The Astysphere - a concept to overcome the polarity between cities and nature and to develop sustainable urban raw material fluxes

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Abstract. The lion’s share of anthropogenic material and energy consumption is caused by cities. Some global chemical element fluxes are already more influenced by human beings as by non-human biological and geological forces. Climate change is produced to a large portion by urban processes. Worldwide, the surface morphology is currently determined by anthropogenic activities. Urbanization has become a major global exogenic geological factor. Nevertheless, catastrophes such as the flooding in the Ahr valley, Germany, or the lava emission on La Palma, Spain, in 2021 are reminding human beings of their vulnerability. The concept of the Astysphere is a further development of the concepts of global spheres such as the lithosphere and the biosphere as it was invented by the Geochemists V. M. Goldschmidt and V. I. Vernadsky. This concept describes the global urban system as balancing zone for chemical element and energy fluxes. Within this concept, cities are reservoirs of specific chemical elements in ratios never occurred in natural history before only created by human activity. It is one of the main tasks of geochemistry to understand why which chemical element occurs where. This knowledge enables to identify raw material resources. Transferring this concept to urban systems is meaning to identify the chemical element resources in urban systems accumulated here by human beings and to explore whether these resources are worth to be extracted. Currently, there is some knowledge available on the amounts of construction materials used in urban systems, such as gravel, asphalt, steel or concrete. Only little knowledge is available on the amounts and speciations of specific chemical elements in urban systems such as e.g. molybdenum, germanium, neodymium or mercury, just to mention some of those. But sustainable development of cities means to know, which chemical elements occur in cities and whether they can be recycled or whether they are a danger for human health. The concept of the Astysphere provides an approach to understand the meaning of cities for global chemical element fluxes and to raise the awareness to control these for a sustainable development of the earth.

Keywords: Astysphere, urban systems as part of natural history, urban chemical element flows, sustainable management of urban resources
1. **The concept of geochemical spheres**

Geochemistry is the science of the dynamics of chemical elements in the system earth. Geochemistry deals with the questions why chemical elements occur where and in which amounts and rates. The concept of spheres helps to understand fundamentally these dynamics on a global scale and was mainly developed by Victor A. Goldschmidt (1888 – 1947) [1].

He described first in detail that chemical elements are associated with specific envelopes of the earth. These envelopes or spheres were formed during the formation of earth. He expected that at one stage of formation the whole earth was molten more or less shortly after its agglomeration from so called planetesimals. According to density and thermodynamic properties the chemical elements formed the siderosphere (earth core), the chalcosphere (mantle), the lithosphere (crust) and the atmosphere. In the siderosphere iron, nickel and platinum group elements are enriched in their elemental form, in the chalcosphere elements occur, which prefer to form compounds together with sulfur, such as copper, cadmium, silver or gold. In the lithosphere the silicates dominate with associated elements like sodium, potassium, aluminum or chromium. Volatile elements not preferring to form minerals, such as nitrogen or noble gases, accumulate in the atmosphere (fig. 1). The related elements are called siderophilic, chalcophilic, lithophilic and atmophilic. This discovery had an important impact on economy geology since now models could be developed helping to forecast the locations of mineral resources. Mineable concentrations of industrial important chemical elements are associated to lithophilic silicate, such as the rare earth elements, whereas other elements can be found in sulfidic ore deposits, which form in connection to volcanic activities. A special sphere is the hydrosphere, not recognized by Goldschmidt but other geochemists [2]. The hydrosphere is the balance space of water, but water is not restricted to oceans, lakes and rivers, it also occurs as vapor in the atmosphere and as fluid in the lithosphere. It can best be described within the system of spheres of Goldschmidt as special part of the Atmosphere. Water is characterized by a higher density as air, but gases still diffuse into water in larger amounts and water evaporates into air, whereas the diffusion of gases into minerals of the lithosphere is quite restricted and the sublimation of minerals into the atmosphere is not common with the exception of ice crystals.
Vladimir I. Vernadsky (1863 – 1945), a Russian geochemist from the same epoch, first recognized the meaning of living organisms for the global distribution of chemical elements. He named the corresponding sphere or balance space Biosphere [3, 4]. The Biosphere according to this meaning does not simply represent living organisms and their ecosystems but describes the space of fluxes of chemical elements caused by organisms. This comprises e.g. the space where free oxygen occurs that was released by plants and microorganisms and also its reaction products. Thus, sandstones cemented by iron oxides is a part of the Biosphere as is the free oxygen containing atmosphere. Without this free oxygen such iron oxides would not have been formed. Also limestone, originally formed by marine organisms, is a part of the Biosphere. However, the chemical elements within the organisms are part of the Biosphere as well. Vernadsky even stated that the biogenic migration of atoms into the biosphere is increasing [5].

Regarding the single chemical elements, those which are of preferred occurrence in the Biosphere can be called biophilic, such as carbon, oxygen, nitrogen or phosphorous. Partly, organisms themselves are even source of the formation of corresponding resources, such as coal and petrol in case of carbon or Guano in case of phosphorous and nitrogen.

**Figure 1:** Concept of chemical earth spheres according to Goldschmidt (changed according to [2])
2. The Astysphere

Regarding this definition, all fluxes of chemical elements initiated by organisms are part of the Biosphere. Since human beings are also organisms, they are part of the Biosphere and the fluxes of chemical elements initiated by them are as well. Apart from microorganisms, plants and animals, human beings’ activities are not only restricted to uptake of food and release of fecal matter. Homo sapiens sapiens learned to increase his food supply by growing crops and livestock breeding, to use fire to produce metal tools and he learned more and more to extract raw materials from geological units to process them to new products such as mortar, concrete, steel, asphalt, plastics, glass, alloys, and many more. Finally, human beings are now able to produce computers, mobile phones, ships, cars, skyscrapers, railways and much more. Often, in these products chemical elements occur in ratios that are unique to nature and could not be established without human beings’ interaction. Homo sapiens sapiens is the only species that established specific production processes for new materials and energy used for his own living conditions outside of his own body such as concrete works, smelters or power plants. The amount of material turnover (metabolic rate) of Homo sapiens sapiens constantly grew from 6 t in Neolithic times to about 25 t around 1800 and to more than 100 t today [6]. This development covers a change from local consumers of a society of hunter-gatherer and early agricultural societies via regional material flows of an early industrialized society towards the current highly industrialized and urbanized global society. The number of human population did grow from less than 50,000 70,000 BC to about 4 Million 10,000 BC towards more than 7 Billion today. In addition to that, since about 2008 more than half of the world’s human population is living now in urban systems and this portion is growing. Today, global geogenic (non-anthropogenic) and anthropogenic material fluxes occur in comparable scales even if considering the annual uplift of mountains [7].

Human activities from a view point of chemical element fluxes can be subsumed under the so called anthroposphere [8]. This sphere can be further distinguished into two spheres or balance spaces. One sphere comprises all chemical element flow initiating activities around agriculture with land cultivation, breeding, planting or fertilizing. The other sphere comprises urban systems including also complex technological systems such as mining operations or remote research stations. Krishna [9] introduced the term Agrosphere for the balance space of chemical element fluxes in agriculture. The Astysphere [10] comprises the sphere of element fluxes initiated by human activities from urban systems. It has to be remembered that the Astysphere with all its chemical element fluxes still is part of the Biosphere. The development of spheres is depicted in figure 2. From an ecological point of view, it is also obvious that urban systems are a natural ecosystem created by human beings for human beings. Here, anthropogenic chemical element fluxes cumulate in form of raw materials such as fossil fuels, gravel, wood, metals but also in form of agricultural products. Furthermore, it hast to be considered that also chemical elements in form of gases enter the Astysphere, e.g. free oxygen that is not only used by human beings for respiration but also for each combustion process in cars and industry. Taking into account all material fluxes the environmental total economic budget calculates an accumulation of 560 Million t of materials in Germany as difference between abstraction from and disposal to the inland and foreign environment in 2016 [11]. This becomes also clear if considering that these days the concept inner urban densification before urban expansion governs urban development in Germany. Urban expansion could be carried out with materials recycled from inner urban demolition but inner urban densification is always an add on. Similar phenomena are the constant increases of the numbers of automobiles, solar panels or wind turbines. They all need raw materials that have to be extracted from geological units and can only partly allocated by recycling.
3. Chemical element flows and land consumption of the Astysphere

Baccini and Brunner [8] showed that the global anthropogenic fluxes of Cadmium exceed five times the geogenic fluxes. Cadmium is used for nickel-cadmium batteries, pigments or solar cells (cadmium telluride thin-film photovoltaics). The cadmium stock in the anthroposphere is constantly increasing and urban systems play a major role for this stock. Also urban stocks of other metals such as Iron, Zinc or Copper are constantly increasing in urban systems. For 2016, the environmental economic total budget of Germany shows that 2.7 billion t of material flow through the anthroposphere, that are 32.5 t per capita [11]. Thus, about 6.7 t material mass per inhabitant accumulates annually in Germany. As long as a net accumulation in the anthroposphere occurs, even a 100 % recycling rate will not be enough to stop the ongoing land consumption for raw material extraction. Under this circumstances a sustainable operation of urban systems is not possible. Furthermore, this unveils the problems of the current strategy of urban development to prefer inner urban densification before urban expansion. In the beginning of this century the daily land consumption in Germany was above 100 ha per day and decreased until 2020 to 54 h per day [12]. However, this calculation refers to a settlement definition that comprises sealed and unsealed areas and does not take into account inner urban densification at the expense of formerly unsealed areas, squares and conversion areas of freight terminals or barracks (fig. 3). Finally, this can mean that even if no further urban expansion is happening accumulation of material in urban systems still can and probably will occur. The loss of inner urban free areas due to densification causes not only a loss of inner urban biodiversity but also negatively affects the health or urban dwellers [13, 14]. Beside of the direct area affected by urban development with erections of buildings and constructions of roads, bridges, railways, industry complexes and many more, each city possess an ecological foot print reaching far above the actual city borders. Folke et al. [15] calculated the area necessary to supply 1 km² of an average Baltic city. About 200 km² are needed for necessary natural resource production (fossil fuels, ores, rocks, timber, food, …) and even 735 km² are needed for waste assimilation (waste gas, waste water, solid waste).
Thus, since the development of the first settlements, such as Jericho founded about 10,000 BC, settlements and cities are accumulators of material and with that of chemical elements. Today, 80% of anthropogenic material consumption and 75% of CO$_2$ emissions take place in urban systems [16]. In Earth’s natural history this material extraction, transport and sedimentation by human beings is an extremely young process but of global relevance and human beings are now a global geogenic force, similar to geogenic erosion, mountain upfolding or volcanic activities.

![Figure 3: Left: Conversion of a former allotment garden colony to a dense residential area in Karlsruhe, Germany. Right: Conversion of a former railway maintenance and freight area to a densely sealed business district in Mannheim, Germany.](image)

4. **Sustainable management of chemical element and raw material fluxes in the Astysphere**

Although some of urban material fluxes become already at least partly recycled, such as asphalt, concrete, metals or bio-waste, limited knowledge is available regarding the specific chemical element fluxes and stocks in urban systems. Baccini and Brunner [8] showed that a typical residential building contains about 54 g/kg organic Carbon, 0.2 g/kg Chlorine, 180 g/kg Silica, 16 g/kg Iron and 0.09 g/kg Zinc. A passenger car contained in the 70ies and 80ies of the last century about 85 g/kg Carbon, 25 g/kg Alumina, 710 g/kg iron, 7 g/kg Copper, 7 g/kg Zinc, 0.5 g/kg Cadmium and 1 g/kg Lead [8]. Today, more and more electric motors are used in cars. The electric motor for wind screen wipers was analysed [17] and it could be shown that these motors are a secondary deposit for Chromium, Iron, Gold, Cobalt, Copper, Lanthanum, Nickel, Silver and Zinc. Transistors of these motors can contain about 1.5 g/kg Gold and 2.5 g/kg Silver. Also asphalt is a carrier of various elements. In Karlsruhe a total of 3.8 million t of asphalt was estimated to be used for streets [18]. This asphalt contained about 0.5 million t Silica, 0.25 million t Calcium, 0.2 million t organic Carbon, 0.06 million t inorganic Carbon, 34,6000 t Alumina, 10,700 t Iron, 13,100 t Potassium, 228 t Chromium, 133 t Zinc, 91 t Vanadium, 76 t Lead or 53 t Copper. The bitumen is equivalent to the electricity supply of 430,000 inhabitants for one year. Vanadium would be worth to be extracted from the ashes. Recently, the stock of solar moduls is enormously increasing in urban systems. One these products, SOLARWATT 60P rail, Glas-Glas-Modul, was chemically analysed and it was shown that it contains 117 g/kg Copper, 12.4 g/kg Alumina, 5.6 g/kg Lead, 1.3 g/kg Silver and 0.8 g/kg Zinc [19].

Besides the management of chemical elements for the viewpoint of a resource and the potentials for urban mining, chemical element fluxes also have to be managed from the viewpoint of environment pollution and health risk. This became recently quite obvious with respect to NO$_x$ emissions from diesel engines of cars and in former times of the 70ies and 80ies of the 20th century regarding the so called Los Angeles SMOG caused by NO$_x$ emissions that induced under sun radiation the ozone
production. In these cases, scientifically found solutions could be invented: filters for aerosol emissions, urea additions to the diesel to avoid NO\(_x\) formation and the development of the platinum catalyst for petrol engines to react NO\(_x\) to N\(_2\) and hydrocarbons to carbon dioxide and water. Although the permanent increasing number of cars is partly compensating the success of these inventions, human beings actively and knowingly counteract health endangering chemical element fluxes.

Another global challenge currently is the climate change due to CO\(_2\) emissions from fossil fuel combustion in various technical processes. On one hand side urban systems comprise the different CO\(_2\) sources and have to find solutions to minimize this emission. On the other hand, side urban systems also contain sinks for CO\(_2\) such as the urban soil and the urban vegetation and especially the urban forest [20]. Urban vegetation is already managed by urban planners but mainly from a viewpoint of recreation and town picture and not from the viewpoint to maximise carbon storage. Kändler et al. [21] showed for the City of Karlsruhe that urban carbon stock of the state forest within the city borders was 200,100 t, the carbon stock of the city forest was about 194,700 t and the single urban trees contained 164,700 t C. Single urban trees vary widely in their carbon content from less than 10 kg to more than 2000 kg carbon according to their species and size, respectively age [22]. Grönmeier et al. [23] exemplarily calculated an equivalent monetary value of 164 €/ha for the carbon storage of single urban trees. A detailed inventory of urban trees can support cities to manage their carbon budget.

This little compilation shows the huge stock of chemical elements, which comprises needed resources for numerous products and activities, but until now mainly gained by mining activities and not as much as necessary by recycling or even not considered. For many technical products the contents of chemical elements still are unknown. Recycling rates can be calculated as End of Life – Recycling Rate on the basis of an input-output balance but are not considering the distribution of chemical elements in numerous technical products. Some chemical elements such as Copper, Iron, Zinc, Silver and Gold show recycling rates above 50%, other elements such as Indium, Arsenic, Vanadium or Germanium show recycling rates below 1 % [24]. Thus, progress in recycling and the knowledge about the fate of chemical elements in the astysphere is needed for a sustainable use of chemical elements.

Considering the necessity to restructure the material consumption in the anthroposphere and with this in the astysphere it is obvious that a comprehensive inventory of chemical elements in man-made (technical) products is desperately necessary. One approach is studied in the “NaMaRes” project in Karlsruhe, Germany, on the establishment of a computer based sustainable management tool to steer urban resources including material fluxes and stocks but also energy and land [25]. Here, indicators are developed for the management of urban resources, such as biodiversity, recreation area, water or construction material, but not at the level of chemical elements. Nevertheless, such indicators enable the urban planners to at least estimate the impacts of development decisions on the quality of life and the sustainability of material consumption in urban systems. However, most important for the balancing of resources is the definition of the system borders. The Astysphere comprises the urban systems on a global scale composed of the single cities or settlements. Since climate change or marine pollution as well as industrial good production happens on a global scale, urban systems and their management always should be considered on this scale. Nevertheless, urban decision makers often have to deal with local challenges and with resource management within the system boundaries of their particular city. Therefore, global balances are not necessarily helpful for local decisions. Here, much more a local inventory with a high level of detail has to be created to improve the efficiency of sustainable resources use but always understood as part of a global network and part of the nature at all. Finally, urban systems are ecosystems created by human beings for human beings and embedded in the overall natural chemical fluxes.

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