that infection did not spare the trees in Szeged either. Even today, there are serious problems with the chestnut trees. In many cases, the individuals lose most of their foliage by the end of July, or the beginning of August and start flowering again in September – which in turn greatly weakens the tree's immune system.

Tilia tomentosa and *Fraxinus ornus* are in the best state of health among the recorded species. The proportion of individuals in the Optimal and Well-cared-for categories is way above 50%. A likely reason is that these species have the youngest stands, many of them having been planted relatively freshly.

DISCUSSION AND CONCLUSION

Urban woody vegetation plays an important ecological role in settlements, however they are not yet always appreciated accordingly in Hungary. There are very few municipalities who have an up-to-date usable tree register. In the current budget cycle (2014-2020) of the European Union there is particular emphasis on the development of green infrastructure. It is no coincidence, since the optimally chosen vegetation can locally mitigate the extremes of global change to a large extent and it can significantly improve the unfavourable living conditions in urban areas. However that requires an up-to-date green space database, which shows health status, location of the individual trees, and is also informative of the performed and to do tasks. Progress in Hungary in this respect has first appeared in some of the bigger cities. Szeged is at the forefront in this, since the city's tree register is constantly extended and updated. Such data are essential to the effective management of green areas, but keeping the data up-to-date is also the most labour-intensive part. During the everyday work trees are continuously replaced, there are rejuvenation actions, cuttings, so changes often occur, which need to be continuously monitored.

Most of the trees are not older than 45 years; and only 10 individuals in the current database belong to the age group of more than 100 years. This can be explained by the fact that tree planting affecting today's Szeged effectively began after the catastrophe of 1879, since trees planted before that time were destroyed by the flood. Wartime cuttings should also be taken into account, when the citizens of Szeged needed to acquire fuel for heating.

The oaks of Korányi Alley are among the oldest individuals that were demonstrably planted first, right following the flood. Therefore when the reconstruction of the river protection wall was carried out this was precisely the reason for the need to exercise caution during the construction works, as these old, healthy individuals represent a huge unique value. The age distribution of the tree population raises interesting questions. The question of how long it is "worth it" to keep an old tree is important for decision-makers and managers; i.e. what is the age when maintenance would become significantly more expensive (due to an increasing need for maintenance works, risk of accident, curled concrete, etc.) than the positive effects of the individual. Such aging populations usually have higher care needs, however due to their large canopy and consequently larger leaf surface can have a very significant air quality improving role;

furthermore such important aesthetic, historical, cultural values are connected to them, which are difficult to express in monetary terms.

The periods of increased tree planting are clearly visible in the age distribution data for each species, as is the fact that the constantly rejuvenated or freshly introduced species are in the best health. In some cases, however, contradictions arise, since *Koelreuteria paniculata* individuals despite the young population are in a poor state so their "profitable" maintenance is more difficult.

Concerning the health status of the Szeged tree population, in the case of certain species the proportion of the “deficiencies” category is relatively high. White-flowered *Aesculus hippocastanum* trees are especially in poor health. When the funding becomes available most probably the red-flowered variant of chestnut (Aesculus × carnea) will be used to replace these, which seems to be resistant to the pest destroying the other type. A noteworthy initiative to improve the health of the remaining population was the opening of the formerly asphalt-surrounded planting spaces in a substantial part of Szentháromság street. The open soil surface was covered with mulch and shrubs, which is supposed to greatly improve the state of the stand through allowing a better infiltration of rainwater. The poor health of the trees is probably related to the sometimes extremely parched urban soils. Unfortunately it is possible that the stand is already so heavily degraded that even this measure will not help.

The health status of species represented by older stands (*Tilia platyphyllos, Platanus hispanica and Sophora japonica*) is also worse than the average, the category of major deficiencies appears in their case. At present, *Tilia tomentosa* has the best health status, which may be the result of partly the young age of the stands, and partly of the fact that this sub-Mediterranean species tolerates urban conditions better than others. Therefore, it is an alternative to be considered when replacing other linden species.

Although the data presented in this study involve only a part of the total of Szeged’s street tree population, even the current database allows a highly complex analysis, of which here only species composition, age-, size- and health status distribution were examined.

The establishment of the appropriate species composition is very difficult. A lot of aspects should be taken into account by the maintainer; different public places have different needs and constraints thus different species can mean the ideal choice. In recent years *Fraxinus ornus* became fashionable; it is a popular species in fresh plantations. However planting a species with a relatively small leaf surface and high transmissivity in certain places (e.g. heavily used public squares) could contradict modern climate-conscious urban planning principles. The answers to these questions may become easier to find through in-depth data analysis and further research, which is the aim of our research group and also meets the needs of the municipality.

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A SPATIOTEMPORAL STOCHASTIC FRAMEWORK OF GROUNDWATER FLUCTUATION ANALYSIS ON THE SOUTH - EASTERN PART OF THE GREAT HUNGARIAN PLAIN

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Abstract

The current study was performed on a Hungarian area where the groundwater has been highly affected in the past 40 years by climate change. The stochastic estimation framework of groundwater as a spatiotemporally varying dynamic phenomenon is proposed. The probabilistic estimation of the water depth is performed as a joint realization of spatially correlated hydrographs, where parametric temporal trend models are fitted to the measured time series thereafter regionalized in space. Two types of trend models are evaluated. Due to its simplicity the purely mathematical trend can be used to analyze long-term groundwater trends, the average water fluctuation range and to determine the most probable date of peak groundwater level. The one which takes advantage of the knowledge of expected groundwater changes, clearly over performed the purely mathematical model, and it is selected for the construction of a spatiotemporal trend. Model fitting error values are considered as a set of stochastic time series which expresses short-term anomalies of the groundwater, and they are modelled as joint space-time distribution. The resulting spatiotemporal residual field is added to the trend field, thus resulting 125 simulated realizations, which are evaluated probabilistically. The high number of joint spatiotemporal realizations provides alternative groundwater datasets as boundary conditions for a wide variety of environmental models, while the presented procedure behaves more robust over non-complete datasets.

Keywords: Monte Carlo simulation, stochastic estimation, spatiotemporal modelling, groundwater, climate change

INTRODUCTION

The water body closest to the surface and mostly above the first confined zone is called shallow groundwater (hereinafter groundwater in this study). Groundwater is a characteristic environmental element of alluvial lowlands. It is important on the one hand as a water source during the dry season for woody, as well as for deep-rooted vegetation, on the other hand, the vertically seeping groundwater means an important recharge for deep-water resources. Climate variability can have significant impacts on the groundwater (Treidel et al., 2012). These impacts are likely to be particularly severe when the watershed is located on an area that is predominantly disposed by the effects of altering environmental conditions, such as the Great Hungarian Plain. As a consequence of climate change the annual distribution of the precipitation tends to become more and more extreme (IPCC, 2013). These harmful processes can be enhanced by other stresses on the hydrological system, as may occur where there are large extractions from the watershed. Groundwater is vital to both environment and society, thus understanding how climate change and human activities may disturb regional water regime is exceptionally important for mitigating future water resources.

The approximate state of the groundwater can be estimated by observing a temporal sequence of the groundwater depth via an observation network operating over the study area. However, the design of the observation network is critical and usually not enough dense to provide a clear view. Even the wells of the Hungarian measurement system, which can be considered much denser compared to other sensing networks worldwide, are located to cover 20-40 km^2 each. Thereby it is extremely important to select a proper method which enables accurate estimations of the groundwater state even from limited information of the measured sequences.

Previous studies (Pálfai, 1994) have revealed that in the recent decades the groundwater of the western part of the Great Hungarian Plain, the so called “Sand Ridge” between the Danube and the Tisza rivers is particularly affected by groundwater changes (predominantly the discharge of water resources). Although these former studies reached different results regarding the ultimate causes, our GIS-based quantitative analysis (Rakonczai and Fehér, 2015) successfully proved that the groundwater discharge is mainly influenced by altered climatic elements.

Our current study set both theoretical and practical goals. First, a brand new stochastic approach for the trend and variability analysis of the groundwater regime is introduced, considering water table as a spatiotemporally dynamic phenomenon. Second, we attempt to quantify the groundwater changes of the recent decade in South-Eastern Hungary.

STUDY AREA

The groundwater time series used in the current study consist of daily measured (depth to surface) water levels over the study site. The data were provided by the Lower Tisza District Water Directorate. The analysis is performed on an approximately 8490 km^2 study area in the South-Eastern part of the Great Hungarian Plain.

Groundwater depth measurements (given in cm) are available from 207 monitoring wells between 1/1/2005 and 17/5/2015. The spatial density of the stations shows locally diverse spatial distribution (Fig. 1). The length of the time series varies from 382 to 3,779 days. Most of the hydrographs has at least three daily measurements, only 5 of them show huge amount of missing data. There is no significant relationship between measurement density and spatial distribution. The area consists of three significantly dissimilar units.

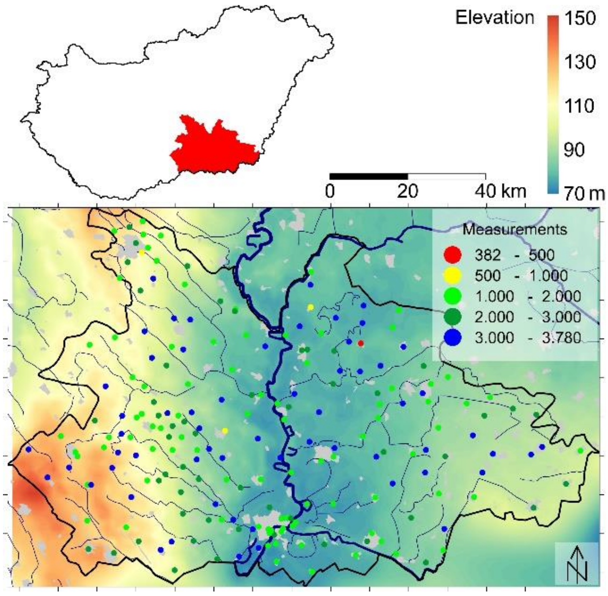

Fig.1 The study site with the operating gauge network alongside the count of available data

The western side is the eastern part of the so called Sand Ridge. This area is significantly affected by regional scale groundwater shortage in the last decades. Basin elevations range from 83 m on the Tisza valley to 143 m on the south-west. The area is deposited by the River Danube (the process was completed approx. 20 – 30 thousand years ago), and most of the landscape is covered by several-meter thick blown sand. Thereby, in the depressions semi-bound sand dunes, salty meadows can be usually observed on the surface. According to the dominant wind direction, the characteristic NW towards SE flow direction of the surface waters is determined by these relatively shallow features. These beds, however, barely carry any water, even in longer time periods.

Due to the elevated geomorphological position of the Sand Ridge, it is important to mention that groundwater resources can only be recharged by precipitation, since the opportunity of neither surface watercourses nor subsurface water flows is possible. This is the main cause of that more intense groundwater shortage which was observed in the higher area since the end of the 1970's when the amount of the annual rainfall significantly dropped for one and a half decade. The typical discharge was around 2 metres, however on higher regions this could surpass 15 metres. In the higher areas this unfavorable situation could not be normalized even after extensive rainy periods. In the lower parts of the ridge however, the groundwater not just recovered from the water shortage, but the water level even increased thus sometimes caused harmful surface floodings after persistent rainy periods.

The eastern part of the study site belongs to the alluvial fan of the river Maros. Basin elevations vay between 80 – 108 m. The landscape is slightly sloping towards west (to the river Tisza) and the north (to the river Körös). The former (approx. 2 – 18 thousand years old, Sümeghy, 2015) river branches can be still observed more or less. Most of the area is constituted by good quality chernozem soils, but in the deeper parts alkaline vegetation is also common. Although groundwater is recharged primarily by precipitation, in this case the subsurface groundwater flow from higher regions plays significant role, through coarser, porous channel deposits of the former river beds encompass the area.

The River Tisza flows southwards in the axis of the some 10-12 km wide central region. This landscape is a young alluvial plain, which was continuously built by the Tisza with its sediments until in the middle of the 19th century the river regulations were completed. This area is the deepest part of the Great Hungarian Plain (as well as Hungary), ranging from 75.8 m to 83 m. In the last one and a half centuries the river flows between dams. Occasionally the groundwater is connected to the Tisza but in common years, (when both low water levels and floods also occur) this kind of effect can be shown only within 5 km to the river.

GROUNDWATER AS A DYNAMIC PHENOMENON

Estimations of large scale and long groundwater hydrographs are important boundary conditions of numerous environmental models. However, no sufficient, continuous information is available about the state of the groundwater table, thereby it has to be determined.

Various forms of geostatistical approaches have been developed to map groundwater table from scattered water-observations solely (Delhomme, 1978; Aboufassi and Marino, 1983; Neuman and Jacobsen, 1984; Dunlap and Spinazola, 1984; Fehér, 2012). The first attempt which involved topography as supplementary data is based on the full cokriging system (Hoeksema et al., 1989), and was later improved to solve multiple usability problems (Xu et al., 1992; Xianlin and Journel, 1999). Kriging with an external drift (KED) provides an alternative to apply soft data into groundwater estimation (Desbarats et al., 2001; Fehér, 2015). However, kriging with local means (Goovaerts, 1997), which is based on undermining the global regression of the groundwater and soft data, offers the least estimation error on some Hugarian study sites (Fehér, 2015; Geiger, 2007).

The above mentioned studies focus solely on the spatial autocorrelation of an available, contemporaneous data thus consider interaction neither on temporal (within groundwater time-series on every single wells) nor on spatiotemporal (between spatially correlated hydrographs) domain. Commonly, the rarer the monitoring network is or the longer the missing data period is, the more important the selection of the appropriate estimation method is.

Global structures of autocorrelation functions, thereby results of any geostatistical estimation are determined by (1) the spatial and/or temporal sampling structure and (2) the stationary covariance function that characterize the relationship between any available observation (Journel, 1989). Resource estimations and analyses of dynamic natural processes are usually investigated by comparison of spatial patterns at different time instants (eg. Malvic and Zelenika 2014). However long-term observation networks rarely if ever provide complete datasets, thus (1) covariance matrices of different sampling patterns differ significantly even if similar covariance functions are assumed and (2) ignorance of the local behaviour of the temporal process or a temporary extreme event (such as locally altering intensity of human activities) will cause significantly different estimation from the expected local process, thus result in false resource estimation (Fehér, 2015). Though the observations are neither temporally nor spatially unique, the interpolation with missing data causes modification on the covariance matrix of any selected kriging system. This leads to a somewhat semantic error, while attempting to relate groundwater levels at two different time instants. Consequently, groundwater maps, which are estimated with distinct data distribution are incomparable, hence inadequate for resource or flow analysis. Furthermore, the application of these data as boundary condition of any type of numerical models, leads to false outcomes.

Numerical models are doubtlessly able to increase reliability of water table estimations by exactly defined physical relationships between groundwater and its influencing factors. However, these approaches are computationally expensive, furthermore uncertainties of model parameterization, temporally incomplete knowledge of the varying environmental factors, and dynamic upscaling of different input datasets make difficult the application of such numerical models (Fehér, 2015). In addition, the influencing factors of groundwater level proceed both temporally and spatially at different scales, so any spatial or temporal averaging or dynamic upscaling of these phenomena would change the original spatiotemporal correlations (Kyriakidis and Journel, 1999).

Groundwater, however, can be characterized in a stochastic framework (Mucsi et al., 2013), by involving soft data into the estimation (Fehér, 2012, 2015; Geiger, 2015), like digital elevation models, even if these models are not capable to explicitly represent dynamically changing relationships between groundwater estimate and a particular influencing process.

Groundwater time series commonly exhibit both spatial and temporal autocorrelation. Early spatiotemporal estimations treated time simply as an additional (2D+1) dimension (Eynon and Switzer, 1983). But, even if spatial autocorrelation is considered constant at any time instant, temporal autocorrelation may significantly differ place to place, due to different local influencing factors. Consequently, conventional interpolation approaches (including any type of 2D kriging algorithm) are inappropriate to handle this kind of joint spatiotemporal autocorrelation.

Since the temporal domain of the groundwater observations is more densely sampled compared to the spatial domain, the estimation of missing data can be more reliably carried out on the hydrographs. The well-informed time domain can be easily exploited by either employing multivariate AR models (Hosung, 1994; Rétháti, 1977a, b), generalized linear models (Gotway and Stroup, 1997) or spectral analysis (Chatfield, 1996; Kovács et al., 2004, 2011), though the results cannot be interpolated over the entire domain (Rouhani et al., 1992), thus these kind of spatial analysis are inappropriate to model groundwater change.

The spatiotemporal variability of the groundwater cannot be accurately characterized via the above mentioned, purely deterministic models, due to the deficient knowledge of the both spatially and temporally altering physical environment and limitations of observation capabilities. Since model parameters (like land use, hydrometeorological conditions, irrigation, pumping, instant state of the canal network etc.) are varying over both space and time (see Fehér, 2015), long term hindcast type deterministic models, which consider these influencing factors static, would make the false sense in the modeller that his all-rounder model is perfect.

In this paper groundwater is considered as a joint realization of a set of spatially correlated time series Kyriakidis–Journel (2001a, b), one for each grid node. Hydrograph model parameters are varying in space thus capturing space-time interactions. The difference of observed groundwater depth from these local trend estimates are regarded as a realization of a stationary spatiotemporal stochastic process.

Geostatistical space-time models provide a framework based on probability theory to analyze and forecast through spatial and temporal autocorrelation among available observations. In most cases a stochastic model by its own cannot explain unusual anomalies of the datasets, although that can often be explained by some other influencing physical processes.

The modelling of such dynamic processes brought various, but somehow similar approaches for numerous scientific and engineering fields including hydrometeorological conditions (Armstrong et al., 1993), precipitation profiles (Kyriakidis et al., 2004), pressure-temparature relationships (Mardia and Goodall, 1993; Hottovi and Stechmann, 2015), variability of geophysical components (Handcock and Wallis, 1994; Bogaert and Christakos, 1997a). Other similar approaches were implied in the estimation of soil moisture (Goovaerts and Sonnet, 1993; Papritz and Flührer, 1994; Heuvelink et al., 1997), diseases (Christakos–Hristopulos 1998), environmental hazards (Mateua and Ignaccolo 2015), deposition of atmospheric particles (Kyriakidis, 2001b; Singh and Gokhale, 2015) and ecological dynamics (Hohn et al., 1993; De Iaco et al., 2015).

These procedures are common in the sense that they separate the dynamic phenomenon into (1) spatiotemporal “trend” component, which expresses some long term patterns and (2) the “residual” component that represents some higher frequency fluctuations around the trend component. The separation of the trend and residual component reflects a subjective decision of the modeler and the available knowledge of the phenomena. The temporal trend can be characterized by deterministic parameters for each gauge (Dimitrakopoulos and Luo, 1997). The spatial correlation between temporal parameters represents every spatiotemporal interaction that exists between all of the influencing factors. The residual component is induced by some small scale, rapid or interim intense effects.

Several studies quantified long term hydrograph patterns of the Great Hungarian Plain. Recently performed time series analyses indicated annual periodicity on about 97% of the gauges (Kovács et al., 2004, 2011), which is clearly explained by annual discharge-recharge cycle (Ubell, 1954). Another questionable 5 and 11 year-long periodicities were also designated, which might slightly be identified by multiannual periodicity of the precipitation (Kovács and Turai 2004). Another 14-17 year-long or even longer periodicities are also detected on a smaller set of hydrographs (Rónai, 1985; Réthási, 1977), but the volume of these effects are negligible. It is important to highlight that despite these longer periodicities are “mathematically” really spotted, yet no clear, physical explanation of the underlying causes can be revealed, consequently, multi-annual periodicities must be treated carefully.

The temporal profiles are spatially non-stationary, due to altering spatial intensity of the environmental factors. Closer to rivers hydrograph trends usually show fewer long-term changes (Bezdán, 2011) and prone to mimic water level of the nearby river. The magnitude of the annual groundwater fluctuation on steeper terrain is less than close to permanent watercourses or even on elevated reliefs. The primary reason for the latter is that groundwater continuously replenished by gravitational flow through porous media from the ridges. By contrast, the only watersource is the periodically intense rainfall in elevated areas (Rakonczai, 2014).

Meteorological conditions show significant annual and local variability in the Hungarian Plain, so groundwater trends can be hardly expressed by polynomial and sinusoidal functions. Long-lasting river level changes, alteration of land use, irrigation and several other factors trigger further high frequency, hardly modelable effects on the groundwater level (Négyesi, 2006). Therefore, it is very crucial to take the patterns of the non-stationary spatial variability of the time series into account.

THE SPATIOTEMPORAL FRAMEWORK

Intrinsic hypothesis of the Simple Kriging requires a stationary variogram model, so that elimination of any relationship between groundwater observations and the spatiotemporal coordinates (Deutsch and Journel, 1998). Comparison of resources of non-complete groundwater datasets may undermine the strong correlation ($\rho = 0.98$) between groundwater elevation (above sea level) and topography (Fehér and Rakonczai, 2012; Geiger, 2015). However, the regression function can also be interpreted as a locally varying spatial trend (Fehér, 2015), thus only the residuals of the regression model need to be estimated (Goovaerts, 2000). Instead of the spatial regression residuals, hereinafter, for practical considerations, the groundwater depth (to surface) is considered spatially detrended.

Groundwater time-series are decomposed into spatial and temporal trend components (Eq. 1) and the fitting error of the trend function. Thereafter the trend components express TOPO spatial as well as $\mathrm{E}(\mathrm{Z_u t}) = \mathrm{m_u}$ temporal, smoothly varying expected patterns, and the rest is considered a frequently changing, stationary $\mathrm{E}(\mathrm{R_u t}) = 0$ residual component.

$$\mathrm{Z}_{\mathbf{u}}(\mathrm{t}) = \mathrm{TOPO} + \mathrm{m}_{\mathbf{u}}(\mathrm{t}) + \mathrm{R}_{\mathbf{u}}(\mathrm{t}) \qquad \text{(Eq. 1)}$$

Hydrograph trends can be expressed via $(\mathrm{K}+1)$ deterministic functions, which are defined by an initially chosen subjective model decision (Dimitrakopoulos and Luo, 1997). Most of the inspected hydrographs shows a downward trend, which was modelled via versatile polynomial functions. Spatial patterns of each estimated $\mathrm{b_k}$ trend coefficient theoretically expresses the locally and temporally varying intensity of some (known or unknown) $\mathrm{f_k}$ background process.

The spatial distribution of these partial trend component intensities can be expressed in two steps. First, a general function (Eq. 2) needs to be fitted individually on each hydrograph, then the given function parameters can be spatially estimated, considering their variograms.

$$\mathrm{m}(\mathbf{u}_\alpha, \mathrm{t_i}) = \sum_{\mathrm{k}=0}^{4} \mathrm{b_k}(\mathbf{u}_\alpha)\mathrm{f_k}(\mathrm{t_i}) \quad \mathrm{t_i} \in \mathrm{T}_\alpha \qquad \text{(Eq. 2)}$$

The spatial consistency for correct reconstruction of the trend field require either (1) to use identic variograms for each component regionalization or (2) to apply a Linear Model of Coregionalization (Deutsch and Journel, 1998; Fehér, 2012) or (3) to perform the estimation on an orthogonalized system, applying dimension reduction. In this study the Principal Component Analysis was applied for the orthogonalization of the trend components. A set of 125 sequential Gaussian simulations (Deutsch and Journel, 1998) of temporal trend PCA-values were generated on a 156×106 grid with a cell size of $1 \times 1\ \mathrm{km}^2$ for ensemble prediction. The number of realizations was determined by the spatial analysis of thickness change of the confidence intervals. The trend field for the entire spatiotemporal domain was thereafter revealed for each $(\mathbf{u}_\alpha, \mathrm{t_i})$ grid node using (Eq. 2), since estimated $\mathrm{b_k}$ trend coefficients are given as a median type estimation of the inverse PCA transformation of each simulated random field PCA score realization.

Since simple kriging is an exact interpolator, each trend estimate preserves its initial value at the exact gauge locations. Consequently, regionalized trend ensemble values at each gauge are quasi identical to the value provided by the fitted trend function at any time instant. In addition, the station specific, detrended, zero mean $\mathrm{R}_{\mathbf{u}}(\mathrm{t})$ residual process is quasi identical to the exact fitting error of the trend model. The ultimate goal of the spatiotemporal residual simulation is to estimate these values.

The first step is, to estimate spatial distribution of the temporal autocorrelation parameters (nugget, sill and range) individually for each variogram parameter, thus each residual time series is divided by its standard deviation thereby proofing its standard normal distribution that enables Simple Kriging to be used in a Sequnetial Gaussian Simulation framework (Deutsch and Journel, 1998; Mucsi et al., 2013). The standard deviation values of the calculated residual sequences were then simulated over the study site. The obtained residuals were back-transformed into the original data dimensions only after the stochastic simulation.

For the sequential Gaussian simulation, a spherical variogram function was automatically fitted individually on each normally distributed residual time series. The obtained nugget, sill and range parameters were then co-regionalized over the study site, by considering their spatial relationships. Here we chose a simple full cokriging method for the estimation (Goovaerts, 2000). In order to determine spatial autocorrelation of the gauges, the spatial variogram of the residuals was also modelled, via cross-validation (Isaaks and Srivastava, 1989). Thereafter the residuals were considered as joint-realization of a spatiotemporal stationary process. Subsequently sequential Gaussian simulation (Deutsch and Journel, 1998) was performed at each spatial coordinates with the appropriate spatial and temporal variogram parameters, thereby 125 temporal profiles were obtained at each unsampled grid node.

As the realizations of the residuals are obtained via conditional Sequential Gaussian Simulation and added to the estimated trend ensembles, 125 geostatistical spatiotemporal distributions of daily groundwater levels were revealed. The $S = 125$ alternative, equiprobable realization enables the probabilistic characterization of both the regionalized groundwater and also some simulated trend components. The following indicators were applied in the current study:

(a) At each node **u** the $\bar{z}(\mathbf{u})$ E-type estimate (the arithmetic mean) of the S simulated values $z^{(s)}, s = 1, \ldots, S$ is given as:

$$\bar{z}(\mathbf{u}) = \frac{1}{S}\sum_{s=1}^{S} z^{(s)}(\mathbf{u}), \quad \mathbf{u} \in D \qquad \text{(Eq. 3)}$$

(b) At each node u the $\sigma(\text{u})$ local standard deviation of the S simulated values $z^{(s)}, s = 1, \ldots, S$ is written as:

$$\sigma(\mathbf{u}) = \sqrt{\frac{1}{S}\sum_{s=1}^{S} z^{(s)}(\mathbf{u})]^2 - \bar{z}^2(\mathbf{u})}, \quad \mathbf{u} \in D \qquad \text{(Eq. 4.)}$$

(c) As E-type values and standard deviations of any individual grid node distributions are already revealed, the $Prob_c\,(\mathbf{u})$ confidence interval can be calculated in any c significance level. Thicker confidence interval indicates higher estimation uncertainty:

$$Prob_c(\mathbf{u}) = \bar{z}(\mathbf{u}) \pm Z_{c/2} \times \frac{\sigma(\mathbf{u})}{\sqrt{S}} \qquad \text{(Eq. 5)}$$

(d) c = 0 significance level of the confidence interval reveals the median-type estimate of the grid node estimation

$$Md(\mathbf{u}) = \bar{z}(\mathbf{u}) \pm Z_0 \times \frac{\sigma(\mathbf{u})}{\sqrt{S}} \qquad \text{(Eq. 6.)}$$

(e) The local probability $p_k(\mathbf{u}; z)$ of the grid node estimation exceeds a given threshold can be revealed as:

$$p_{(\mathbf{u},z)} = \frac{1}{S}\sum_{s=1}^{S} i_k^{(s)}(\mathbf{u}, z), \quad \mathbf{u} \in D \qquad \text{(Eq. 7)}$$

where $i_k^{(s)}(\mathbf{u}; z)$ is the indicator of $z^{(s)}(\mathbf{u})$, its value is: $i_k^{(s)} = 1$, if $z^{(s)}(\mathbf{u}) > z$, otherwise 0.

RESULTS

The groundwater level is simulated as joint ensemble images of a set of spatially correlated time series. Each hydrograph is decomposed into a spatiotemporal trend and a spatiotemporal residual component. The analysis proceeds by first comparison of goodness of fit of different parametric trend functions, followed by the regionalization and spatial evaluation of the revealed trend coefficients and long term groundwater alteration on the site.

Dimitrakopoulos and Luo, (1997) proposed three types of trend models which can be applied for time series modelling. The considered models satisfy both the tensorial invariance condition and provide a unique solution for the kriging system (Deutsch and Journel, 1998). These models are constituted by the sum of different degrees of polynomial and Fourier components. In this study we compared each combination of models from first to third degree polynomial and first to third degree Fourier models. The resulting mean average fitting error is ranging from a significant 41 to 50 cm. Our analysis highlighted that the increase of the components does not necessary result a siginificant increase of the fitting performance.

In this study we developed another model which involve some temporal pattern in the fitting process. The latter provided a 16-18 cm matching error, depending on the degree of the applied model parameters. Consequently, the latter is more suitable to express local dynamics of groundwater changes. Despite the significant matching error, the former model is still appropriate to interpret long-term differences of the groundwater dynamics.

Trend modelling without a temporal pattern model

Spectral analysis (Kovács et al., 2004, 2011) indicated annual cycle as dominant periodicity on the individual time series. Among analyzed function structures the first order polynomial (linear) function (Eq. 8) with annual periodicity provided besides very good function match, an easily interpretable result.

$$m(\mathbf{u}_\alpha, t_i) = b_0(\mathbf{u}_\alpha) + b_1(\mathbf{u}_\alpha)t_i + b_2(\mathbf{u}_\alpha) \cdot \cos\left(\frac{2\pi}{365.25}t_i\right) + b_3(\mathbf{u}_\alpha) \cdot \sin\left(\frac{2\pi}{365.25}t_i\right)$$

$$m(\mathbf{u}_\alpha, t_i), i \in T_\alpha \qquad \text{(Eq. 8)}$$

where $b_0(\mathbf{u}_\alpha)$ characterizes the initial depth of the groundwater on 01/01/2005, whereas $b_1(\mathbf{u}_\alpha)$ expresses long term recharge or discharge of the groundwater in the surroundings of any individual gauge.

The $a(\mathbf{u}_\alpha)$ amplitude of annual periodicity express an expected groundwater fluctuation range and the $\phi(\mathbf{u}_\alpha)$ phase value designates the serial number of the date concerning to the highest groundwater level. These indicators are averaged over the considered 10-year period and both are expressed by $b_2(\mathbf{u}_\alpha)$ and $b_3(\mathbf{u}_\alpha)$ Fourier components:

$$a(\mathbf{u}_\alpha) = \sqrt{[b_2(\mathbf{u}_\alpha)]^2 + [b_3(\mathbf{u}_\alpha)]^2} \qquad \text{(Eq. 9)}$$

$$\phi(\mathbf{u}_\alpha) = \tan^{-1}\left(\frac{b_3(\mathbf{u}_\alpha)}{b_2(\mathbf{u}_\alpha)}\right) \qquad \text{(Eq. 10)}$$

The $b_k(\mathbf{u}_\alpha)$ intensity coefficients for each gauge were calculated individually by Ordinary Least Squares algorithm. Note that the selected ordinary least squares (Searle, 1971) algorithm is a subjective model decision which completely determines the trend component estimation. The resulting components are thereafter regarded as exact data and estimated individually by sequential Gaussian Simulation (Deutsch and Journel, 1998; Mucsi et al., 2013) and evaluated later. The analysis of the correlation does not indicate any significant relationship among component pairs, unless some quasi relation between long term linear trend and periodicity. In practice this may indicate the relationship between low annual periodicity and a deep water level or high annual periodicity with lower altitude.

Trend analysis and stochastic simulation of the groundwater using a temporal pattern

The former chapter pointed out that elementary polynoms and sinusoidals provide poor efficiency in representation of frequent and uncommon hydrograph divergences by annually predicted periodicity and long term trends. In the forthcoming chapter a more accurate approach is presented. This chapter is based on the theory that a set of influence factors that affect large scale trend of the groundwater, are represented on every single hydrograph, while their intensity is varying over the site under study. The analysis begins with modelling of a common profile. This profile describes the most likely pattern, thus resulting minimal fitting error on most of the time series.

First, this profile can be a particular auxiliary data, for example satellite gravimetry (Gravimetry Recovery and Climate Experiment – GRACE, eg. Wardlow et al., 2016). Second, an intrinsic solution might be a series of arithmetic means or medians of time instants as it is presented hereafter. The joint time series model can be calculated in three subsequent steps:

1. Shifting every single time series by its mean value (normalization)
2. Dividing every single time series by its standard deviation (standardization)
3. Eventually, standard-normal values of different time series that belong to the similar time instant are considered as a statistical set, whose arithmetic mean or median can be calculated. The series of these values constitute the finally established joint time series model (Fig. 2).

The obtained joint model thereafter can be successfully fitted to the majority of hydrographs, using affine transformations (rotation, translation, scaling) and Fourier modulations (phase shifting). Note that arithmetic mean is more sensitive to outliers that are likely present in the dataset, additionally median is a more robust method if the statistical distribution of a set is non-normal. This way median over-performs the arithmetic mean, even if it does not appear on the fitting error comparison significantly.

The task is then to determine proper transformation parameters for every single $\mathbf{u}_\alpha$ gauge:

$$\begin{aligned} m(\mathbf{u}_\alpha, t_i) &= \sum_{k=0}^{K} b_k(\mathbf{u}_\alpha) f_k(t_i) \quad t_i \in T_\alpha \\ &= b_0(\mathbf{u}_\alpha) + b_1(\mathbf{u}_\alpha) Md(t_i) + b_2(\mathbf{u}_\alpha) t_i \\ &\qquad + b_3(\mathbf{u}_\alpha) \cdot \cos\left(\frac{2\pi}{12} t_i\right) \quad + b_4(\mathbf{u}_\alpha) \\ &\qquad \cdot \sin(\frac{2\pi}{12} t_i) \end{aligned}$$

$$m(\mathbf{u}_\alpha, t_i), i \in T_\alpha \qquad \text{(Eq. 11)}$$

where $b_0(\mathbf{u}_\alpha)$ indicate translation by y-axis, $Md(t_i)$ equals to the i^{th} value of the above discussed joint median time series model (Fig. 2). The joint time series is modulated by b_1 intensity along y-axis. $b_2(\mathbf{u}_\alpha)$ parameter defines the rotation of the temporal trend profile, $b_3(\mathbf{u}_\alpha)$ and $b_4(\mathbf{u}_\alpha)$ expresses the phase shifting along x-axis, thereby adjusting station specific differences of the annual groundwater phase. Note that higher order polynomials do not increase fit performance significantly, but their application would unnecessarily complicate the analysis.

The $b_k(\mathbf{u}_\alpha)$ intensity coefficients were calculated for each gauge individually by non-linear least squares (Gauss-Newton) algorithm. Note that the selected non-linear least squares (Searle, 1971) algorithm is a subjective model decision thereby completely determines the trend component estimation. The resulting components are thereafter regarded exact data. Although

Fig. 2 The applied joint median type time series model compared to a satellite gravimetry sequence (dimensionless units)

a very good fitting performance is achieved, the temporal trend model does not represent each hydrograph similarly. The proportion of the explained standard deviations (Fig. 3) shows that some hydrographs can not be modelled well locally. In these cases, the residual model will express the proportion that does not fit to the local trend.

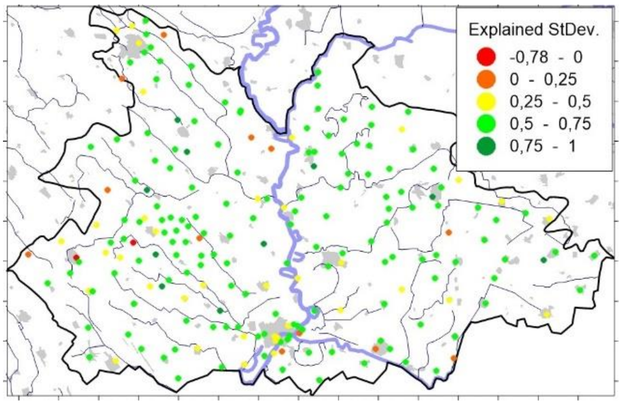

Fig. 3 Proportion of the explained standard deviation by gauge

Mathematical interpretation of the trend functions

The study proceeded by analysis of three characteristic hydrographs (Fig 4.). Limited information is available on Kecskemét gauge at the initial period. This well is located in an elevated area of the Sand Ridge, close to an urban area. In the initial period the groundwater seems shallow related to other time instants, until it unexpectedly drops by 4 metres in 2007. This deep state does not change until an extreme precipitation period in 2010. It can be also recognized, that the water level does mimic long range trend pattern only when it is not deeper than 150 cm. Csánytelek metering station follows the global trend until the end of 2010, thereafter the groundwater suddenly drops by 80 cm, while the hydrograph shape is still almost identical to the global trend model. Probably the precipitation this time still recharges groundwater with unchanged intensity until the water level is restored to the global trend in the winter of 2012—2013. The sudden discharge might be due to some anthropogenic inventions around the gauge. The well near Hódmezővásárhely shows uninterrupted groundwater trend. Analyzing long term trends, Hódmezővásárhely station is permanent, Kecskemét observator indicates increasing whereas the Csánytelek station shows a downward trend. Weak periodicity can be recognized in Kecskemét well in contrast to the other gauges introduced.

As shown in Fig 4. both fitting approach can represent long term tendencies just fine, whereas median based matching can reproduce hectic patterns of the groundwater dynamics better. While annual periodicity can somehow be reproduced, sudden uplifting of the groundwater around 2010 and 2011 can be hardly handled by pure Polinomial – Fourier models, due to extreme precipitation conditions (Szalai et al., 2012). The approach implementing a median type temporal pattern provides definitely a more sophisticated solution

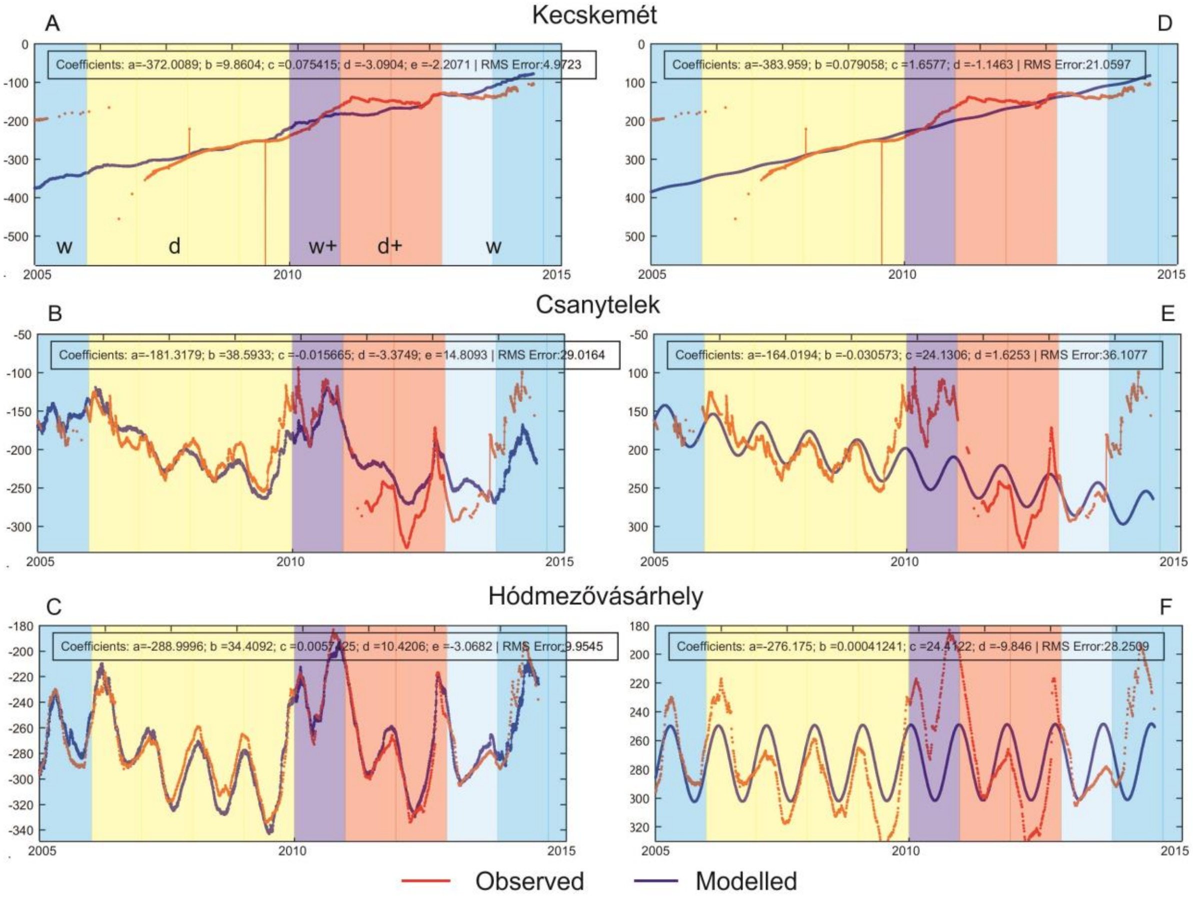

Fig. 4 Comparison of some characteristic groundwater time series (red) and their calculated temporal trend functions using purely mathematical (right column) and median type temporal pattern (on the left). W and D indicate wet or dry periods, whereas + means an extreme event.

compared to the one based on solely mathematical functions. Consequently, the median type model is very efficient in the estimation of missing observations.

By contrast, the purely Polynomial – Fourier type method is capable to interpret long-term (10 year) average groundwater tendencies for each individual gauge. The determined trend model parameters differ from gauge to gauge which enables to estimate long-term groundwater tendencies, by spatial interpolation of the appropriate model parameters. Through the analysis of the 1-year-long trend of every single observation of a hydrograph is represented by similar weight, consequently the fitted trend is not too sensitive to a small amount of outliers, rather more to the long period of missing data. In the present case the main analyzed factors (slope, fluctuation range and the date of the typical date of the highest water level can be determined by these restrictions.

Spatiotemporal estimation of the groundwater level

Spatiotemporal estimation of the groundwater is performed by sequential Gaussian simulation (Deutsch and Journel, 1999; Mucsi et al., 2013) of median model parameters. 125 equiprobable realizations were generated thus enabling geostatistical evaluation of the results. Cross covariance matrix of the given b_k parameters (not presented) highlighted some discrepancy among parameters, thus principal component analysis was performed to project them into x_k orthogonal planes. In the forthcoming step a spatial estimation of the components was reconstructed from these orthogonal planes, and the values of the appropriate grid node alongside temporal coordinates were substituted into Eq. 11. The analysis is proceeded by spatiotemporal geostatistical simulation of residual components. The temporal hyperparameters are modelled automatically via spherical model and regionalized by simple cokriging. The spatial variogram parameters are modelled via cross-validation.

The stochastic component of the groundwater at most cases characterized by at least a half-year-long temporal range, which represents the length of the autocorrelation within the hydrograph. Consequently, a half-year-long sampling interval would be enough to make good estimations on the stochastic origin changes of the groundwater.

The relatively small standard deviation values indicate that the applied temporal trend function was very effective, whereas the low value of temporal sills represents the portion of the autocorrelation function which can be expressed by the applied spherical model. The higher volume means the less randomness of the time series.

Eventually, 125 equiprobable realizations of time series were generated for each spatial grid node using sequential Gaussian simulation (Kyriakidis, 2001a). The results are added node-by-node to the Median-based temporal model realizations. These joint realizations were finally evaluated geostatistically by Eq 3. – Eq. 7. The multiple generated realizations made enable to probabilistically characterize (1) temporal change of volume, (2) estimation uncertainty, (3) spatial pattern, and (4) gravitational flow of the simulated groundwater and evaluate its environmental effects.

DISCUSSION

The investigated 2005-2015 period is very interesting from the hydrometeorological point ofview. Since the beginning of the detailed meteorological measurements (more than 100 years ago), the two highest and also the lowest precipitation volumes have been measured during the analyzed period in Hungary. The spatial average of the arrived precipitation over Hungary was 938 mm in 2010, but just 407 mm in the subsequent year. At the beginning of the investigated period, the precipitation exceeded the multi-annual average (note that 2005 was the second rainiest year), but due to the preceding dry period, groundwater resources yet showed significant deficit (compared to preceding decades) on the investigated site (Fig. 5). During the four subsequent dry years (alongside the well-defined annual periodicity), the depletion of groundwater resources occurred. The volume of the water shortage on the study site is at least 3 km^3.

In the very rainy year of 2010 the water shortage of the previous years not just recharged, but a significant water surplus was generated. Consequently, inland excess water occured in multiple areas, as a result of the increase of the groundwater levels. Right after an extremely wet year as an effect of an extremely dry year, a significant groundwater shortage was generated again. 2013 and 2014 were again rainier than the average, thus groundwater resources recharged again to the stage where they were 10 years ago.

We found that groundwater discharge primarily affected the higher altitude areas in the preceding 40 years.

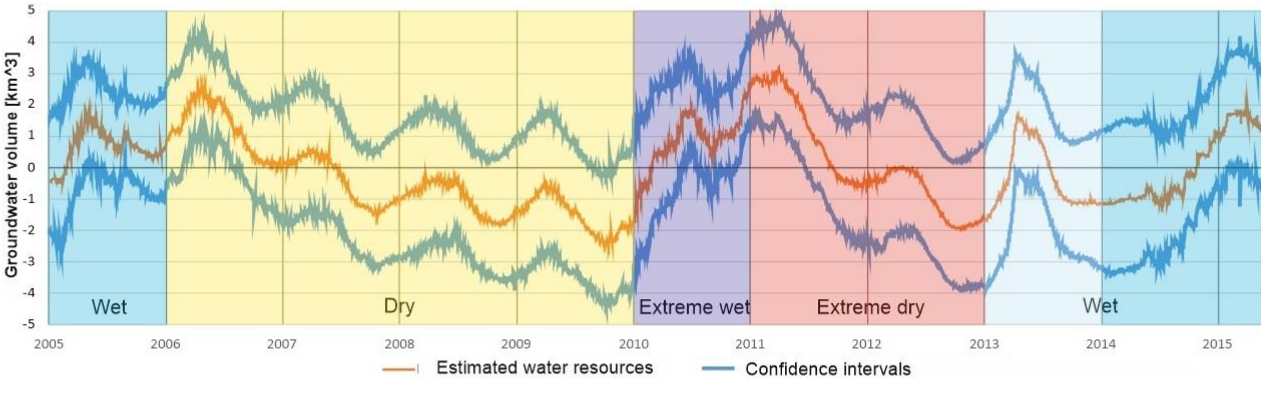

Fig. 5 Estimated groundwater resources related to the average of 2005-2015 versus precipitation related to the average of 1970-2000

However, we recognized that during the investigated 10-year-long time period, a downward tendency continued on the study site, but, at the same time, together with long-term trends, an exciting thing was observed: in the following years the depletion is more intensely affected the lower altitudes (Fig 6.).

At first sight this fact can be hardly explained, but it has a very clearly identifiable cause: in the recent years the characteristic spring and early summer floods of the Tisza River are absent. The river stepped out from its bed only once for a short time (in May 2013) between the spring of 2011 and the end of 2015. Nearly three years ago its water level was really deep, in spite of the Serbian river damming. The underground water flow probably increased towards the river, due to the permanent low water level. Due to the reverse flow direction in general case in a particular part of the year (when the Tisza is flooding), the groundwater resources can recharge some km wide along the river. This has importance not only because of the recharge of the water resources but also because of the tendency of minimal groundwater levels too. Indeed, if the groundwater level close to the river decreases, the underground water flow from several-meter high area towards the river possibly increases. This may explain the observed groundwater discharge on transient altitude zones.

A possible reason may arise the decreasing infiltration due to continuously developing wastewater sanitation system, however its effect should be more significant in a longer time period. Not surprisingly, due to the foregoing, extreme steep, a decisively downward trend can be experienced on the hydrographs along the River Tisza.

Locally such steep down- or upward trends can be experienced often, that hydrographs of the neighboring gauges absolutely do not confirm. These are probably consequences of a specific anthropogenic effect (like, exploitation of irrigation water from groundwater due to serious drought), long-lasting floods or inland excess water.

In the next step we analyzed average water level changes of the hydrographs from 2005 to 2015. Gauges located close to the Tisza River show the highest fluctuation within a year (Fig. 7.). On the alluvial fan of the Maros River slightly smaller, on the central area of the Sand Ridge some minimal water fluctuation can be detemined. Note, that these values are averaged to the whole analyzed 10 years (Fig. 4 D, E, F), however interannual values significantly diverge from the multiannual average. The average water fluctuation range in the observed area mostly can be determined within a 10 cm confidence interval, however the highest and lowest uncertainties were also observed along the Tisza river. Note that the lowest uncertainty area around Szeged (a city lying in the southern central area) are probably affected by the effects of the urban area.

The average date of the highest groundwater level is also determined in the 10-year long time series. As awaited, this pike value can be expected in most cases in March and April (Fig. 8.), however it can be determined with high uncertainty (with 30-60 day wide confidence interval). At multiple locations significantly different pike time moments can be experienced. This may refer to water inundation.

Our analysis indicated that the least groundwater was stored on 12/10/2009, and the most was available on 24/03/2011 (Fig. 5). Accordingly, the water resource

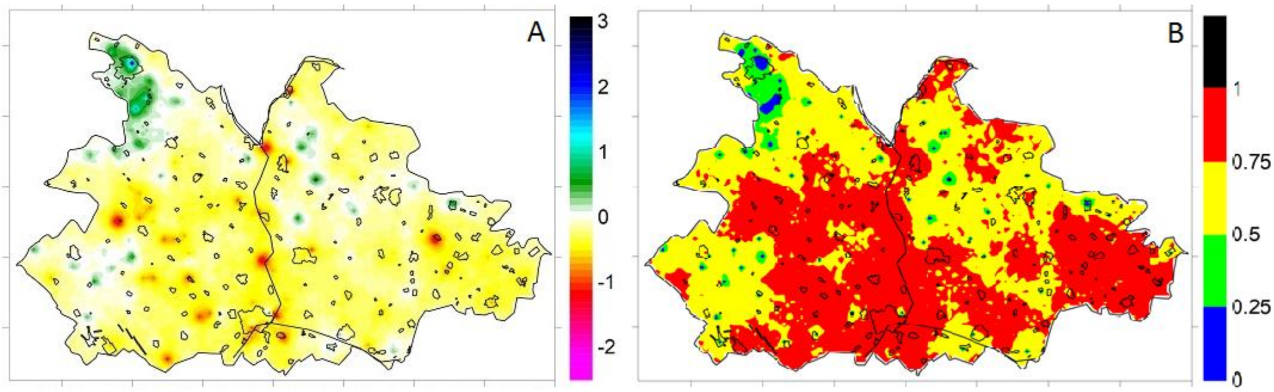

Fig. 6 Average annual change of groundwater in cm (A) and probability of the groundwater discharge over the 2005-2015 period (B)

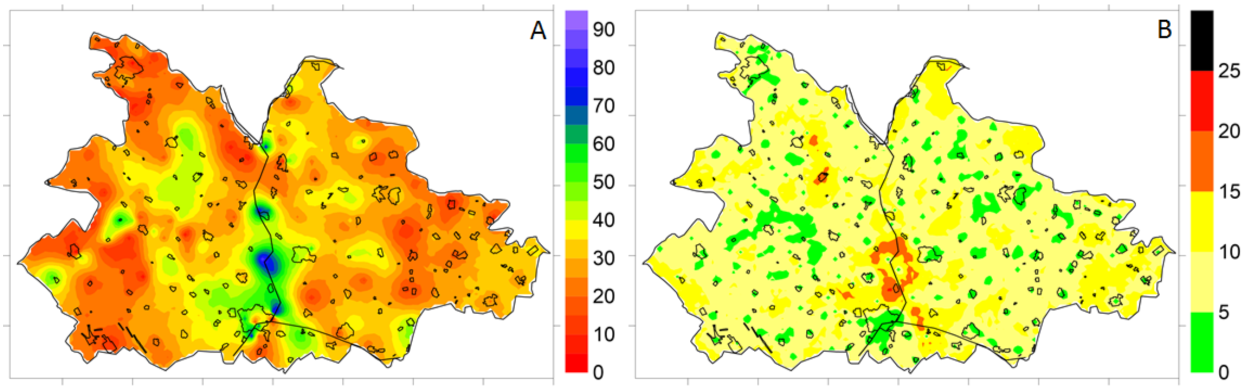

Fig. 7 Estimated groundwater fluctuation range averaged over 2005-2015 (A) and the estimation uncertainty expressed in cm (B)

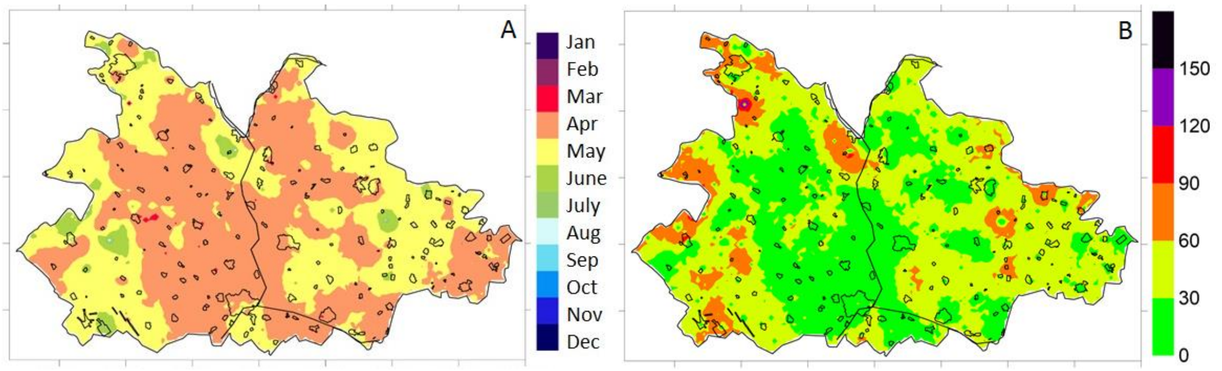

Fig. 8 Estimated date of the pike groundwater level averaged over 2005-2015 (A) and the estimation uncertainty expressed in days (B)

shows cca. 5.5 km^3 fluctuation (discharge) in one and a half years. The groundwater level map of these two moments is illustrated in Fig. 9. Extremely low groundwater level can be seen in 2009 on the western site, whose spatial pattern draws well the Sand Ridge. In contrast, the highest water level can be seen not along the Tisza River, as it was expected, but half way between the Sand Ridge and the river. This has two possible reasons: (1) the river plays a role as a “drainage channel”, thereby tapping the water resources from its neighborhood, and (2) the water resources are significantly replenished by gravitational flow from the Sand Ridge even in drought periods. The relatively higher water levels of the eastern part of the study site can be considered similarly as a result of uplifting underground flows through former water beds.

The situation in 2011 is at least as interesting as the above explained. On the area of the Sand Ridge some 2-3-meter-deep water levels evolved, which means 2-meter recharge there. However, from agricultural perspective a very harmful situation occurred. On most of the site, the water depth was shallower than 1 meter, and in worst cases it inundated the surface. For example, in the eastern zone of the Sand Ridge, the subsurface water flow from the higher areas elevated the groundwater level insomuch that it caused floodings on the ground. The pattern of the groundwater on the former alluvial fan of the Maros river quasi designate the former main river beds, probably attributable to the the permeable bed deposits.

CONCLUSION

The methodology originally proposed by Kyriakidis and Journel (2001) has been improved to the stochastic analysis of non-complete, daily observed groundwater levels on a South-Eastern Hungarian site.

Groundwater hydrographs are considered spatially correlated due to the similar long-range background processes. The well-informed time domain was capitalized to improve reliability of a spatiotemporal estimation. The simulated hydrographs provide a probabilistic framework to estimate and evaluate both temporal and spatial patterns, furthermore, changes of

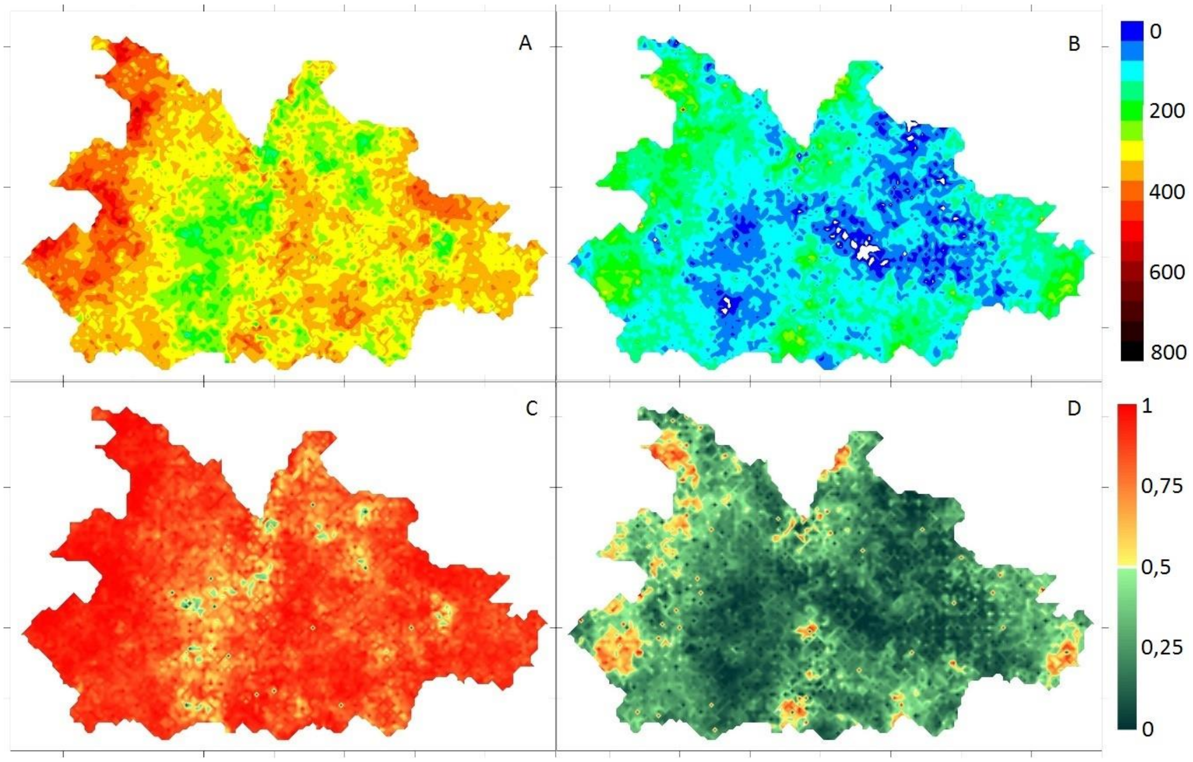

Fig. 9 Stochastic evaluation of 125 joint spatio-temporal stochastic simulation. E-type estimation of the groundwater depth in 12/10/2009 (A), in 24/03/2011 (B) and the probability of the groundwater deeper than 2 meters in the similar time instants (C and D respectively)

available water resources on the site alongside the space-time uncertainty of the estimations. The methodology can be well supplied to determine spatial and temporal patterns of the groundwater resources.

After the 1970s in Hungary, a serious groundwater discharge had occurred on the Sand ridge, between the river Danube and the Tisza. In some particular sites this depletion seems irreversible. The main causes are attributed to water extraction and the increasing area of forests. Nevertheless, our study shows that in a decisive part of the area, besides groundwater depletionc the meteorological (and climatic) changes can be identified. Specifically, in the whole Danube-Tisza interflow, whose area is about twice as large as the area of the western part of our study site (to the west of the Tisza river), cca. 2 km^3 of potable water was exploited in the recent 40 years, while the effect of a specific drought year could exceed this volume.

Though, instead of the continuously cumulating effect of water exploitation, the resource trend pointed to the close relationship with rainfall conditions. Investigations on the other hand highlighted indirect (stealthy) effects of climate change. Due to the decrease of the arriving precipitation on the Tisza catchment, the water resources of the river were reduced. This also had a negative effect on the groundwater resources.

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TREE-RING WIDTH AND ITS INTERRELATION WITH ENVIRONMENTAL PARAMETERS: CASE STUDY IN CENTRAL HUNGARY

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Abstract

Tree ring width is influenced by several internal and external factors, among which climate became one of the most dominant due to the altering conditions and patterns of precipitation and temperature. The study aims to analyse the interrelationship between tree ring-width and the dominant environmental parameters in a landscape exposed to water scarcity in the past decades due to climate change and human interventions. Scots pine (*Pinus sylvestris*), black locust (*Robinia pseudoacacia*) and white poplar (*Populus alba*) plantations were sampled to reveal their exposure to climatic forcing and water scarcity (different water availability). Correlation and similarity analysis were carried out to compare the calculated ring-width indices to climatic parameters and aridity indices. Tree ring sensitivity was assessed to reveal the impact of water scarcity on yearly ring-growth. Spatial overlapping of significance levels and mean sensitivity with the hydrological changes of the past decades were evaluated to reveal presumable spatial differences of the investigated samples. In the study area (South Danube-Tisza Interfluve) droughts and the deep groundwater table had both impacts on tree growth. The spectacular decrease of ring-width corresponds to the drought years determined by the investigated aridity indices. The relationship between the climate parameters and the ring-widths varies spatially with the changing site conditions. The highest level of correlation coefficients was experienced in areas with the lowest level of water availability. Ring-width sensitivity assessments showed an increasing tendency of sensitivity when comparing the consecutive decades, except for samples with favorable water availability.

Keywords: tree ring, sensitivity, climate change, water scarcity

INTRODUCTION

Recent climate change influences the species distribution and tree growth in many regions of Europe (Lenoir et al., 2008; Way and Oren, 2010) and due to the projected changes in climate extremities further impacts are expected (Mátyás, 2010; Lindner et al., 2014). Tree responses depend on both internal (species characteristics) and external (local site conditions) factors (Fritts, 1976). Climate change results in both positive and negative responses on forests, e.g. drought-induced increase of mortality and species range retraction (Allen et al., 2010; Hlásny et al., 2011), increased risk of forest fires (Venäläinen et al., 2014), and increased productivity at higher elevations and latitudes (Jolly et al., 2005). Due to the experienced impacts of the past decades, there is an increased need for the exact knowledge on how and to which extent the factors influence the functioning of the environmental systems.

Consistent with global and continental trends an increasing trend of the regional temperature was experienced in the Carpathian Basin. There is also a rise in the regional intensity and frequency of extreme precipitation, while the total precipitation has decreased (Bartholy and Pongrácz, 2007). As a result, the area has been increasingly exposed to hydro-climatic extremes e.g. drought, inland excess water, high magnitude flood (Pálfai and Herczeg, 2011; Mezősi et al., 2014). According to regional climate model predictions, more areas will face increasing temperature and changing precipitation conditions (Bartholy, 2011; Blanka et al., 2013), and the further increase of the hydroclimatic extremes is also projected (Mezősi et al., 2014).

The relation between tree ring growth and climatic parameters was investigated for several species in Hungary. The impact of precipitation on Turkey oak (*Quercus cerris*) was investigated by Szabados (2008), where tree rings were sensitive to the annual changes of precipitation, furthermore precipitation from April to June proved to be the most important period of tree growth. Kern et al. (2013) carried out separate investigation on early and latewood width of Pedunculate oak (*Quercus robur*), where the correlation analysis revealed relatively strong response to growing season precipitation for both, and the strongest correlation was found with the precipitation total from November of the year preceding the tree ring growth to August of the growth year. The impact of climate change on beech (*Fagus sylvatica)* was assessed by Garamszegi and Kern (2014), who identified late spring-early summer precipitation as the primary climatic factor governing the beech growth. The authors indicated no evidence of a distinct decline in radial increment, but a significant increase in climatic impact on growth including probable changes and shifts in the vegetation period. Szabados et al. (2012) analysed black locust *(Robinia pseudoacacia L.)* samples from Nyírség region, and found the precipitation of May-July period, especially the precipitation in May as the most determinant for tree increment. The increasing temperature of the vegetation period has negative impact on tree growth.

The consequences of climate change and the anthropogenic activities (e.g. water drainage, water exploitation) contributed to groundwater table decrease in significant part of the Great Hungarian Plain (Pálfai, 1994; Kuti et al., 2002). The highest lowering is experienced in the Danube-Tisza Interfluve, where the missing groundwater resource is approximately 6-9 km^3 in dry years that almost equals to the annual water consumption of Hungary (Rakonczai, 2011, 2014). Several studies investigated the causes and the consequences of this phenomenon in the past 3 decades and estimated the role of the natural and anthropogenic factors. Nowadays, the natural factors (decreasing precipitation, increasing temperature and evapotranspiration) are assigned as the most dominant contributing parameters to the phenomena, especially on the higher-elevated part of the Interfluve (Völgyesi, 2006; Szanyi and Kovács, 2009; Rakonczai, 2014). The water scarcity became the most dominant limiting factor for vegetation in this region and results in changes of wetland habitats (Biro et al., 2007; Deák, 2010; Ladányi et al., 2010; Rakonczai, 2011) and decreased forest productivity determined by remote sensing (Kovács, 2007). The knowledge of forest responses to different hydro-climatic changes in this region is scarce.

This study aims at the investigation of the interrelationship between tree ring-width and t dominant environmental parameters by correlation analysis of time series and by the assessment of their spatial distribution. The study area is highly exposed to water scarcity, thus the main question is how tree-ring sensitivity is influenced by the different availability of water.

STUDY AREA

The study area is located between the Hungarian sections of the Danube and Tisza rivers in the Carpathian Basin (Fig. 1). The area developed of fluvial sediments, the ancient alluvial fan of the Danube River (Borsy 1989). The surface is covered by blown sand on most of the area, but silty and clay sediments are also appear close to the rivers. The area is influenced by continuous groundwater table decrease compared to the 1970s due to climate change and anthropogenic activities (Rakonczai, 2011). The present groundwater level has high spatial variability: in the highly elevated areas it varies between 5-20 m (e.g. Illancs microregion in Bácska Plain Mesoregion), and towards the rivers it decreases. Close to the rivers the depth of groundwater table is around 1 m or less. Thus vegetation growth is highly dependent on precipitation, especially on elevated areas. These areas are the most exposed to water shortage in drought years, thus vegetation development is strongly influenced by the changes of the climate parameters. The annual mean temperature is around 11 °C and the annual amount of precipitation is between 500-600 mm. In July the mean temperature is around 21 and 23 °C, the precipitation in the summer half-year is at about 300 mm (OMSZ, 2014). The temperature shows

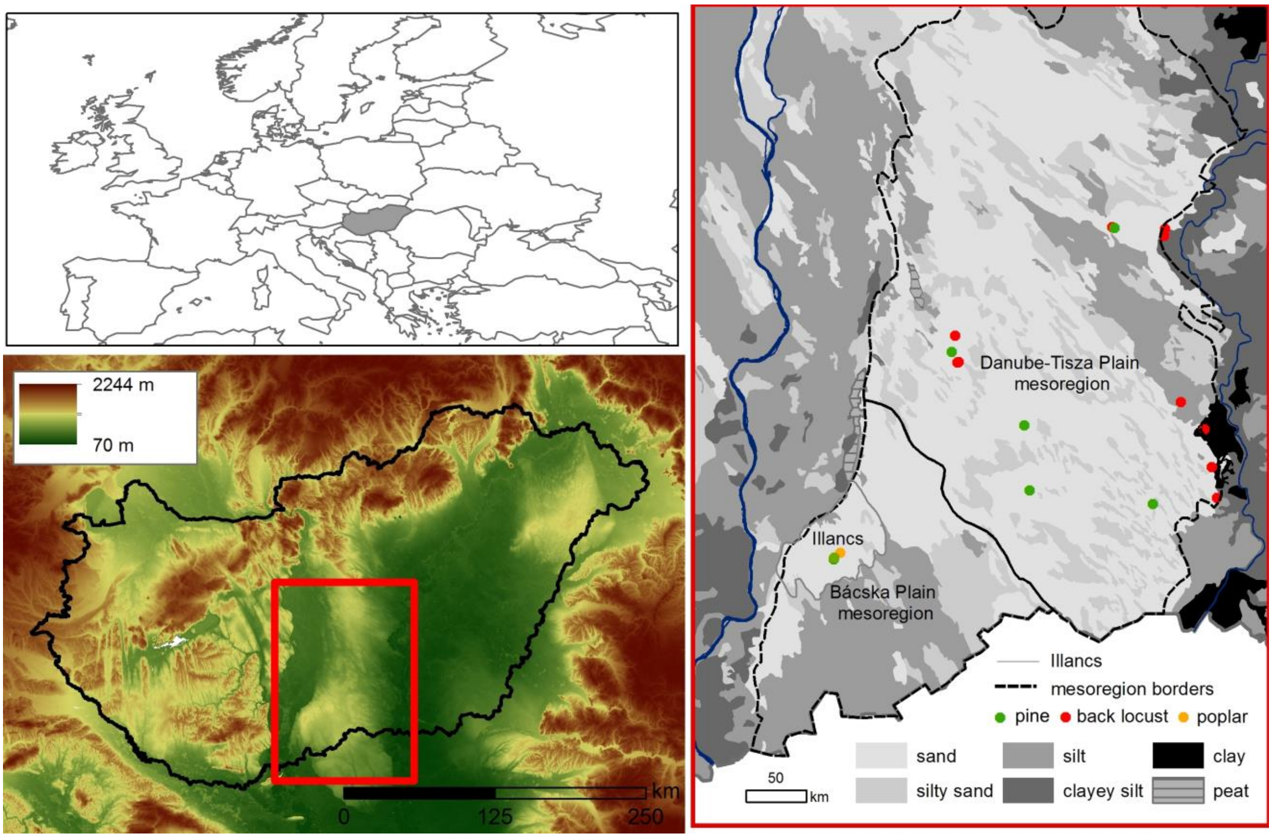


Fig. 1 Location of the study area in the Carpathian Basin and the sampling sites

significant yearly variability, however, an increasing tendency of the temperature can be clearly detected. Since the 1990s, warm years occurred more frequently. In terms of the precipitation conditions of the area, decreasing tendency can observed, years drier than the average occur more frequently and the temporal distribution of precipitation is less favorable. Therefore, drought years occurring increasingly frequently.

The dominant land use type in the area is arable land based on Corine Land Cover 2006. The proportion of forests is low and large part of them are planted with introduced species (e.g. *Robinia pseudoacacia*, *Pinus sylvestris* and *Pinus nigra).*

METHODS

Scots pine (*Pinus sylvestris*) (abbr. pine), black locust (*Robinia pseudoacacia*) and white poplar (*Populus alba*) (abbr. poplar) planted forests were investigated to analyse the sensitivity and the exposure of forests to climate parameters. Altogether 10 pine and 10 poplar trees from two forests were sampled in the highest-elevated, blown sand covered areas in the Bácska Plain mesoregion (Illancs microregion), further 5 pine and 9 black locust plantations were also investigated at lower elevation of the sand ridge (Danube-Tisza Plain mesoregion) on soils characterised by sand, silty sand and silt textures. During sampling tree height, tree health, foliage and trunk were considered. The age of trees varies between 23-47 years (Table 1).

Table 1 Age of the investigated samples

	Age of trees (Illancs, Bácska Plain mesoregion)	Nr of trees (pcs)	Age of trees (Danube-Tisza Plain mesoregion)	Nr. of trees (pcs)
pine	31-45 yrs	10	24-37 yrs	5
black locust	-	-	23-47 yrs	9
poplar	27-43 yrs	10	-	-

Samples were mostly collected by increment borers, though trunk slices were also studied, where investigations were carried out for 4 main directions. After sample preparation ring widths were measured using LINTAB 5 Tree-ring measuring station and TSAP-Win software.

Ring widths vary not only with the fluctuations of environmental conditions, but also with systematic changes in tree age. The standardization of ring-width measurements are necessary to remove the decrease in size associated with increasing age of a tree (Alestalo, 1971). Thus, ring-width indices were calculated by fitting a curve to each measured series and dividing each ring width by the corresponding value of the curve (Fritts, 1976) (Fig. 2).

Detailed assessment was carried out at the highest elevated Illancs microregion. Here, ring-width indices were compared to climate parameters (annual precipitation (Pa), precipitation of the vegetation period (Pv) and mean temperature in the vegetation period (Tv)) based on the neighboring meteorological stations (Szeged, Kiskunhalas), furthermore to drought indices that combine basic meteorological parameters to describe the yearly exposure to water scarcity or surplus. In the assessment Pálfai Drought Index (PAI, Pálfai, 1990) and Forest Aridity Index (FAI, Führer et al., 2011) were calculated (Eq.1-2). For the comparison of climatic indices and ring-width indices correlation coefficients were calculated. The similarity of ring-width and drought index pattern was also evaluated, based on the Gleichläufigkeit test method (Schweingruber, 1989), which analyse the agreement between the interval trends of two curves. The similarity was expressed in percentage.

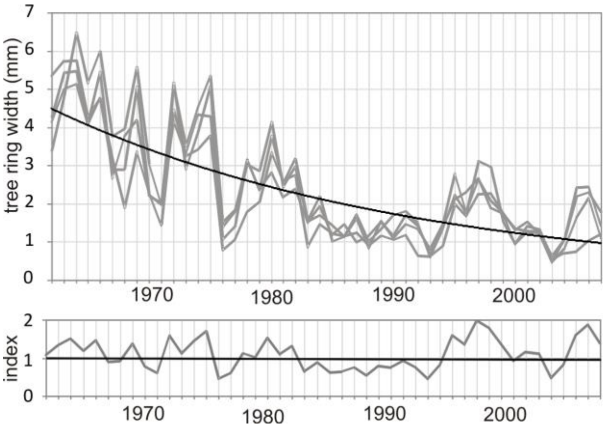


Fig. 2 Method of ring width index calculation

Forest Aridity Index (Führer et al., 2011):

$$\mathrm{FAI} = \frac{T_{VII-VIII}}{P_{V-VII}+P_{VII-VIII}} * 100 \qquad \text{(Eq.1)}$$

where, T: monthly mean temperature, P: monthly precipitation sum

Pálfai Drought Index (Pálfai, 1990):

$$PAI = \frac{t_{IV-VIII}\,(°C)}{P_{X-VIII}\,(mm)} * 100 * k_1 * k_2 * k_3 \qquad \text{(Eq.2)}$$

where, T: monthly mean temperature, P: monthly precipitation sum, k_1: correction factor estimating heat waves, k_2: correction factor estimating duration of dry spells, k_3: correction factor estimating groundwater depth.

Based on the calculated ring-with indices, ring-width sensitivity was also assessed (Eq. 3-4) which showed the variability of ring-widths in the consecutive years reflecting changing environmental conditions. Ring width sensitivity was calculated following Fritts (1976):

$$S_{i+1} = \frac{(x_{i+1} - x_i) * 2}{(x_{i+1} + x_i)} \qquad \text{(Eq. 3)}$$

where S_{i+1} is the sensitivity of the tree rings in i+1 year, x_i is ring width

Mean tree-ring sensitivity was defined as:

$$S = \sum_{i=1}^{i=n-1} \frac{Si}{n-1} \qquad \text{(Eq. 4)}$$

where n is the total number of tree-rings

According to Horváth et al. (2003), mean tree ring sensitivity classes are the followings:

S<0.2 low sensitivity
0.2<S<0.3 medium sensitivity
S>0.3high sensitivity

At the study sites of Danube-Tisza Plain mesoregion tree-ring sensitivity was calculated, furthermore correlation coefficients of ring-width and PAI and FAI were calculated for spatial assessment.

Based on the results, spatial assessment was carried out, where the correlation coefficients of PAI and FAI and the tree-ring sensitivity were analysed to reveal the effect of exposure to water scarcity (different water availability) on tree growth.

RESULTS

Assessment of tree samples in the highest elevated Illancs microregion

Pine samples showed increasing variability in the past two decades compared to previous periods (Fig. 3a). The lowest ring-width indices were experienced in the most severe drought years (e.g. 1993, 2003) and the humid periods (e.g. the end of the 1990s) were indicated by the highest values. The period between the end of the 1970s and the early 1990s showed the lowest variability of ring-width indices.

A strong similarity of the ring-width to aridity indices could be identified. The percentage of the years, where the interval trends of two curves agree, varies between 64.3–85.3% and 60.0–85.3% in case of PAI and FAI respectively. The percentage values were somewhat higher in case of PAI compared to FAI at all pine samples.

Poplar samples also showed increasing variability in the past two decades compared to the previous periods (Fig. 3b). The lowest and highest ring-width indices were experienced in the same periods as it was observed in case of pine trees. In this case the 1980-1990 decades had the lowest variability of ring-width indices.

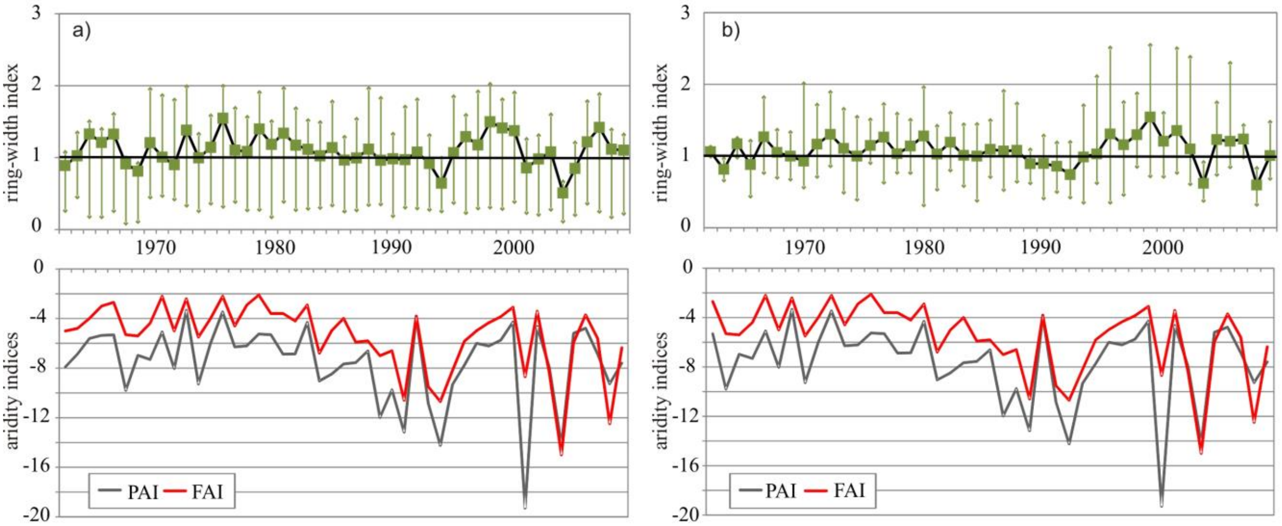
The similarity of the ring-width and the aridity indices of poplar samples were similar to the pine, percentage values related to PAI and FAI were 61.0–81.4% and 60.5–88.4%, respectively. However, in case of poplar trees the higher percentage values varied between PAI and FAI from sample to sample and FAI showed higher similarity in case of 7 samples.

As a result of the correlation analysis, PAI and the FAI values indicated the highest correlations with the ring-width indices in the case of all samples (Fig. 4a). The correlation was significant at the 0.01 level and the 0.05 level for 50-50% of the samples, respectively.

The relationship of the ring-width indices with the precipitation (Pa and Pv) was lower compared to the aridity indices, and in case of a few samples the correlation was not significant, however the correlation with the precipitation of the vegetation period (Pv) was somewhat higher. The lowest level of correlation could be identified in case of the mean temperature of the vegetation period (Tv) with the ring-width indices, and more than half of the samples showed no significant correlation with this factor.

The relationship between the investigated variables was not so evident like it was in case of the pine trees, they showed a higher standard deviation. PAI was the investigated factor, where the most samples showed significant relationship with the ring-width indices (Fig. 4b). The relationship with the precipitation was higher compared to the temperature in this case as well.

The calculated decadal mean tree-ring sensitivity of the pine samples indicated medium and high sensitivity of ring-widths for almost the whole period, except for some samples between 1970-1980 and 1980-1990 periods (Fig. 5). An increasing tendency in sensitivity values was identified towards the past two decades.



%	1	2	3	4	5	6	7	8	9	10
PAI	79.5	80.4	82.6	81.2	64.3	68.7	85.3	78.5	77.5	77.5
FAI	75.0	76.1	73.9	78.1	60.0	62.5	85.3	80.5	72.5	67.5

%	1	2	3	4	5	6	7	8	9	10
PAI	61.0	78.4	81.4	75.0	79.5	70.0	56.1	64.1	55.8	69.2
FAI	73.2	81.1	88.4	71.9	76.9	73.3	61.0	61.5	60.5	73.1

Fig. 3 Mean, minimum and maximum values of the investigated ring-width indices and the similarity between the samples and the aridity indices of pine (a) and poplar samples (b)

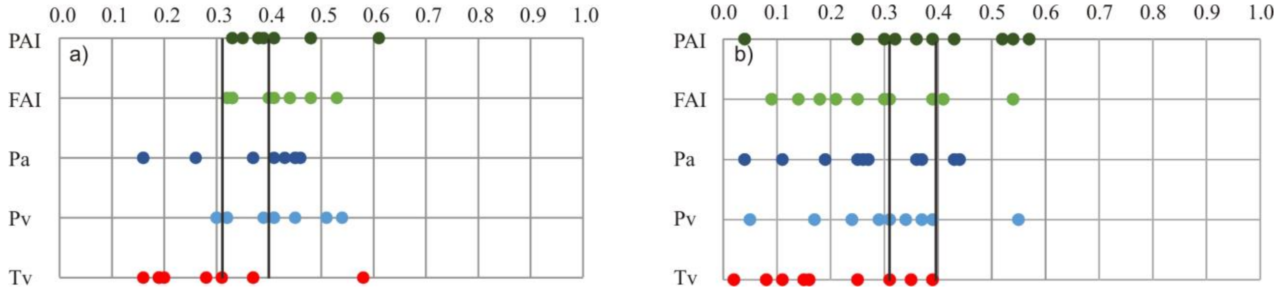


Fig. 4 Correlation factor (|R|) between the ring-width index of the samples and the investigated variables in case of pine (a) and poplar samples (b); PAI: Pálfai Aridity Index, FAI: Forest Aridity Index, Pa: annual precipitation, Pv: precipitation of the vegetation period, Tv: mean temperature of the vegetation period. The black lines represent the significance levels (0.01 and 0.05)

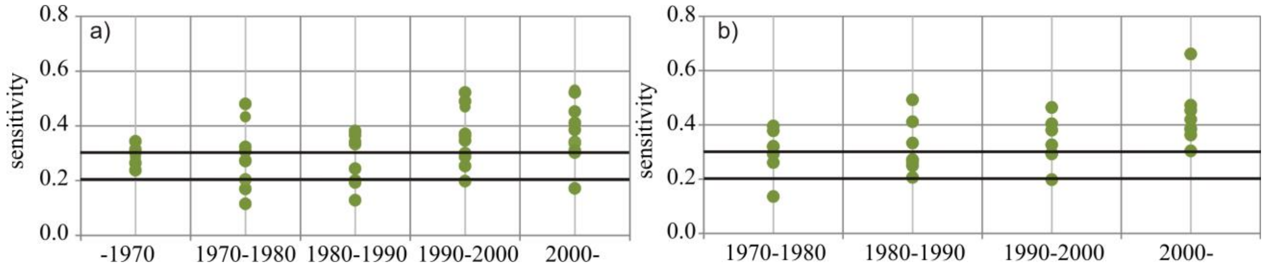


Fig. 5 Tree ring sensitivity (Illancs, Bácska Plain mesoregion) in case of pine (a) and poplar samples (b). The black lines represent the thresholds of low, medium and high sensitivity

Similarly to pine samples, the calculated decadal mean tree-ring sensitivity of poplar also indicated medium and high sensitivity f ring-widths for almost the whole period (Fig. 5b). The increasing tendency of sensitivity values was much more intensive compared to the pine samples and for the past decade, all samples were described by high sensitivity values.

Assessment of samples at Danube-Tisza Plain mesoregion

On the lower lying areas ring-width indices show lower correlation with the PAI and the FAI values. Only 21 % of the samples (1 pine and 2 black locust samples) showed significance at 0.01 level and further 57 % at the 0.05 level with the PAI. The correlations with the FAI were similar to the PAI, except for a few samples. The correlation was significant at the 0.01 level and the 0.05 level for 64% of the samples.

The similarity of the ring-width with the PAI varies between 60.7%–77.1% for pine, similarly to the samples from the Illancs microregion. The variability of the similarity values were higher in case of the black locust samples (48.8%–82.6%). With the FAI the similarity values were slightly lower (57.1%–75.0% for pine and 51.2–71.7% for black locust). In case of only a few samples (4 of the 14) similarity was higher with the FAI.

A strong similarity of the ring-width with the aridity indices was identified for black locust. The percentage of the years, where the interval trends of two curves agree, varied between 64.3–85.3% and 60.0–85.3% in case of PAI and FAI, respectively. The percentage values were somewhat higher in case of PAI compared to FAI at all samples.

The decadal mean tree-ring sensitivity for samples of the other part of the study area was lower compared to the samples of Illancs microregion (Fig. 6). In case of pine mostly low or medium sensitivity was observed, only one sample showed high sensitivity. The tree ring sensitivity of the sampled pine trees not increased in the last decades as it was observed in the Illancs region.

The samples also indicated low or medium tree ring sensitivity in case of black locust and few sample showed high sensitivity. The sensitivity changes of the

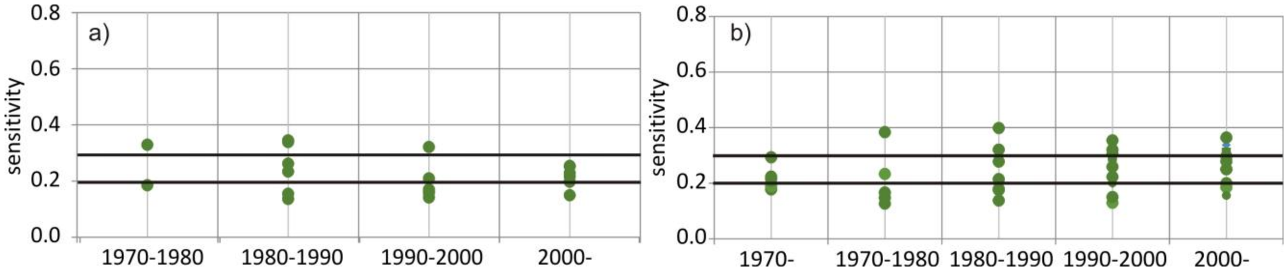


Fig. 6 Tree ring sensitivity (Danube-Tisza Plain mesoregion) in case of pine (a) and black locust samples (b). The black lines represent the thresholds of low, medium and high sensitivity

black locust trees showed higher variability, and most of the samples did not show increasing values, only in case of a few samples increasing sensitivity was observed and the rate of increase was lower compared to the samples of Illancs microregion.

Spatial assessment of ring-width and site conditions

The effect of exposure to water scarcity (different water availability) on tree growth was revealed by spatial assessment. The significance level of correlation between ring-width index and aridity indices, and the mean tree ring sensitivity were overlapped by the relative groundwater depth on Figure 7. In case of pine samples the strength of the correlation increased with the decreasing groundwater depth in case of both PAI and FAI. Samples closer to the rivers, where groundwater level situated closer to the surface, no significant relationship was identified. Similar spatial pattern was recognized in case of the black locust compared to pine samples. The poplar samples from the highest elevated Illancs microregion also confirmed the revealed spatial relationship between the tree growth and the exposure to water scarcity.

The spatial pattern of mean tree-ring sensitivity values (calculated for the whole tree sample) indicate similar differences than the correlation pattern. High sensitivity was identified in case of the samples from the Illancs microregion and from areas of low groundwater table. All the other samples belonged to the medium and low categories of sensitivity.

DISCUSSION AND CONCLUSIONS

Ring width is influenced by several external factors that can be both permanent and variable in a few decades-long period. Soil conditions and relief are among the factors that do not significantly change, however, meteorological and hydrological factors can vary significantly. As it is well-known, severe drought years result in narrow ring widths, while humid years cause wide increment. The changes of the groundwater availability can also be a limiting factor of tree growth.

In the study area droughts and the deep groundwater table have both impact on tree growth. Tree responses to these changing conditions were reported earlier from this area: the decrease of green biomass and foliage in drought years were described by Kovács (2007) using remote sensing methods.

The spectacular decrease of ring-width (in arid years even below 1 mm for both pine and poplar in the highest elevated Illancs microregion, where the most significant high groundwater table decrease was recorded since the 1970s) corresponds to the drought years determined by the investigated aridity indices. Their yearly changes compared to the changes of the ring-width indices are also relatively high and varies between 60-88% in Illancs region. The other samples are characterized by the same or lower similarity when closing to the rivers or areas of more favourable water supply.

The relationship between the climate parameters and the ring-widths varies spatially with the changing site conditions (e.g. elevation, groundwater depth, soil). The highest level of correlation coefficients were experienced in the highest elevated Illancs microregion, while the lowest ones occurred on the relatively lower lying areas, especially near to the Tisza River, where ground-water supply ensures sufficient water for tree growth.

The ring-width sensitivity assessments showed an increasing tendency of sensitivity when comparing the consecutive decades. Along with the increasing extremities and the lowering groundwater-table, the yearly variation of ring-with increases to the highest rate in Illancs microregion, while towards the rivers, the increasing tendency becomes moderate, and in certain cases even no trend can be observed.

The investigated planted forests are in a landscape that is dominantly used by agriculture and which is exposed to high water scarcity. The exposure to climatic forces will tend to continue (Bartholy et al., 2011; Blanka et al., 2013; Mezősi et al., 2014) that is why the more ex-

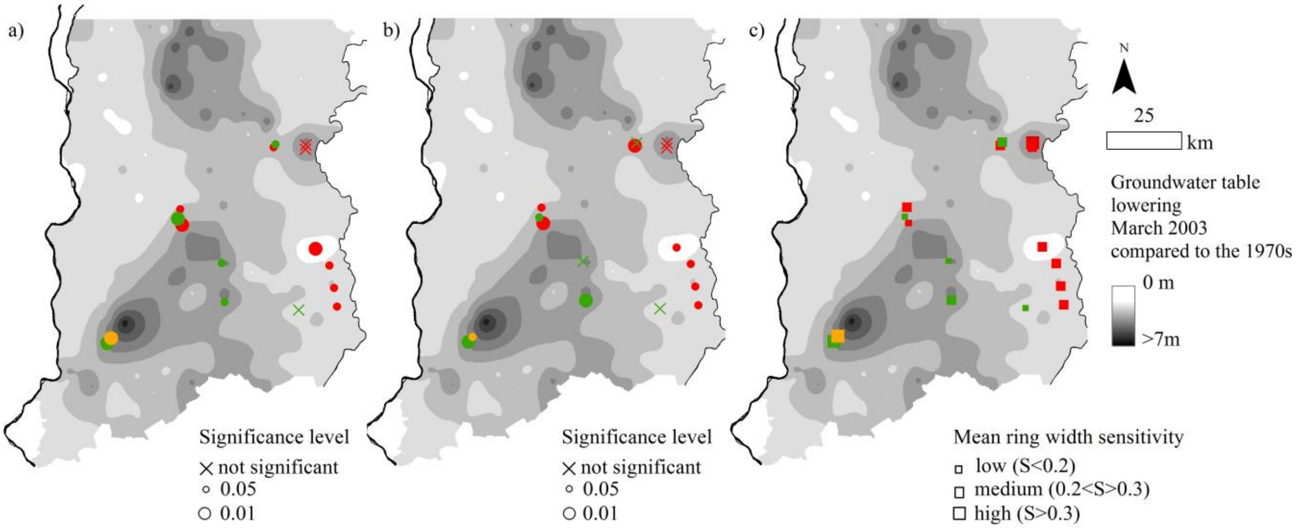


Fig. 7 Spatial distribution of correlations between pine (green), black locust (red) and poplar (orange) samples and aridity indices in the case of PAI (a) and FAI (b), and spatial distribution of mean ring width sensitivity (c)

act knowledge on impacts is highly important. The detailed information on the observed changes can help adaptation and mitigation measures to the potential impacts of climate change.

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