Title

Framework for Urban Metabolism and Life Cycle Assessment of Hardscape

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A White Paper from the National Center for Sustainable Transportation

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National Center for Sustainable Transportation

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NCST

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EXECUTIVE SUMMARY

According to the United Nations, 54 percent of the world's population lived in cities in 2014, and this figure is projected to be 66 percent by 2050. Job opportunities, better quality of life, and greater access to services are some of the attractions of urban areas that lead to the expansion of city boundaries, land use development and an increase in the use of resources. The use of materials and energy in urban areas, particularly large urbanized areas, is intense. Whether urbanization is more or less efficient per capita than other forms of development is uncertain. Regardless of whether urbanized development, and particularly large urbanized areas, are more efficient than other forms of land development it is clear that the trend towards urbanization is increasing as GDP increases, and that goals for improved efficiency of those urbanized areas are needed to reduce their impact on the planet through global warming, and to improve the health, safety and quality of life for the people living in them and in the surrounding areas from which they draw their resources.

Urban hardscapes can be defined as human-altered surfaces in contact with the earth in urban areas other than alterations for horticulture. Hardscape covers large portions of the urban surface area, and has potentially large influence on air emissions, truck traffic and its associated problems, and the potential for flooding. Modeling the inflows of hardscape materials and the outflows of demolished hardscape and other rock-based products from buildings and other civil infrastructure is expected to provide a means to find solutions for reducing these flows and their impacts. Modeling of urban hydrology with respect to the effects of hardscape on surface and groundwater flows from precipitation is expected to provide a means to find solutions that will reduce the risk of flooding and improve groundwater recharge.

The goal of this white paper is to advocate that researchers and policy-makers use the analytical approach of combining urban (UM), material flow analysis (MFA) and elements of life cycle assessment (LCA) to measure and improve the efficiency of urban hardscape in large urbanized areas with respect to environmental impacts affecting global warming, safety and quality of life through use of alternative hardscape structure and materials and more permeable hardscape.

A summary of the proposed methodology, literature review on the topic of UM and LCA of hardscapes and discussions with experts on the topic subject are presented in Section 2 of the white paper. Section 3 provides details on the proposed UM-LCA framework. Additionally, several data sources and modeling tools were identified that can be used in the UM-LCA framework to quantify material and energy flows and environmental impacts including water flows. An effort was also made to identify data for a few of the cities in California in order to demonstrate parts of the data collection and presentation process. The framework developed is not limited to a single U.S. state, rather it can be used in any geographic region of the U.S. The

findings of this study are summarized in Section 4 along with the recommendations from the authors.

Based on the literature survey, and discussion with materials, freight and water management systems topic experts, an UM-LCA framework that is capable of quantifying water and hardscape material metabolism for an urban area was the resulting product of this federally funded research project. The framework consists of horizontal and vertical flows; horizontal flows are hardscape material flows which include asphalt products, concrete products, aggregates, crushed concrete demolition materials from building and other structures, additives, admixtures and recyclable materials and the vertical flow consists of the hydrologic cycle. The framework can be used to reduce environmental impacts of urban hardscape through analysis and rethinking of hardscape management, including design, construction, maintenance, rehabilitation and end-of-life (EOL) to produce and compare alternatives to current practices. It can also be used to assess changes in stormwater flows for different degrees of full and partial permeability of hardscape, and resulting changes in flood risk, stormwater quality and groundwater recharge.

Planners and engineers can use the framework to analyze and quantify the hardscape material and water flows of an urban area and support them in evaluation and decision support regarding changes in the systems and their operation. The results are intended to also be used by policy-makers regarding land use and hardscape planning and design.

Testing the UM-LCA framework in order to demonstrate its use with actual city data was not in the scope of this study and is the logical next step. Detailed case studies using data from different climate regions can help decision makers to quantitatively assess the material and water flows of the city in consideration.

1. Introduction

1.1. Background

According to the United Nations, 54 percent of the world's population lived in cities in 2014, and this figure is projected to be 66 percent by 2050 (1). Among the attractions of urban areas propelling this expansion are job opportunities, better quality of life, and greater access to services.

Urbanization tends to increase in tandem with economic development. Chen *et al.* (2) investigated the major changes in global urbanization and economic growth over the last 30 years using cross-sectional, panel estimation and geographic information system methods. Strong positive correlations were found by the authors between urbanization level and gross domestic product (GDP) per capita from 1980 to 2011.

The use of materials and energy in urban areas, particularly large urbanized areas, is intense. Whether or not urbanization is more efficient per capita than other forms of development is uncertain. In a study by Kennedy *et al.* (3), energy and material flows in megacities of the world were studied as of 2010, and it was found that 27 megacities (6.7% of the global population) produced 14.6% of global GDP and were responsible for 12.6% of global waste. The study also found that the two U.S. cities, New York and Los Angeles were among the highest resource consumption cities, especially for the resource categories of electricity, water and waste. The authors also indicated that the per capita data suggests opportunities for resource reduction.

A recent UN Habitat study (4) stated that “resource use per person in urban areas is actually lower than in sparsely populated areas, and that higher population density, proximity to businesses, reduced transportation needs, all associated with well-designed compact cities, can boost urban sustainability”. They also stated that “governance and policy-making processes play a role in determining the ability to implement efficient integrated urban planning and to design a vision for the future”, and that “the main challenge is to avoid conflict between actions taken at different levels and by different actors. Adopting strategic frameworks that set out targets for the future can act as a driving force for change.”

Regardless of whether urbanized development, and particularly large urbanized areas, are more efficient than other forms of land development it is clear that the trend towards urbanization is increasing as GDP increases. It is also clear that goals for improved efficiency of those urbanized areas are needed to reduce their impact on the planet through global warming, and to improve the health, safety and quality of life for the people living in them and in the surrounding areas they rely on. As stated by the UN Habitat report (4), defining a vision for the future of urban areas, setting targets for the future, and adapting strategic frameworks and policy-making processes are steps needed to achieve the integrated urban planning needed to achieve these goals. Good policy-making processes must be supported by good data and analysis.

The goal of this white paper is to advocate that researchers and policy-makers use the analytical approach of combining urban metabolism, material flow analysis and elements of life cycle assessment to measure and improve the efficiency of urban hardscape in large urbanized areas. Efficiency is defined here as reduction of the environmental impacts affecting global warming, safety and quality of life, and the initial scope of investigation proposed is the use of alternative hardscape structure and materials and more permeable hardscape.

1.1.1. Urban Hardscape and Its Costs

Urban hardscapes can be defined as human-altered surfaces in contact with the earth in urban areas other than alterations for horticulture. Urban hardscapes include streets, parking areas, sidewalks, driveways, alleys, paths, paved play areas, plazas and courtyards. While there are different approaches for quantifying “paved area”, studies indicate that the range of the proportion of urban surface area that is urban hardscape ranges between approximately 25 and 60 percent (5,6). These studies also indicate that greater portions of the hardscape are devoted to motorized vehicle uses, i.e., portions of streets for vehicles and vehicle parking, in more recently developed cities, even though suburban development tends to result in decreased percentages of surface area being paved compared with the percentage of paved surface area in core city areas. The recent study by UN-Habitat argues that attention to providing sufficient street connectivity is important for improving quality of life in cities, provided that the streets are not primarily designed for and devoted to motorized transportation (4). From these studies it is clear that hardscape makes up a significant portion of urban surface areas, and this fact is not going to change even if the uses of that hardscape change.

It is difficult to find aggregated information regarding financial resources needed to maintain urban hardscape, although information is more readily available for street pavement. It has been estimated that $73 billion per year is spent for the construction and maintenance of all the roads and bridges in the U.S. (7). Approximately 41 percent of the national population, totaling 136 million people, lives in the 42 largest urbanized areas recognized by the U.S. Census Bureau that have a population of 1 million or more. Seven[1] of the 42 large urbanized areas are in California, and those seven have 20 million people, representing 60 percent of the state’s population and 15 percent of the national population living in large urbanized areas. Another 10 percent of California’s population lives in nine more urban areas with populations between 0.3 and 1 million (8).

Total annual spending on streets and roads by cities in California in recent years has been about $4 billion per year (9) excluding lighting and signals, of which it is estimated that about $1 billion per year has been spent on street and road pavement maintenance not including other types of urban hardscape or new construction (10). Passage of a recent tax measure in California will approximately double city spending on transportation infrastructure.

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[1] Los Angeles—Long Beach—Anaheim, San Francisco—Oakland, San Diego, Riverside—San Bernardino, Sacramento, San Jose, and Fresno.

A gross estimate of spending on streets and roads in the largest urban areas in the U.S. is $20 billion per year, and $3 billion per year for California urbanized areas with populations of one million or more, equal to $152 per year per capita[2]. A gross estimate of spending just on pavement maintenance in urban areas in the U.S. with populations of one million or more is $5 billion per year and $770 million per year for the seven California large urbanized areas, which is $38 per year per capita. These figures do not include the spending on state highways in urban areas. The cost per vehicle user in large urbanized areas is harder to estimate. It is probably not an appropriate metric considering that hardscape affects all city dwellers and that urban hardscape is funded by a mix of fuel taxes, sales taxes and other funding sources which come from all tax payers, not just vehicle users. For example, approximately 66 percent of funding for streets and roads in California comes from local sources other than fuel taxes, while the 23 percent of funding coming from the state and 11 percent coming from federal sources are both primarily from fuel taxes (9). The state constitution does not allow cities to tax fuel. Recent levels of city street funding in California have resulted in deteriorating conditions for city streets in the state (10).

1.1.2. Hardscape Material Use

As urbanization spreads, populations grow, and wealth increases with commensurate demands for better quality of life, better planning and more sustainable solutions become more important for urban areas. Urban hardscape as it currently exists and as it is expanded through new development and perpetuated through maintenance, rehabilitation and reconstruction requires mining and importation into the urban area of large quantities of materials and exportation of demolition waste out of the urban area. Standards that require extensive vehicle parking for new housing and other development increases the amount of hardscape, and street standards can increase that further depending on requirements for street width.

Siting of new quarries for the crushed gravel and sand that are the primary materials for urban hardscape is increasingly difficult near many urban areas due to concerns about emissions, dust and noise from truck traffic, as well as the depletion of nearby sources. While some parts of the country do have long-term quarries nearby, many parts of California have only a small fraction of their needs to 2050 permitted. Importation of hardscape materials can be fairly low impact where water transport has access into the urban area. Transportation impacts increase where rail and especially truck transportation is required. New quarries can often take up to 10 years to permit, and with decreasing probabilities of success in getting approval. Consequently, heavy

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[2] The seven largest California urbanized areas account for 60 percent of the total population of the state, and 77 percent of the population living in all incorporated cities in the state. To estimate per capita spending in large urban areas across the U.S. and California, the California spending number for all cities was prorated based on the population of the state's largest urbanized areas relative to the population of all cities in the state. That per capita cost was multiplied by the population of the national large urban areas to estimate national large urban area spending. California urban transportation construction costs per pavement area are most likely on the order of 1.5 (inland) to 2 times (coastal) larger than those of mid-western and southeastern cities. California coastal construction costs are likely similar to those of other west and east coastal cities where more than half of the nation's large urban areas are located.

quarry materials[3] are transported from increasingly farther distances to urban areas, ironically increasing the emissions from the additional ton-miles of truck hauling and also damaging more of the road network.

For example, 12.5 billion ton-miles or 9.7 percent of the 127.6 billion ton-miles of in-state cargo hauled on California roads in 2016 carried crushed gravel and natural sand, of which an unknown but large percentage were used for hardscape (11). This can be estimated to equate to approximately 1.25 million truck trips for urban hardscape other than state highways for the seven urbanized areas in California with populations over 1 million[4]. Most of these urbanized areas are in federal non-attainment zones for particulate matter (PM2.5) and air pollution (8-hour ozone) (13). All of these numbers are highly conjectural because of lack of data, illustrating the gaps in information needed to calculate impacts of hauling hardscape materials for urbanized areas.

At the same time, rehabilitation, renovation and reconstruction of cities requires the demolition of existing hardscape much of which must be hauled out of the urban area for recycling at the quarries or to landfills. Concrete vertical infrastructure (buildings, walls, etc.) is also useful for hardscape after processing, which has become more common as part of building site renovation. For example, in California 4.6 percent of ton-miles hauled on California roads in 2016 were waste and scrap (11) of different types of which an unknown portion was demolition from urbanized areas. Using the same assumptions as for sand and gravel, except assuming that four percent of waste and demolition is from hardscape, this equates to approximately another 0.23 million truck trips. As noted previously, the recently reaffirmed California tax measure on fuel to be used for street and highway repair is expected to approximately double the amount of money spent, significantly increasing the ton-miles of hardscape material hauling as well.

State highway pavements are primarily intended to carry heavy vehicles at high speeds. Most current urban hardscapes are scaled down versions of pavements used on state highways. There has been considerable work towards reducing cost and environmental impact by minimizing the quantities of virgin materials used over the life cycle on state highways. These improvements have come through improved construction quality to extend life, improved materials and structure design, reclamation and reprocessing of existing pavement materials both in-place and off-site, reductions in the use of the highest impact materials through substation of other materials, and development of new materials and pavement structures (13).

However, the hardscape in urbanized areas has not been evaluated as a system, nor considering the differences between urban areas and state highways of construction

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[3] One cubic foot of material weighs approximately about 125 pounds on average for sand, gravel, concrete and asphalt (2 metric tons/cubic meter).

[4] Calculated assuming that gravel and sand use is proportional to population, that these materials are typically carried in 20 ton loads in transfer trucks with trips averaging 25 miles, and that 10 percent of these trips carry hardscape materials, and half of the hardscape materials are used by local government and half on state highways,

constraints, material sourcing locations, functional requirements, and interactions with other urban systems.

1.1.3. Urban Hardscape and Stormwater

Urban hardscape also plays a role in stormwater flooding, groundwater recharge and water quality. Urban development using conventional impermeable hardscape decreases the permeability of flat surfaces to zero, and because hardscape makes up a large percentage of urban surface area, urban hydraulic patterns are dramatically changed. When urban hardscape receives rain, water that previously percolated through the surface, or was slowed by vegetation and rough soil before reaching surface streams and rivers instead flows rapidly over urban hardscapes into stormwater conveyance and then streams and rivers. Figure 1 shows qualitatively how urban development increases the speed with which stormwater enters the stormwater conveyance system, and how it increases the peak flow that the stormwater system must be built to carry, or in the case of existing infrastructure what it must be rebuilt or expanded to carry. In many areas this requires large investments in drainage infrastructure to minimize risk to lives and property.

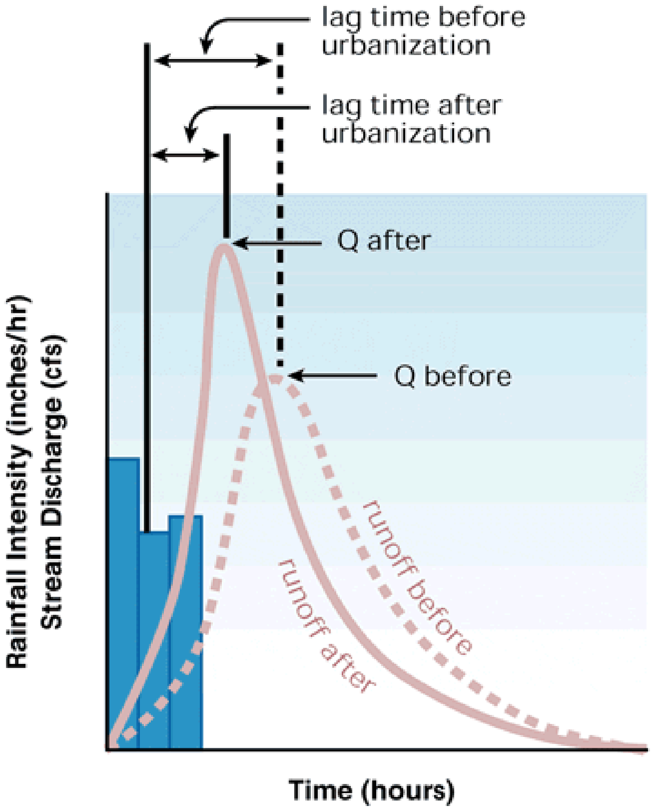

Figure 1. Effects of urbanization on stormwater flow lag time and peak flow (14).

Data from the U.S. National Climate Assessment (2018) shows that the U.S. is getting warmer and receiving more frequent and heavier precipitation events and overall precipitation due to climate change which is reducing infrastructure performance and life, and causing increased flooding (15). During the past 50 years, the average temperature across the U.S. has risen more than 1.11 ºC while precipitation has increased by an average of about 5 percent. Some extreme weather events have also become frequent and intense which include heat waves, regional droughts, hurricanes and temporary changes in sea levels with storm surges (16). Such events pose risks and challenges for human and natural systems such as the transportation infrastructure. Hence, anticipating and adapting to the effects of climate change is required.

Information in the Fourth National Climate Change Assessment (17) shows that the intensity of rainfall for the most extreme annual events, defined as the 99th percentile storm event, has increased across the country and particularly east of the Mississippi River, as can be seen in Figure 2. Climate change modeling indicates that these intensities are expected to continue to increase significantly as shown in Figure 3.

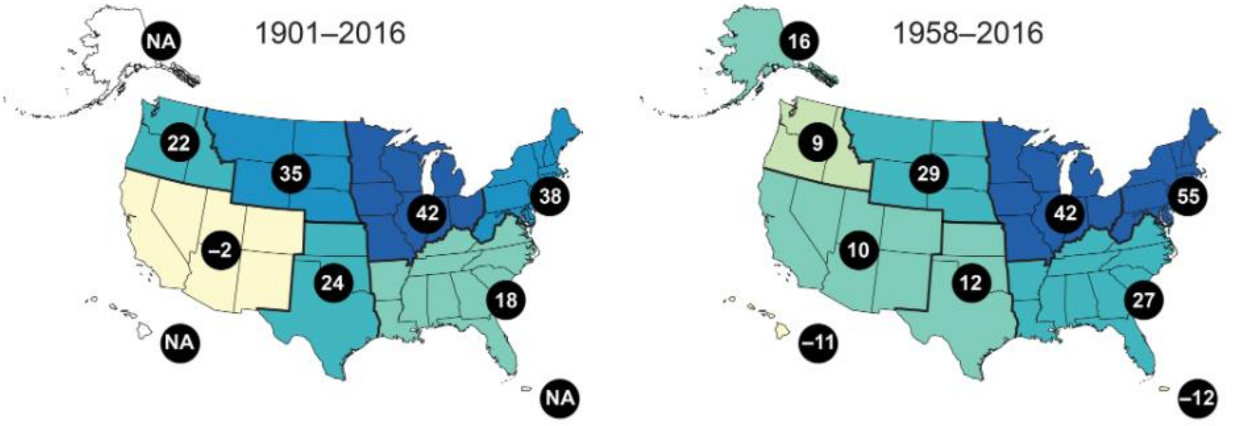

Figure 2. Observed change in total annual rainfall occurring in 1% heaviest rainfall events (17).

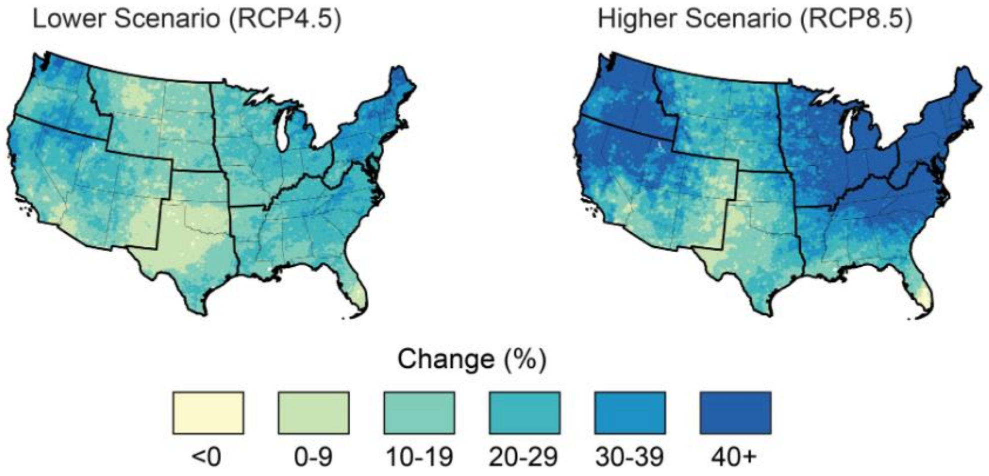

Figure 3. Projected change in total annual rainfall occurring in the heaviest 1% rainfall events by late 21st century under two modeling scenarios (17).

Increasing the permeability of urban hardscape can decrease total stormwater flow and peak intensity and increase lag time. Fully permeable pavement that includes infiltration into groundwater can reduce total stormwater flow. Such pavements can be designed and constructed to handle heavy truck loads, and can be used for parking areas, pedestrian and bicycle paths, and sidewalks and other urban hardscape applications. Fully permeable pavements can also be used to significantly slow stormwater runoff where the native soils below are not sufficiently permeable for infiltration or there are other reasons to not infiltrate the water. The full life cycle material flows and impacts of fully permeable pavement relative to conventional pavement have not been sufficiently analyzed to make broad comparisons with conventional impermeable pavement (18).

Partially permeable pavements involve using permeable materials for the surface of otherwise impermeable pavement, causing stormwater to flow more slowly below the surface as it moves to the stormwater conveyance system. Life cycle assessments of partially permeable surfaces show that they do not last as long as impermeable surfaces, with 25 to 50 percent shorter functional lives. However, impermeable surfaces are usually thin (between 0.8 and 2.4 inches [20 to 60 mm] thick). In addition to flood control benefits, both fully permeable and partially permeable pavements offer important stormwater runoff quality benefits by capturing significant amounts of pollutants in the pavement. Research indicates that the durability of permeable pavements can be improved through additional research and development. Both fully permeable and partially permeable pavements are not widely used in the U.S., primarily due to institutional issues between transportation, stormwater quality and flood control agencies as well as gaps in the technical information available regarding performance and life cycle costs and impacts. There is also a need to consider reductions in stormwater quality and flood control benefits when comparing permeable pavements with conventional impermeable pavements (13).

1.1.4. Urban Metabolism, Material Flow Analysis, and Life Cycle Assessment

Urban metabolism (UM) is a method for quantifying consumption and use patterns in urban environments and has typically been applied to accounting of energy and materials inputs and outputs for cities. The term “metabolism” is used because this method uses the analogy of living organisms to understand the consumption of resources and materials, growth, and waste generation. The primary approach for urban metabolism proposed by this white paper is the use of material flow analysis (MFA). In MFA, the material flows into and out of the urban area are inventoried, and changes in material, including degradation from burning which changes the mass and produces emissions and heat energy, or other changes are also tracked through mass balance analysis. The impacts of the material flows can be assessed in terms of energy flows divided into different sources of energy where possible or considered qualitatively in terms of the masses being moved and the distances they travel and the types of materials. In addition to material and resource flow accounting, UM can be expanded in ways that allow more comprehensive and integrated assessments of the patterns and processes of urban systems. Definitions of system boundaries and time horizons for UM are generally not strictly defined. Life cycle assessment (LCA) principles can be used to help define system boundaries and time horizons to MFA and can also be used to help quantify the impacts of the results of MFA.

LCA is a standardized methodology that can be used to quantify the resource use, energy consumption, and air, water and land borne emissions of a system. Once quantified, the results can be used to identify strategies for reducing emissions and finite resource use. The strength of this methodology is that the systems analysis is done over the life of the system in a cradle to grave approach. The International Organization for Standardization (ISO) standards 14040 and 14044 describe the process of performing an LCA for a product, system or a process (19, 20). The process is comprised of four phases, namely goal and scope definition, inventory analysis, impact assessment and interpretation. The problem statement is defined in the goal and scope phase of an LCA and system boundaries and functional description of the system are set ensuring consistency in performing the LCA. The environmental inputs and outputs that are associated with the product or system are identified and quantified in the inventory analysis phase. The system related outputs are translated into environmental impacts in the life cycle impact assessment phase. In the interpretation phase, results and conclusions are to answer the questions posed in the goal and scope phase.

Life cycle thinking refers to conceptual models that require consideration of systems over their life span and may also require consideration of the supply chains they rely on. Life cycle thinking approaches such as life cycle cost analysis (LCCA), environmental life cycle assessment (which is referred to simply as LCA) and social life cycle assessment (SLCA) can be used to evaluate life cycle costs, environmental impacts and socio-economic impacts of existing and new large systems or processes, respectively. Due to an increase of migration from rural areas to urban areas, the energy and resource demand of the urban areas is rising, and so is the consequent pollution, referred to as the “urban metabolism disorder” (21).

Application of life cycle thinking to cities at the urban area scale combined with the urban metabolism perspective offers the potential for insights into improving the sustainability of urban areas and the quality of life of their residents. The proposed approach makes use of UM, MFA and LCA to model and evaluate current practice and alternatives for urban hardscape that may reduce important impacts on urban quality of life and the environment. Figure 4 provides a conceptual view of the proposed approach. The principles of UM and MFA would be used to define the urban surface area boundary and define the hardscape within the boundary by function. The current typical hardscape structures and materials would be identified, as well as typical life cycles including construction, maintenance, rehabilitation and reconstruction or demolition. As noted previously, at this time it is difficult to separate materials flows for hardscape materials moving into urban areas and hardscape demolition moving out of those areas from aggregated values that are available. The urban hardscape flows into and out of urban boundary would be calculated and checked with other data such as materials transport and economic data. The flows would be summarized over a future life cycle analysis period using LCA principles to be able to consider all stages of the hardscape life cycle, including material production, construction, maintenance and rehabilitation, and end-of-life.

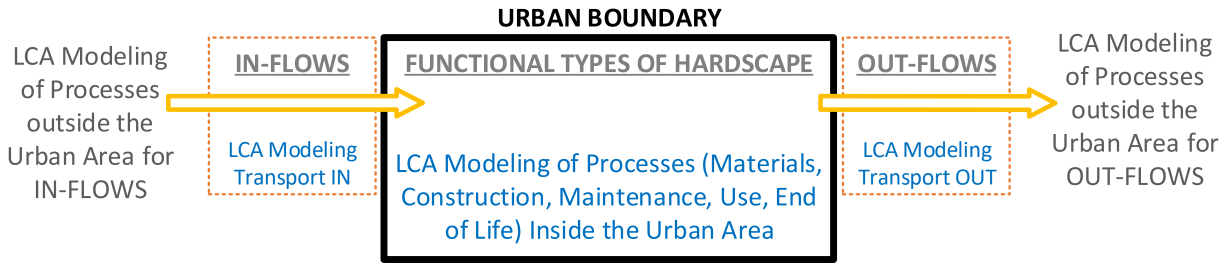

Figure 4. Conceptual view of the proposed approach combining urban metabolism, material flow analysis and life cycle assessment.

The life cycle analysis could look at a future steady state after full application, but a more sophisticated analysis would consider expected rates of hardscape replacement and market penetration of new practices over the analysis period. The analysis could include use stage interactions with other systems, vehicles in particular. Initially, a greatly simplifying assumption would be that all hardscape would need to meet the same functional requirements with regard to vehicle interaction. Effects of hardscape on vehicles in cities include vehicle degradation and increased fuel use due to roughness, and increased fuel use due to energy consumption from deformation of the pavement itself (13). Very few cities manage their pavements based on roughness, and many do not want to manage roughness because of difficulties in handling roughness caused by manholes and other accommodations for under-pavement utilities. Deformation related energy consumption is primarily an issue for asphalt pavement carrying heavy, slow-moving trucks on hot days.

Processes associated with those hardscape material flows, both inside and outside the system boundary would be modeled, as well as transportation of the materials, following LCA principles. The flows are the scaling factors for the processes at the urban area scale. Alternative scenarios for changes in the amount and types of materials, structures, changes in the amount of hardscape in different functional types (such as parking, streets, etc.), and changes in the amount of recycling within the urban boundary to reduce material transportation, and changes in the processes both within and outside the urban boundary to supply urban hardscape could be compared with current practices.

First-level analysis would look at the life cycle material flows, such as materials by type, mass-distances of transportation and where applicable, land area needed within the urban area for stockpiling and processing. Second-level analysis would include calculation of important mid-point LCA indicators providing quantification of impacts of changes in flows.

Hydrologic modeling of the most intense storm events would be performed to consider the hydrological impacts of changes in urban hardscape to make it more permeable, including partially and fully permeable pavement where they can both be used to also meet other functions. The effects of the changes in material flows and impacts from changing those flows caused by use of this type of hardscape would also be analyzed.

In general, the quantification framework developed in this study could help identify where on the curve shown in Figure 5 we stand as of today. Implementation of better practice can cut down imports (such as resources) and flows (such as materials and water) resulting in lower costs and other environmental impacts.

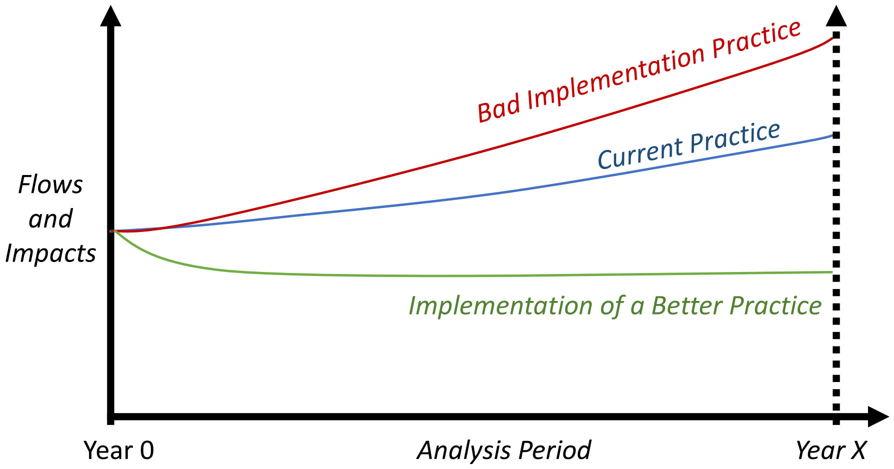

Figure 5. Comparison of implementation practices affecting flows and imports for urban areas over an X year analysis period.

1.2. Problem Statement, Purpose, Audience, Expected Outcomes

Hardscape covers large portions of urban surface areas, and has potentially large influence on air emissions, truck traffic and its associated problems, and the potential for flooding. Modeling the inflows of hardscape materials and the outflows of demolished hardscape and other rock-based products from buildings and other civil infrastructure is expected to provide a means to find solutions for reducing these flows and their impacts. Modeling of urban hydrology with respect to the effects of hardscape on surface and groundwater flows from precipitation is expected to provide a means to find solutions that will reduce the risk of flooding and improve groundwater recharge.

The sustainability of urban areas can potentially be improved through changes in the built infrastructure of urban hardscapes. A conceptual framework does not exist, but is needed, that considers the entire urban area in order to evaluate high-level effects of changes in the design, construction and renovation of urban hardscape.

The purpose of this white paper is to identify a conceptual framework for the UM-LCA of urban hardscapes, focused initially on rock product material (quarry materials) and water flows. The framework will provide a basis for considering alternative pavement materials and structures as well as ways to increase the reuse of hardscape and building demolition products within an urban area, thereby reducing transportation and the depletion of high-quality sources, although potentially increasing the need for land to stockpile materials. The framework will also consider the expected effects of climate change on storm events and the effects of creating more permeable surfaces on urban hydrology. Some initial examples of potential strategies to achieve the emissions, resource use and hydrology goals that should be evaluated using the framework are also presented.

The intended audience for this white paper is first researchers and policy-makers, and it advocates for them to contribute to the development of data, models and tools for the UM-LCA approach. The white paper advocates that this approach be used to analyze and reduce the impacts of the urban hardscape systems of large urbanized areas while increasing the benefits that they provide. The white paper suggests some current ideas for achieving these objectives. The second audience is current policy-makers and planning and engineering practitioners to whom this white paper advocates that they think of urban hardscape as an integrated system. It further advocates that attention to the interactions in this system will provide insight into better managing its cost, the large quantities of materials it requires, and its effect on mobility, safety, air quality, water quality, flood risk, noise and thermal environments in urban areas, while meeting multiple functional requirements. The third audience is future policy-makers and practitioners to whom this white paper advocates bringing the expected results of greater insight into standard practice.

The expected outcomes from the actions advocated in this white paper are greatly improved data and methods for analyzing urban hardscape as a system, and increased benefits and reduced impacts from those systems.

1.3. Approach to Assembling the White Paper

The following tasks were performed to develop this white paper:

1. The initial idea was formulated.
2. A literature review was performed on UM and different analytical approaches for UM.
3. Interviews were conducted with the experts on topics such as urban metabolism, storm and rain water management, flood management, and climate change to identify the key issues and approaches that could be included in the framework.
4. The UM-LCA framework was developed.
5. Potential data sources that could be used as inputs in the framework were identified.

2. Summary of Proposed Study Approach, Literature Review, and Data Collection from Interviews

2.1. Summary of Proposed Urban Metabolism-Life Cycle Assessment Approach

The original idea for combining UM and LCA to investigate urban hardscapes came from a plenary presentation at the Pavement Life Cycle Assessment Symposium in Davis, CA by Stephanie Pincetl from UCLA (22).

Using Pincetl and her colleagues' work (22) as a starting point, a system's approach that considers rock products and hydrological flows was selected for the modeling. An urban area can be considered as a system, with the city or developed urban area limits defining the system boundary as shown in Figure 6. From the standpoint of material and resource flows, this system can hypothetically be optimized if it maximizes reuse of existing resources within the system boundary; i.e., energy and material flows are generated, consumed, and restored within the system.

Hardscape materials are primarily sand, gravel and crushed stone, collectively called aggregate, by mass, with small amounts of binding agents such as asphalt binder and Portland Cement, and even smaller amounts of other materials such as recycled tire rubber, other polymers, and chemical additives. A substantial part of most pavement structures is comprised of base and subbase layers consisting of compacted aggregates. For pavement surface materials, aggregates comprise 80 to 85 percent by volume of typical asphalt concrete and 62 to 68 percent by volume of concrete (23). On a mass basis, aggregate is about 95 percent of the mass of asphalt concrete and 85 percent of the mass of hydraulic cement concrete because the aggregate is much denser than the binding agents. The facts that aggregate makes up the large portion of hardscape materials, compacted aggregate is very dense (typically between 2.2 and 2.9 times heavier than water), and aggregate must typically be hauled to cities from quarries has strong effects on the fuel use for its transportation and on the damage to the roads over which it is hauled.

The environmental impacts of imports of new materials and exports of waste materials into and out of the urban area can be assessed using LCA-type calculations. If material use is reduced through recycling and reuse within urban boundaries, these environmental benefits or impacts of such changes can be quantified by comparison to current conditions. Potential unintended negative consequences of materials reuse include increased land use and environmental problems from storage and processing of reused materials in the urban area, which can also be quantified by UM-LCA.

Innovative approaches to hardscape systems that move towards a balance in demand and supply from reuse of material resources will require less material from outside the system boundaries and may require less transportation. Furthermore, the system may potentially produce less waste and pollution in the urban area and will export less waste and/or pollution out of the system. Opportunities to move closer to such a system can be analyzed based on the flows of import and export of resources, waste and emissions within and outside the system for environmental impacts in a life cycle perspective.

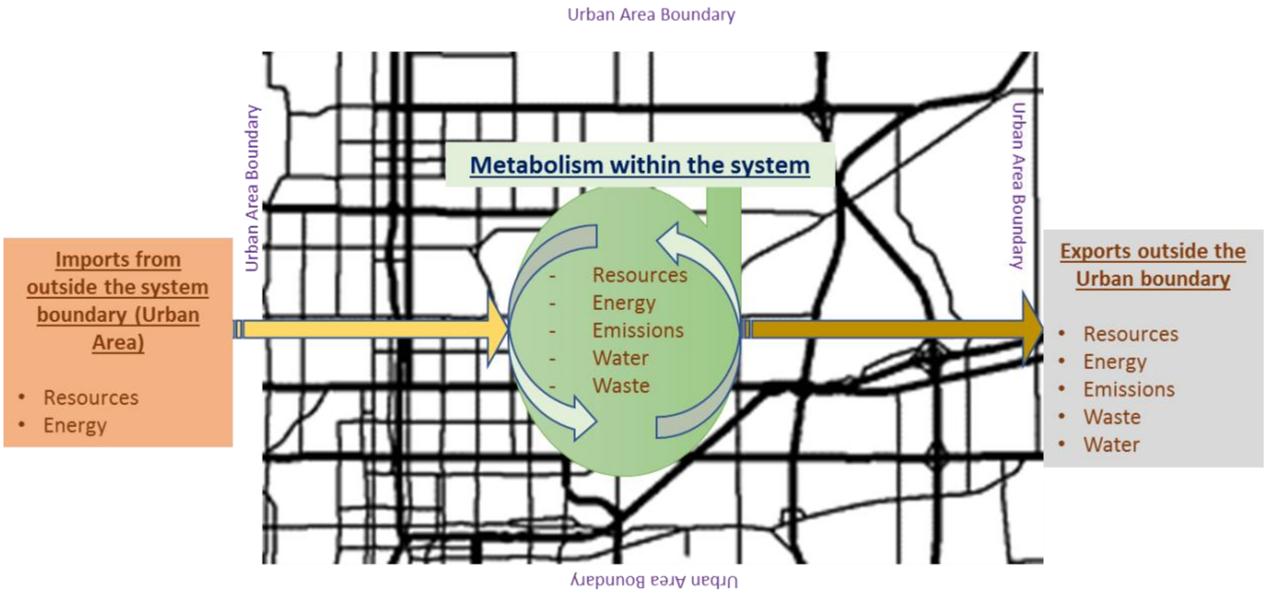

Figure 6. The overall UM-LCA system of an urban road network

Changes in hardscape extent and technology that improve permeability so as to capture, detain and infiltrate stormwater can be analyzed with respect to flooding, stormwater quality and groundwater recharge. Some of the means for increasing the permeability of hardscape include the use of permeable pavement, bio-swales, and catchments, all of which increase the infiltration of stormwater through the surface. All of these approaches also slow the rate of runoff, and where infiltration occurs, reduce total runoff. There are various types of permeable pavement available, all of which include a sub-surface porous layer made with gravel to retain or detain the water. Different kinds of catchments and bio-swale designs are also available for different contexts.

The needs of different urban areas for improvements in flood control, water quality and recharge will differ greatly depending on current and predicted climate change effects on precipitation patterns, their topography, size, drainage systems and land use patterns. Together, the potential changes in hardscape systems to be more permeable and re-usable within an urban system can be analyzed together with the proposed framework.

2.2. Literature Review

The UM model accounts for the energy and material flows within urban areas and between the urban area and its surroundings, helping researchers to study the interactions of nature and human systems, affecting the environmental impact of a city and effects on human and natural ecosystems. Kennedy et al. defined urban metabolism as “the sum total of the technical and socioeconomic processes that occur in cities resulting in growth, production of energy and elimination of waste" (24). Although others have studied the relationship of cities to their surroundings, Wolman in 1965 (21) presented metabolism concept to address air and water quality in the U.S. (25) and determined that increased urban population and industry growth created problems of water and air pollution. Furthermore, Wolman postulates that it is not the depletion of the water resource, but rather its mismanagement, that creates water problems.

In subsequent years numerous cities worldwide including Brussels, Cape Town, Hamburg, Hong Kong, Lisbon, York, London, Singapore, Stockholm, Sydney, Tokyo, Toronto, and Vienna have been examined using the UM approach (25-34). Kennedy et al. (26) studied data from urban metabolism studies since 1965 for eight metropolitan regions around the world and analyzed four fundamental cycles of energy, materials, water and nutrients. The authors found that water inputs per capita for six studies since the 1990s were higher than the four studies from the early 1970s. Due to the expansion of the cities, water table levels were found to be lower because of increased water demand for some cities such as Beijing and Mexico City while several other cities in the world (Karachi, Kuwait, London) water tables were found to be rising and water quality being highly affected mainly due to the discharge of wastewater into the ground. An increase in commercial and industrial waste was seen, however, the cities that had implemented recycling strategies at a large scale were producing less waste. The data also air pollution emissions over the same period. The study concluded that the urban metabolism results were different from city to city.

Li et al. (35) developed a general framework of an urban ecological infrastructure (UEI). Blue land (wetlands, lakes, ponds), green land (forests, green spaces), grey land (pavements, drainage), exits (emissions, waste) and arteries (wind and water systems, material flows) build up the UEI system. All the sub-systems are tightly integrated and distributed amongst each other. Researchers have investigated transportation and street networks within the 'grey land' category (hardscapes) have not been looked at in detail and almost no literature exists to guide roadway and other hardscape design in urban areas in light of responding to climate change effects on precipitation (7).

Different methods such as the emergy (36) or material flow analysis (MFA) can be used in the UM approach. MFA is the most common and internationally accepted method that can be used to study the flows of resources into a city (imports and/or ingestion), followed by processing and consumption of resources, and flows of resources out of the city (exports) and emissions production (to air, land and water) (37).

MFA approaches are typically focused entirely on the flows of materials or substances. However, researchers have also applied the UM approach under the umbrella of the three pillars of sustainability (economy, society and the environment) (38, 39) and developed tools such as the integrated UM analysis tool (IUMAT) (39). Others have suggested studying systems in a life cycle perspective and understanding urban sustainability by coupling UM and LCA, as is done in this whitepaper (24, 40-43). Goldstein *et al*. applied the UM-LCA framework to five global cities and assessed the environmental impacts directly and indirectly caused by the mass and energy flows through the cities (42). The author concluded that the results of the study are first gross estimates due to inadequate data. Chester et al. presented evidence that better understanding of sustainable urban systems could be achieved by integrating UM and LCA frameworks, which would help in understanding physical flows and urban infrastructure system problems (43).

A predecessor to this application of the UM-LCA framework to urban hardscape, Chester *et al.* (44) used LCA to estimate the environmental impacts of building and operating parking spaces. Fraser and Chester used UM-LCA type analyses to estimate the materials and emissions investment in streets and roads in the Los Angeles area over time and the transition from heavy impacts from initial construction to increasing impacts from vehicle use and increasing demands for financial resources for maintenance and rehabilitation (45). This latter work indicates the importance of looking at urban impacts over a long enough analysis period, per LCA methods, to capture changes in impacts as the hardscape infrastructure both grows, or potentially shrinks if hardscape is converted to buildings or back to green space, and ages.

Reyna and Chester evaluated the age and rate of demolition of building stock in Los Angeles (46). Recycling of concrete from building demotion recycling of all types of existing hardscape are the sources of raw aggregate (rock) based materials for new hardscape, the use of which is one of the cases proposed for exploration later in this document.

LCA data and analysis approaches for use in an UM-LCA framework have greatly improved over the last ten years. An international LCA conference is held every two to three years that focuses on sustainable transport infrastructure, in particular pavement and hardscape. The most recent of these conferences was held in Champaign, Illinois in 2017 (47). This symposium was a continuation of earlier conferences and workshops beginning with the Pavement LCA workshop held in Davis, California in 2010 (48); the RILEM Symposium on LCA for Construction Materials held in Nantes, France in 2012 (49); and the Pavement LCA Symposium held in Davis, California in 2014 (50). These conferences act as a platform to bring together international construction material industries, contractors, consultants, researchers, academia and the transport administrations (federal and state, local). One of the major aims of these conferences is to implement life cycle thinking for transport infrastructures and promulgating the use of quantitative environmental assessment methods that help in decision support, such as the LCA. The most recent conference focused on data collection, inventory development, and data quality.

Data essential for the UM-LCA approach is rapidly being improved through the work of various collaborators in industry and government, many of whom come together semi-annually through the Federal Highway Administration (FWHA) Sustainable Pavement Task Group (51). A framework has been developed for pavement LCA which can easily be extended to all urban hardscapes (52). Data availability for urban hardscape materials is becoming more widely available through several efforts being organized by consortia of government, industry and academia, such as the Federal LCA Commons (53), and the other efforts (54).

Climate change is a pressing problem that cities will have to deal with and adapt to, but they have often not started making changes in infrastructure engineering and management (55). Reasons for this delay include short term priorities driving design and planning, and inefficient use or omission of climate change data in infrastructure planning processes (56, 57). A group of academics and transportation practitioners who are involved in the Infrastructure and Climate network (ICNet) in the northeastern region of the United States has addressed the systematic incorporation of climate change in infrastructure engineering and has worked to connect climate experts to front-line transportation infrastructure managers and designers. This approach provides a model for further improvement of communication between climate change modelers and infrastructure managers, particularly with regard to converting climate change predictions into actionable data for engineers.

Kim *et al.* (58) looked at urban flooding and the transition of design of infrastructure to handle uncertainty of future extreme events from a “fail-safe” approach based on risk analysis to a “safe-to-fail” approach. Their argument is that estimates of risk are difficult in the face of climate uncertainty which makes the reliability of designs meant to prevent failure (fail-safe) difficult to confidently estimate, and that a more resilient system (safe-to-fail) can be found if there is a transition to infrastructure designed and operated with the following principles:

- “Focusing on maintaining system-wide critical services instead of preventing component failure (59).
- Minimizing the consequences of the extreme event rather than minimizing the probability of damages (60).
- Privileging the use of solutions that maintain and enhance social and ecosystem services (61).
- Designing decentralized, autonomous infrastructure systems instead of centralized, hierarchical systems (60).
- Encouraging communication and collaboration that transcend disciplinary barriers rather than involving multiple, but distinct disciplinary perspectives (61, 62).”

Kim *et al.* applied their approach to look at urban flooding in Phoenix, Arizona under recent intense rainstorms (58). They modeled the flooding of important nodes on major streets and highways using the Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) and used multi-criteria decision-making to evaluate several alternatives for making the infrastructure more resilient to extreme rainfall. Interestingly, the use of permeable hardscape does not appear to have been considered.

Ahern (61) emphasized multi-functionality of infrastructure within the constrained space of urban areas as a key design principle to improve resilience. Ahern also discussed increasing resilience through decentralization by means of designing multiple smaller modules to deliver the functionality of major infrastructure systems rather than relying on a large single unit. Tye et al. noted that a workshop at the National Center for Atmospheric Research, USA, had "brought together climate scientists, civil engineering practitioners and governmental departments to discuss how scientific and engineering approaches to weather and climate extremes should be transformed to reduce societal vulnerability" (63). Also discussed by Tye et al. was the importance of collaborating with the insurance industry regarding their considerations of risk (62). The ability to obtain insurance is an important indicator of risk and the ability to quantify it can drive public policy. Furthermore, the capacity of insurance companies to successfully survive major events is an important consideration for protecting quality of life in terms of the financial stability and viability of communities.

Permeable pavement is one approach to using hardscape for the multiple functions of transportation, stormwater quality management, groundwater recharge and flood control, but it has been used in a small fraction of the potential places where it might provide multi-functional benefits. In early 2017, the University of California Pavement Research Center (UCPRC) and the National Center for Sustainable Transportation (NCST), working with the Interlocking Concrete Pavement Institute (ICPI), identified gaps in knowledge and other barriers to wider implementation that were perceived to be holding back the full potential for deployment of pavements that can simultaneously solve transportation, stormwater quality, and flood control problems. A workshop was organized in November 2017 based on those discussions with the goal of identifying knowledge, information, and communication barriers to adoption of permeable pavement of all types, and creation of a road map to address and overcome them. The workshop brought together a diverse group of stakeholders from the planning, stormwater quality, flood control, and pavement communities to listen to presentations, exchange and discuss unanswered questions identified by the group, and then to discuss a proposed road map to fill the gaps in knowledge, processes, and guidance.

Some of the major findings in the final report (18) from the workshop regarding the institutional and informational obstacles to making use of permeable pavement more acceptable to designers echo the principles identified by Chester *et al.* for improving the resiliency of flood control infrastructure. These include recognition of the benefits of designing decentralized, autonomous infrastructure systems, such as making major portions of urban paved areas permeable instead of, or in addition to, building centralized stormwater conveyance and storage systems; and, encouraging communication and collaboration that transcend disciplinary barriers rather than involving multiple, but distinct disciplinary perspectives. In this case, difficulties in identifying roles and relationships between urban transportation departments, stormwater regulatory agencies, and flood control agencies in determining responsibility for maintaining the multi-functionality (transportation, stormwater, flood) of permeable pavements emerged as an obstacle. Technical issues were also identified by the workshop, as well as the need for better cost and performance data.

A presentation at a workshop by Haselbach (65) discussed how the risk of flood damage increases in downstream cities built along rivers in long flood plains, such as those along rivers in Texas, when upstream cities expand their urban hardscape and flood conveyance to rapidly shed water. Thus, there is increased risk of flooding in each city as the area covered by hardscape increases, and that risk cascades and is multiplied significantly for downstream cities as upstream systems release water to protect the integrity of their own infrastructure and local urban areas.

2.3. Discussions with Experts

In addition to the review of the published literature, meetings were held with researchers at UC Los Angeles (UCLA), UC Davis (UCD) and the University of Southern California (USC) to review the concept for the UM-LCA framework presented in this white paper and potential data sources. The consulted experts included Stephanie Pincetl and Eric Fournier at UCLA, Jay Lund and Jon Herman at UCD and George Ban-Weiss at USC.

As an example of data collection, Pincetl and Fournier pointed to the LCA framework and tool called City Road Network (CiRN) LCA developed for the roadway system in Los Angeles and used by Fraser and Chester (45) and other studies. The data tracks the location of streets and highways over time and was developed in a GIS environment. To complement this source of information for hardscape, potential data sources for soil permeability information were identified to assess where permeable hardscape could successfully be used to infiltrate water into the soil versus areas where permeable hardscape can only store water for later discharge. The SSURGO and STATSGO spatial data layers from the National Resources Conservation Service of the U.S. Department of Agriculture were identified as the most promising data sources. Information from the Permeable Pavement Road Map Workshop indicated that the scale of these maps is not sufficiently fine to capture the permeability for project design purposes, but should still provide adequate data on the scale of urban metabolism studies.

Pincetl and Fournier pointed to use of fly-over maps to identify hardscape paved areas that can augment the estimates of surface areas of highways, streets and roads available from state and local government sources. Data regarding material flows can be obtained down to a sub-urban area level from the IMPLAN database (67) and tool. They indicated that data regarding building ages can be obtained from the California Economic Development Division by business data centers. This is the data approach used by Reyna and Chester (46) to also indicate the rate of demolition of buildings. The rate of demolition of publicly owned roads and streets would have to be estimated from maintenance and rehabilitation data from local and state government sources, inferred for private sources, and compared with estimates of civil infrastructure demolition hauling ton-miles.

3. Urban Metabolism and Life Cycle Assessment (UM-LCA)

3.1. UM-LCA Framework

An UM-LCA framework was developed that can quantify water and hardscape material metabolism for a defined area/boundary as shown in Figure 7. It is based on the literature survey and discussions with experts in water management systems, stormwater runoff quality, freight systems and materials across number of institutions and agencies. For initial use in California, Caltrans adjusted urban area boundaries derived from the 2010 census and approved by FHWA are being considered as the system boundaries for the framework. The framework consists of horizontal and vertical flows. Horizontal flows are hardscape material flows which include asphalt products, concrete products, aggregates, crushed concrete demolition materials from building and other structures, additives, admixtures and recyclable materials. The vertical flow is the hydrologic cycle which is considered in the framework.

The goal for development and use of the framework is to reduce environmental impacts of urban hardscape through analysis and rethinking of hardscape management, including design, construction, maintenance, rehabilitation and end-of-life (EOL) to produce and compare alternatives to current practices. In addition to the typical environmental impact-indicators in the FHWA pavement LCA framework (52), it is proposed that later development should consider inclusion of the social LCA indicators developed in a separate recent report (68). It is also proposed that additional impact indicators that consider the phenomena listed below related to human comfort and quality of life in urban areas be further developed for inclusion:

- Human thermal comfort through consideration of localized (locations within the larger urban area) urban thermal environment
- Human aural comfort through consideration of localized urban noise environment
- Human visual glare comfort through consideration of localized reflectivity environment

Initial indicators have been developed for thermal comfort, focused on outdoor or pavement-related thermal comfort (69-73) rather than inside-building comfort, aural comfort (74, 75) and glare comfort (76-79). Only some of these references look at development of life cycle impact indicators; most are focused on comfort indices that could serve as mid-point indicators rather than indicators of effects on human health over the life cycle and considering all stages of the life cycle. Effects of pavement on the overall urban heat island for the entire urban area and the resultant impacts on thermal comfort, summertime cooling, wintertime heating and energy use from heating and cooling can also be considered. Consideration of overall urban heat island effects requires climate modeling, and consideration of the energy sources for heating and cooling. A recent study in California (80) found that the energy and greenhouse gas emission impacts of changing pavement surfaces to increase albedo and decrease urban area (as opposed to localized areas within the urban area) heat island were primarily dependent on the changes in pavement materials, and the effects of resultant changes in building energy use were much smaller. This result will change depending on the climate region and sources of electrical energy for air conditioning and building heating.

The initial focus of the framework is on material flows in and out of the urban areas, stormwater flows, groundwater infiltration, and stormwater pollution flows. The intent is that the framework will be expanded in the future to consider other important flows affecting the environment and human quality of life in urban areas. The final work will use the building blocks of pavement LCA, permeable pavements, development of hardscape materials with greater on-site recycling, stormwater management, pavement asset management, and construction practices.

3.2. Data Sources

With help of several stormwater, water management, climate change, material producers and other topic experts, different data sources were identified that could be used for quantifying the life cycle impacts related to water and hardscape materials for the urban area in consideration.

3.2.1. Hardscape Material Flows

There is no single source for data for hardscape material flows. Some of the common data sources include databases, LCA literature, public documents, surveys, etc. A comprehensive list of data sources for different materials were compiled in previous research conducted for development of an LCA framework for aviation pavements (81) as well as the FHWA pavement LCA framework report (52) as shown in Table 1, and which can be translated for use in the UM-LCA framework.

In LCA, the terms foreground and background data are often used to differentiate between data that defines or represent the study application (i.e., a city’s hardscape) and the datasets used to describe the background systems on which they rely (i.e., the supply chain that provides aggregates to the city, or the electricity grid, including the energy resources power plants that supply it, that provide electricity to a city. Often, background data is provided by reference life cycle inventory (LCI) datasets derived from databases. The LCIs include the full life cycle burdens of the materials or processes which they represent. Table 1 include references to both background and foreground data sources, but mostly background data sources.

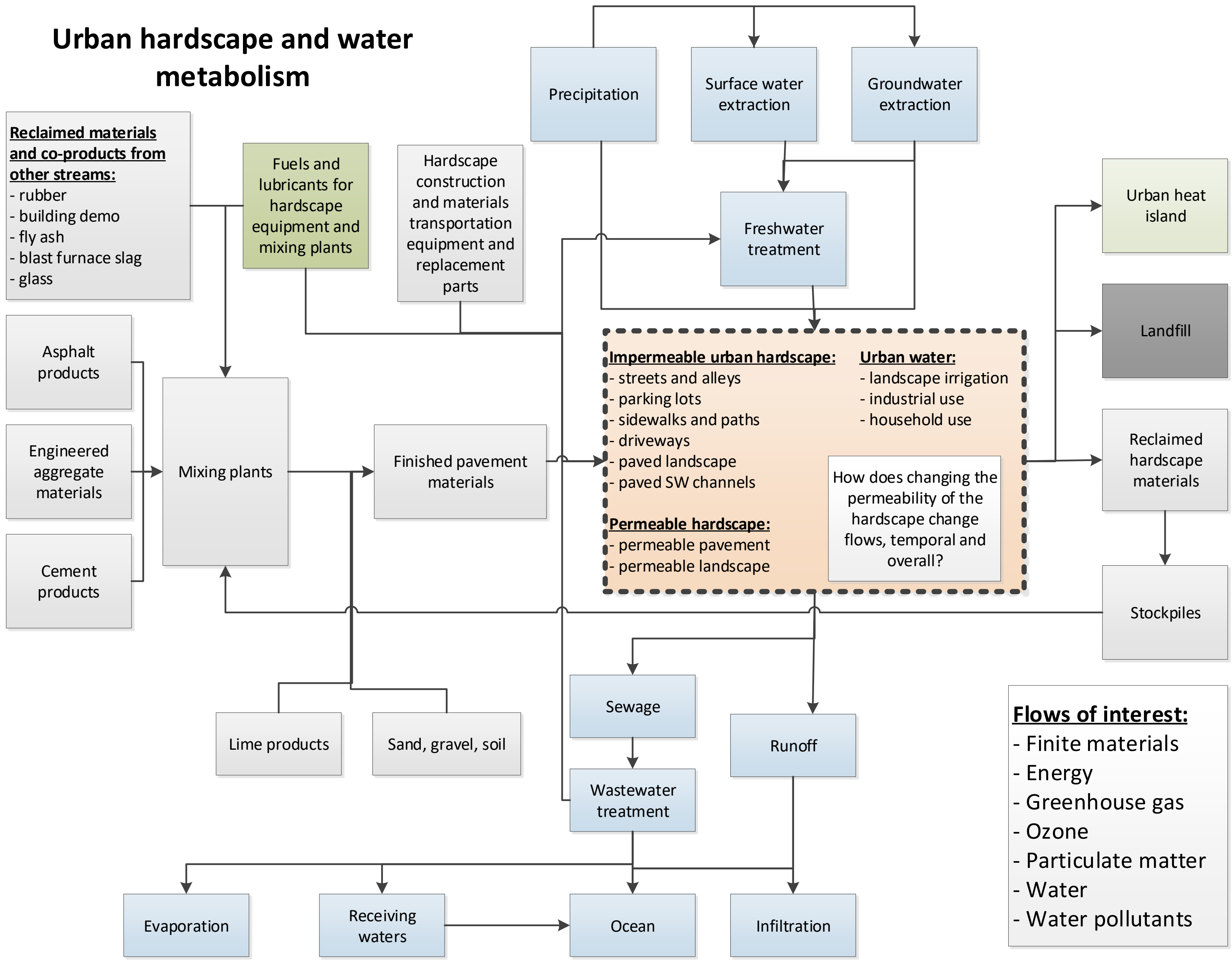

Figure 7. UM-LCA framework for urban hardscape materials and water metabolism

Table 1. Data sources that can be used as secondary data (modified version from 52, 81)

Data Collection Stage	Unit Process	Data Sources
Materials & Production	Asphalt mixture production	Ecoinvent 3.1 (82), Hot mix asphalt plants emission assessment report (83), EIO-LCA (84), Butt et al. (85, 86, 87), Stripple (88)
	Ready mix concrete production	Ecoinvent 3.1 (82), Portland Cement Association (89), Medgar (90), Nisbet *et al.* (91, 92)
	Asphalt binder production	Ecoinvent 3.1 (82), Eurobitume (93)
	Portland cement manufacturing	Ecoinvent 3.1 (82), Marceau *et al.* (94), EIO-LCA (84), Huntzinger and Eatmon (95), Valderrama *et al.* (96), Josa *et al.* (97)
	Drainage	EcoInvent 3.1 (82), USLCI (98), and ELCD (99) databases
	Aggregate production	Crushed Stone Emission Factors chapter (83), Sand and Gravel Processing Emission Factors chapter (83), PCA (89), Korre and Durucan (99), Jullien et al. (101), Athena (102), Häkkinen and Mäkelä (103), Butt and Birgisson (87).
Construction and Maintenance	Equipment emissions and fuel use	NONROAD (104), Wang et al. (105), Skolnik, Brooks, and Oman (106).
Drainage Use Stage	Water pollution from leachate and runoff	EPA IWEM (107)
End of Life	Waste	Doka (108, 109), database on waste management technologies (110).
Transportation	Hauling truck/rail/barge	EPA MOVES (111), Ecoinvent 2.2 (112), EPA/IPCC Emission Factors (113), Emission Measurements from a Crude Oil Tanker at Sea (114), CARB's EMFAC model (115), CARB's OFFROAD model (115), SimaPro (116).
Fuel and Electricity	Fuel	GREET (117), Ecoinvent 2.2 (112), Skone and Gerdes (119), NONROAD (104), SimaPro (116), IEA (120)
	Electricity	Ecoinvent 2.2 (112), EPA eGRID (121), SimaPro (116), IEA (120)

For California, the UCPRC has previously developed LCI datasets for construction materials tailored to California conditions, which are particularly suitable for projects in California. UCPRC updated LCA models with new inventories, processes, and models recently (2017) to expand the capacities of LCA for improving the sustainability of pavement operations in California (122). The updates included new inventories for pavement materials such as asphalt, concrete, terminal blend rubberized asphalt concrete, warm-mix asphalt, open-graded friction courses, pre-cast concrete slabs, reinforced concrete, aggregate bases, cement treated bases, asphalt treated bases, maintenance treatments such as chip seals, slurry seals, and reflective coatings, and the different types of full- and partial-depth recycling strategies that are typically used by Caltrans. Furthermore, the UCPRC LCIs have been critically reviewed by three LCA experts for data assumptions, collection, processes and quality. These LCIs and impact calculations are included in a new LCA tool called *eLCAP* (environmental Life Cycle Assessment for Pavements, 123). Similar activities could be undertaken at any state or city level to generate geographically appropriate LCAs and eLCAP or other similar tools could include updated regionally adjusted inventories for locations outside California.

Quantification of flows of materials that are transported in and out of the urban boundary are needed to be able to apply the unit process data. The Commodity Flow Survey (CFS) is conducted under the partnership of the Bureau of Transportation Statistics and the U.S. Census Bureau every few years. CFS data covers movement of forty-three goods that are transported in and out of the boundaries of the U.S. and U.S. cities by road transport.

The Freight Analysis Framework Data Tabulation Tool (FAF4) (124) is another data source that can be used to collect data for a specific city or region in the U.S. that can then be used in the UM-LCA framework. The FAF4 tool is divided into four flow types; total flows, domestic flows, import flows and export flows. Total flows include domestic and foreign shipments between domestic origins and destinations whereas domestic flows do not include foreign trade flows. Import and export flows includes goods movement between domestic and foreign origins. In the pavement industry, the majority of the materials used for construction, which are primarily composed of gravel, sand and crushed stone, are relatively local materials, unless there is access to water transport. An exception is specialized engineered materials/chemicals such as admixtures and additives. Figure 8 shows the order in which user input/selection is required before the tool outputs a comprehensive summary data of different commodities in tons, ton-mile and/or dollar costs in tabular form.

In this white paper, examples of domestic flow types are presented. Within the domestic flows, seven tables are presented that require user input. Each table has a drop-down list to select from. The CFS data is being collected every five-years since 1997. Data were also collected for the years 2013, 2014 and 2015. Additionally, users can extract future projection data based on macroeconomic forecasting model starting from 2020 to 2045 for every five-year interval (125). The origin and destination can be at the country, state or city level. The city and state boundaries in FAF4 are defined as FAF zone specific and the 132 domestic zones are a hybrid of core-based statistical areas that have been defined by the office of management and budget and state boundaries (126).

The data on movement of commodities between cities in different U.S. states can be extracted. In order to illustrate the data that can be extracted from FAF4, the following California cities were selected as shown in Table 2: Los Angeles, Sacramento, San Diego, San Francisco, and Fresno. The CFS tracks commodity sectors based on North American Industry Classification System (NAICS) codes. Examples of sectors required for the UM-LCA hardscape framework include building stones, natural sands, gravel, fuel oils, plastic/rubber and waste/scrap. The transportation modes that are covered by FAF4 include truck, rail, water, air (includes truck-air), pipeline, and multiple modes and mail. **Error! Reference source not found.** shows an example of data that can be extracted using the FAF4 tool. Additional data are needed to further identify which of these building material flows are used for hardscape. Review of quantities in public contracting records is one option for identifying flows for public hardscape. Review of sales data from quarries supplying a given area, properly avoiding identification of the seller, can be used as an independent check, and will also provide information about privately owned hardscape. At this time there are no know surveys or other databases containing this type of information.

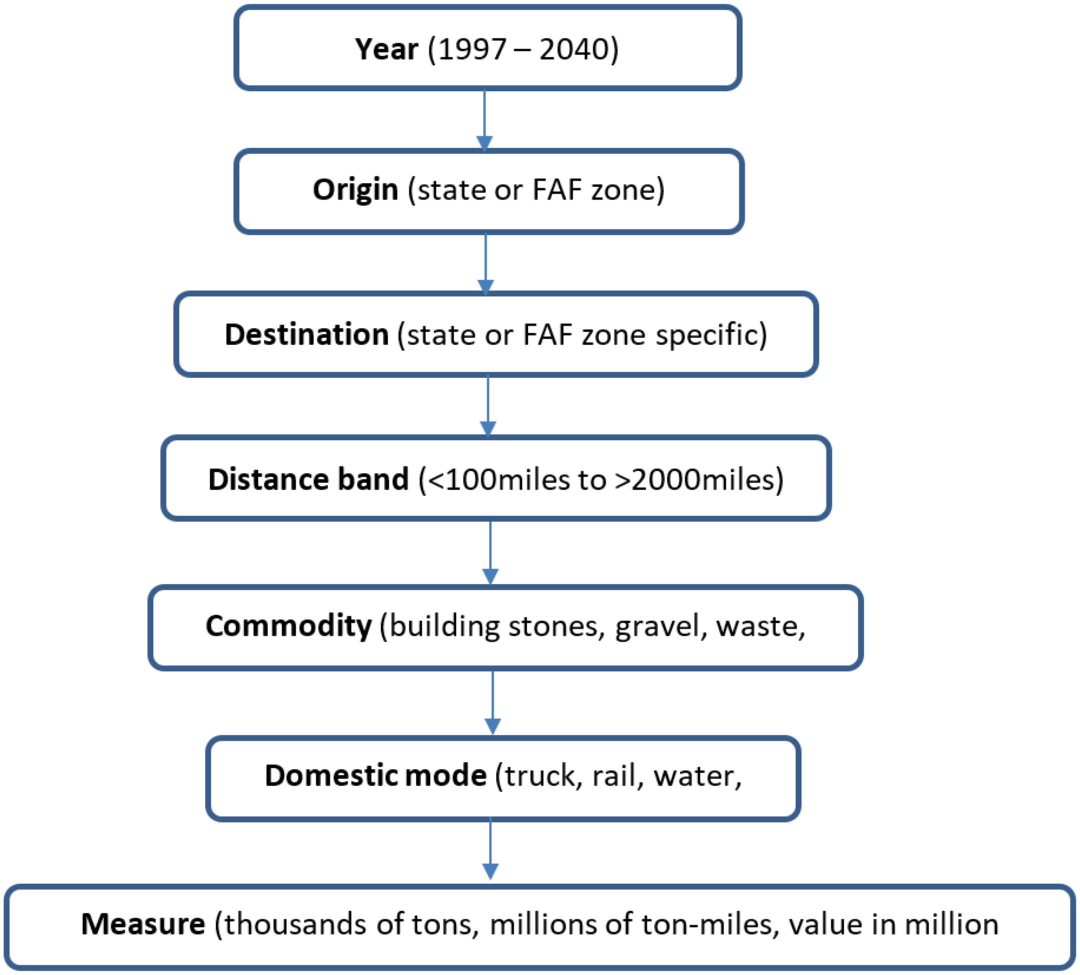

Figure 8. FAF4 Data Tabulation tool

Table 2. Output from the FAF4 tool for California region for truck transport mode

		Year 2015				Year 2030 (Projection)		
Destination	**Material transported**	**Total KTons in 2015**	**Total Ton-Mile in 2015**	**Total M$[1] in 201**	**Total Current M$[1] in 2015**	**Total KTons in 2030**	**Total Ton-Mile in 2030**	**Total M$[1] in 2030**
Los Angeles CA	Building stone	3.9	1.9	2.9	3.0	1.9	0.9	1.4
Los Angeles CA	Natural sands	99.3	15.6	2.6	2.9	114.0	17.9	3.0
Los Angeles CA	Gravel	1814.0	564.5	11.1	12.1	1977.7	615.4	12.1
Los Angeles CA	Plastics/rubber	279.3	80.8	138.3	136.5	405.0	117.2	200.5
Los Angeles CA	Transport equip.	0.3	0.1	110.2	115.6	0.6	0.1	216.8
Los Angeles CA	Waste/scrap	23.0	12.4	25.2	17.9	29.1	15.7	31.9
Sacramento CA	Building stone	3.6	0.6	2.8	3.0	2.1	0.4	1.6
Sacramento CA	Gravel	60.6	19.1	0.8	0.9	66.1	20.8	0.9
Sacramento CA	Plastics/rubber	3.3	1.1	12.7	12.6	4.9	1.6	19.1
Sacramento CA	Waste/scrap	51.8	10.8	31.0	22.0	59.3	12.4	35.5
San Diego CA	Building stone	1.6	1.0	1.2	1.3	0.5	0.3	0.4
San Diego CA	Gravel	3.9	1.9	0.2	0.2	4.2	2.0	0.2
San Diego CA	Plastics/rubber	10.7	4.9	13.2	13.0	15.8	7.2	19.3
San Francisco CA	Building stone	398.7	96.5	10.7	11.3	551.7	133.6	14.8
San Francisco CA	Natural sands	630.7	200.2	15.9	17.9	724.6	230.0	18.3
San Francisco CA	Gravel	140.8	40.2	2.9	3.2	153.5	43.8	3.2
San Francisco CA	Fuel oils	0.6	0.1	0.6	0.3	0.3	0.0	0.3
San Francisco CA	Plastics/rubber	29.4	6.5	81.2	80.2	43.6	9.6	120.4
San Francisco CA	Waste/scrap	122.8	37.6	40.3	28.6	108.2	33.1	35.5
Fresno CA	Building stone	0.1	0.0	0.6	0.7	0.0	0.0	0.2
Fresno CA	Natural sands	258.0	41.8	12.3	13.8	296.3	48.1	14.2
Fresno CA	Gravel	156.6	39.7	3.8	4.1	170.7	43.3	4.1
Fresno CA	Gasoline	2.2	0.4	2.8	1.6	0.5	0.1	0.6
Fresno CA	Fuel oils	50.8	7.7	50.4	27.5	11.4	1.7	11.3
Fresno CA	Plastics/rubber	13.8	3.6	37.6	37.1	23.2	6.1	63.1
Fresno CA	Waste/scrap	3.2	1.0	1.1	0.7	5.9	1.9	2.0

[1] **$M : cost in million dollars**

3.2.2. Water Flows

As noted in the introduction, modeling of climate change indicates that the intensity of rainfall during extreme events will increase significantly, with the amounts depending on the extent of continued human contributions to greenhouse gases (127. The UM-LCA modeling of rainfall should consider both current rainfall events and predicted future severity of events.

The UM-LCA model covers stormwater flows that are associated to pervious or impervious hardscapes and may cause flooding. Stormwater runoff is the water on surface of the ground received from rain and/or snow that does not infiltrate into the ground or evapotranspirate (evaporation of water from ground and plants). Increased urbanization is one of the factors that has affected urban flooding and stormwater runoff due to development in the flood plains and construction of impervious hardscapes. Figure 9 through Figure 11 show qualitatively how degrees of average perviousness of urban surfaces affect stormwater runoff, infiltration and evapotranspiration.

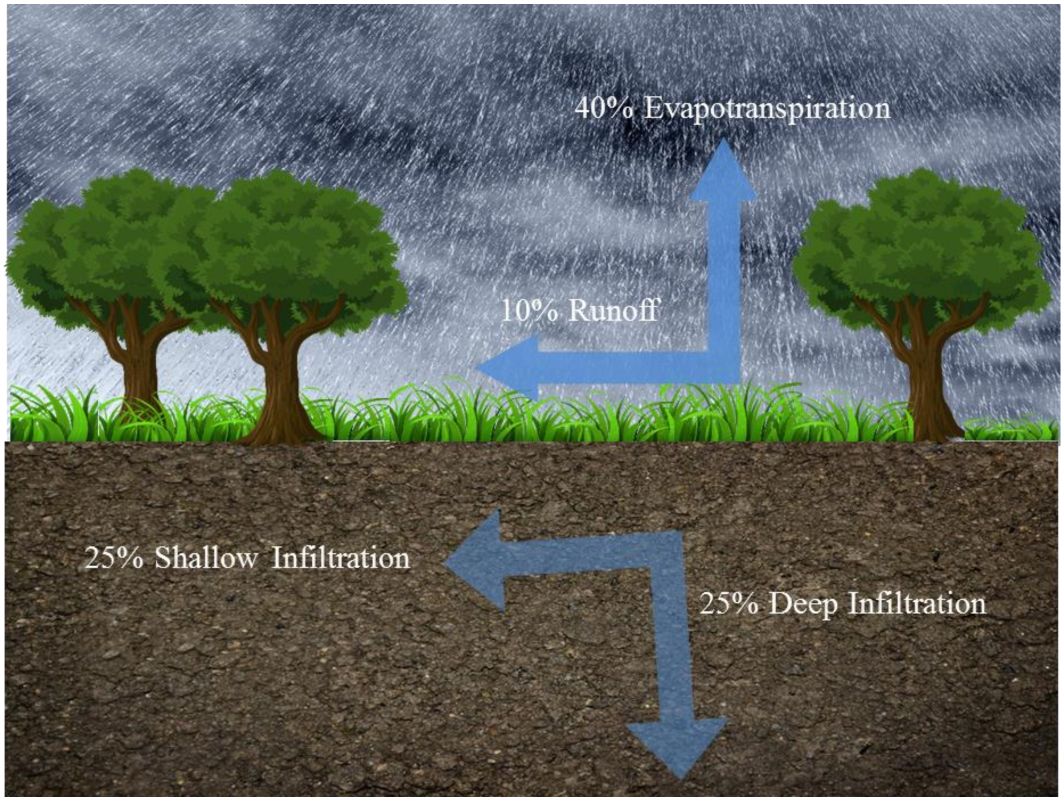

Figure 9. Stormwater runoff on natural ground cover (recreated figure from FISRWG [128])

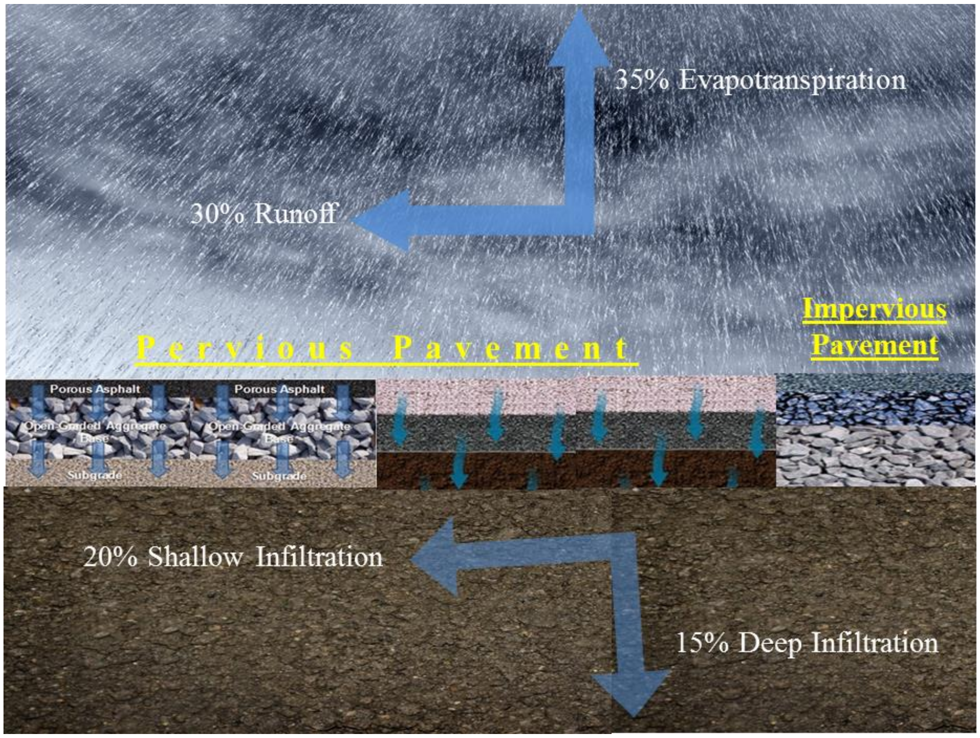

Figure 10. Stormwater runoff due to 35 to 50% impervious surface (recreated figure from FISRWG [128])

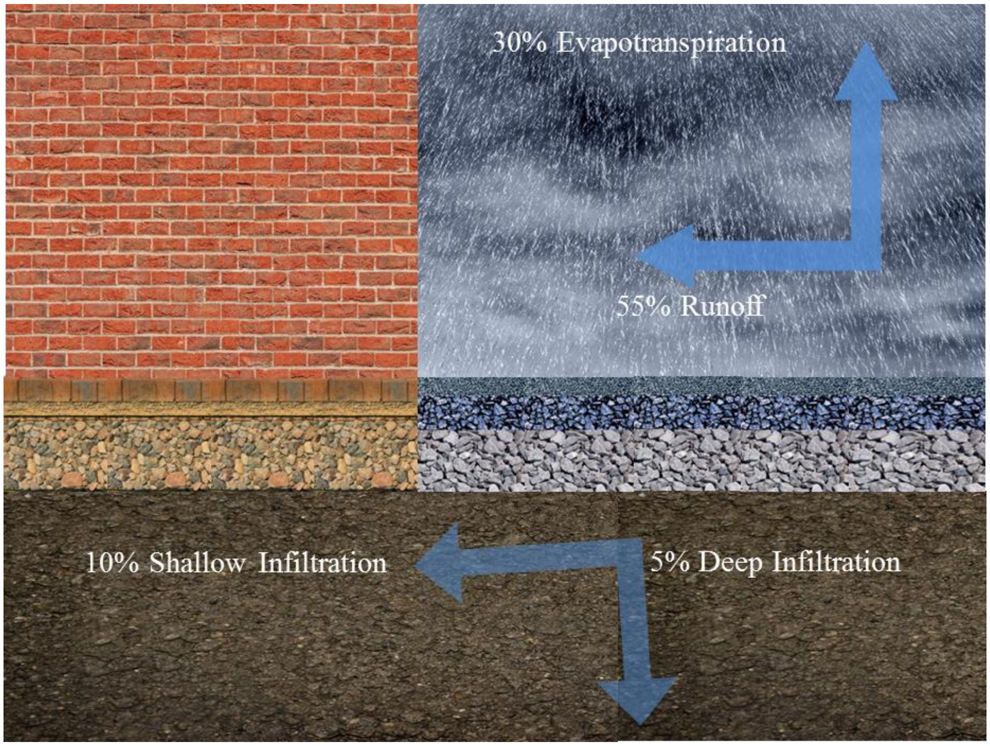

Figure 11. Stormwater runoff due to 75 to 100% impervious surface (recreated figure from FISRWG [128])

3.2.2.1. General information about SWMM

The Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) is a simulation program which can perform dynamic rainfall-runoff modeling (129). The simulation can be conducted for both a single event or over a longer period of time (continuous modelling) and the program can analyze quantity and quality of runoff from different urban regions. The SWMM model works based on an assembly of sub catchment regions in which precipitation is received and runoff is generated. SWMM then uses simulation of a combination of pipes, storage devices, pumps and regulators, to model transport of this runoff. SWMM can record the quality and quantity of generated runoff in each of these sub catchments. It also can calculate the flow rate, flow depth and quality of water in pipes and channel sections for the duration of simulation. The hydrological processes that can be simulated in SWMM include evaporation, snow accumulation, infiltration, percolation of infiltrated water, water interflow between groundwater and drainage system, etc.

To overcome spatial variability in all these processes, the actual area of interest is divided into smaller sub catchment regions in which the hydrological properties are homogenous. Then, the overland flow can be dispelled between sub catchments, drainage systems or sub-areas. SWMM is also capable of analyzing runoff pollutant loads under different conditions such as dry-weather pollutant buildup, pollutant wash-off during storm incident, contribution of rainfall deposition, and reduction of concentration due to water treatment.

The UM-LCA framework developed for this study aims to build a foundation for future assessments of alternative types of urban hardscape. Using materials such as pervious concrete, permeable pavers and porous asphalt and designs for construction of permeable pavements that allow the stormwater to pass through the structure into the ground water table is one way to reduce stormwater runoff through infiltration and detention, which also increases groundwater recharge and can help improve stormwater quality. The water cycle can be quantified using the SWMM model.

3.2.2.2. The SWMM Model

SWMM simulates a drainage system as a combination of water and material flows amongst many different environmental “Compartments”. A given SWMM simulation does not require having all Compartments in a model. Figure 12 below shows the interactions of the Compartments schematically.

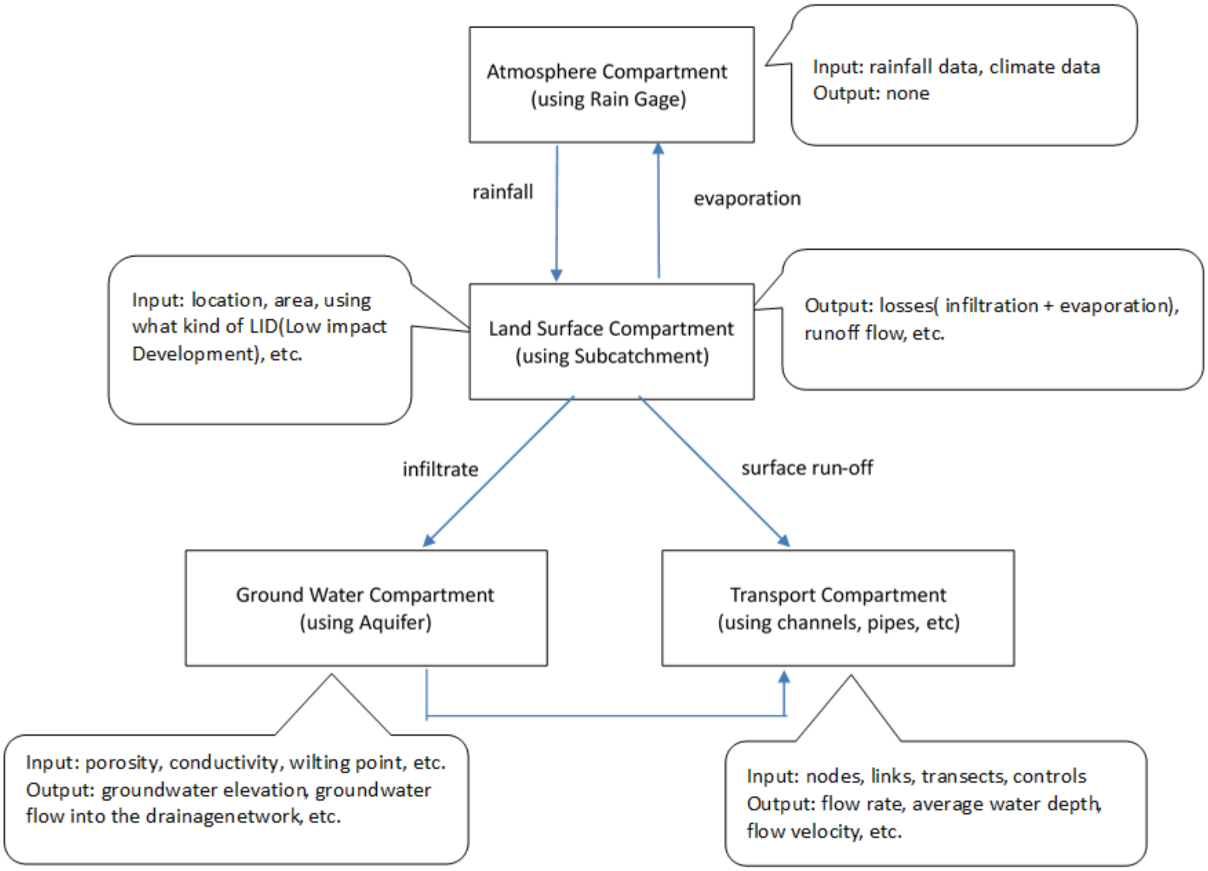

Figure 12. The flowchart of the inputs and outputs in the four Compartments of SWMM.

The Compartments and objectives of SWMM include:

1. The Atmosphere Compartment which simulates the rainfall precipitation and pollution that is deposited on the land surface.
2. The Land Surface Compartment which is defined by a combination of sub catchment objects. It has rainfall input from the Atmospheric Compartment, then it provides outflow to the Groundwater Compartment as infiltration and sends surface runoff and associated pollution to the Transport Compartment.
3. The Groundwater Compartment receives input from the Land Surface Compartment in form of infiltration. This Compartment then, transfers part of this infiltration as an inflow to the Transport Compartment.
4. The Transport Compartment has a network of drainage elements such as channels, pipes, pumps, and regulators. It also contains storage/treatment units which are responsible for water transportation to outfalls or to treatment facilities. This Compartment receives inflow input from surface runoff, groundwater interflow, sanitary

dry weather flow or a user-defined hydrograph. In this Compartment the elements are modelled as node-link connections.

SWMM provides additional capabilities relevant to urban hardscapes. There is an additional section called Low Impact Development (LID) which defines the properties of low impact technologies such as the permeable pavements. LID is an approach that manages stormwater on-site by sustainable land planning and engineering design practices i.e., use of recyclable materials, permeable hardscape designs, and in-place recycling are some of the example practices. The LID module in SWMM includes the following technologies: bio-retention cell, porous pavement, infiltration trench, rain barrel, and vegetative swale. The Atmosphere Compartment contains climate information which determines how much precipitation LID will receive. The Land surface Compartment contains information about LID's area. The Transport Compartment transfers extra rainwater which LID cannot absorb. The Ground Water Compartment depends whether the LID allows stormwater to recharge ground water. For example, the green roof conveys stormwater into the drainage pipes and the water does not infiltrate into the ground directly. Therefore, in this case the Ground Water Compartment can be omitted. However, use of Ground Water Compartment is necessary if a structure, such as permeable pavements, allows water to infiltrate into the groundwater table.

3.2.2.3. SWMM Inputs and Outputs

The climate information and rainfall are required for almost all the SWMM simulations. The data can be collected from National Climatic Data Center (130). The information about the modelled area is also one of the required inputs. As mentioned earlier, SWMM divides the defined area into several sub catchments according to the land usage (parking, roads and so on). The properties of the subcatchment are: 'X-Coordinate' and 'Y-Coordinate' which defines the location of the sub catchment area on the map, 'Area' which shows the size of the sub catchment, and 'Rain Gauge' which determines the duration and intensity of the rain.

The following are input parameters that are used in the LID module: surface layer, pavement layer, storage layer, underdrain layer, and subgrade layer.

After completion of the analysis, LID provides the following outputs: total inflow volume, total evaporation loss, total infiltration loss, total surface outflow, total underdrain outflow, initial storage volume, and final storage volume. These outputs are available for any analyzed time step and can be viewed on the map in the program, tabulated or plotted for the further statistical analysis.

Several data sources have been determined that can be used in the SWMM model as inputs. Data from cities in California was taken as an example to illustrate what type of information can be extracted from the sources reported in order to run the SWMM model.

The following sources can be used to collect the information of the rainfall and climate for cities and regions in the U.S.

- Rainfall and Climate: DSI-3240 - hourly record of rainfall at U.S. National Weather Service (NWS) and Federal Aviation Agency stations
- DSI-3260 - record of fifteen-minute rainfall at NWS stations
- DSI-3200/ DSI-3210 - climate data that can be collected from the National Climatic Data Center (130)

SWMM can simulate the process lasting for several hours such as a single rainfall event or for an entire year, which means the rainfall data files vary from 15 minutes precipitation to hourly precipitation. The inputs of rainfall and climate can be found in the NCDC (130127). Usually a city will have several weather/climate stations; however, selection of a particular climate station and rainfall data type depends on the SWMM model.

SWMM requires details of the urban planning of a specific area such as the land usage, the underdrain system, and other systems. For instance, in Los Angeles the inputs can be found from Los Angeles’s Department of City Planning under Map Gallery and ArcGIS Shapefiles tab (131). Data for permeable pavement are readily available for LID inputs.

4. Summary and Recommendations

This white paper proposes the development of an urban metabolism-life cycle assessment (UM-LCA) framework for urban hardscape systems in large urbanized areas that follows the principles of UM and LCA, and can be used by planners and engineers to analyze and quantify the hardscape material and water flows of an urban area, and support them in evaluation and decision support regarding changes in the those systems and their operation. The results are intended to also be used by policy-makers regarding land use and hardscape planning and design. The framework is intended to address the impacts of providing hardscape in terms of environmental and later human quality of life impacts of hardscape material flows and impacts of use of different types of hardscape on flooding and groundwater infiltration in urban areas. The framework can also be used to investigate the effects of reducing hardscape and increasing building and green space in the urban area through reduction of parking and other hardscape features. The recommended steps for development of this approach and its use are:

1. Researchers and policy-makers, and advocates are encouraged to contribute to the development of data, models and tools for the UM-LCA approach.
2. The white paper advocates that this approach be used by researchers and policy-makers to analyze approaches to reduce the impacts of the urban hardscape systems of large urbanized areas while increasing the benefits that they provide. The white paper suggests some current ideas for achieving these objectives by identifying more efficient, and less impactful materials and structures, location of virgin materials sourcing and greater use of in-place and near-site recycling and use of more partially permeable and fully permeable structures. However, many more ideas should be identified and evaluated.
3. Current policy-makers and planning and engineering practitioners are encouraged to think of urban hardscape as an integrated system that is costly, requires large quantities of materials, and affects the mobility, safety, air quality, water quality, flood risk, noise and thermal environment of urban areas, while meeting multiple functional requirements.
4. The white paper advocates that future policy-makers and practitioners should bring the expected results into standard practice.

The expected outcomes from the actions advocated in this white paper are greatly improved data and methods for analyzing urban hardscape as a system, and increased benefits and reduced impacts from those systems.

A number of data sources and modeling tools were identified that can be used in the UM-LCA framework to quantify material and energy flows and environmental impacts including water flows. An effort was also made to identify data for a few of the cities in California in order to demonstrate parts of the data collection and presentation process. The framework developed is not limited to a single U.S. state, rather it can be used in any geographic region of the U.S.

Testing the UM-LCA framework in order to demonstrate the use of it using real city data was not in the scope of this study and is the logical next step. Detailed case studies using data from different climate regions can help decision makers to quantitatively assess the material and water flows of the city in consideration. Furthermore, the strengths and shortcomings of the framework itself as well as ability to find and use the data needed for the analysis will be better identified.

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