2017

Surveying and Projecting Sustainability and Urban-Water-Energy-Nexus Applications in Rhode Island

Fabian Wagner

University of Rhode Island, fabian_wagner@my.uri.edu

Follow this and additional works at: <https://digitalcommons.uri.edu/theses>

Recommended Citation

Wagner, Fabian, "Surveying and Projecting Sustainability and Urban-Water-Energy-Nexus Applications in Rhode Island" (2017). *Open Access Master's Theses*. Paper 1079.
<https://digitalcommons.uri.edu/theses/1079>

This Thesis is brought to you for free and open access by DigitalCommons@URI. It has been accepted for inclusion in Open Access Master's Theses by an authorized administrator of DigitalCommons@URI. For more information, please contact digitalcommons@etal.uri.edu.

SURVEYING AND PROJECTING SUSTAINABILITY AND
URBAN-WATER-ENERGY-NEXUS APPLICATIONS IN RHODE ISLAND

BY

FABIAN WAGNER

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
CIVIL AND ENVIRONMENTAL ENGINEERING

UNIVERSITY OF RHODE ISLAND

2017

MASTER OF SCIENCE THESIS
OF
FABIAN WAGNER

APPROVED:

Thesis Committee:

Major Professor Ali Shafquat Akanda

Farhad Atash

Thomas Boving

Nasser H. Zawia

DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND

2017

ABSTRACT

Rhode Island is both the smallest and 2nd most densely populated state, which already characterizes its unique situation within the United States of America. About 90.7% of the inhabitants live in urbanized areas, creating a more beneficial situation for the state's cities and towns equates to establishing improved conditions for a majority of its citizens.

This thesis constitutes a comprehensive approach on assessing sustainability in Rhode Island and its communities via implementation of a municipal ranking with 75 social, environmental and economic indicators. The rating is based on the best and worst performances of various indicators, thus allowing for concise comparison within the local context of the state. In this analysis, while the communities around Providence tend to perform unfavorably, the southeastern coastal communities are above average performers. The ranking results also show a certain link to both income and population density of the municipalities. The proposed tool allows for comprehensive evaluations and identification of areas for improvement for all municipalities of the state.

The second research focus is to evaluate linkages between water and energy provision in the state with a distinct focus on the urban environment. Both water supply and power generation exhibit advantageous characteristics, but rely on adequate data gathering to enable more refined research approaches. In addition, interactions between these vital resources were assessed by evaluating pollution sources and urban heat island implications. The latter reveals a high share of people residing in areas with significantly increased temperatures, which results in considerable, potential benefits by mitigating the associated UHI. Accordingly, abatement thereof may increase resilience of the public water supply infrastructure.

ACKNOWLEDGMENTS

To begin, I want to thank both my parents and grandparents for their ongoing support, thus enabling me to partake in graduate studies at the University of Rhode Island. Next to raising me and thus shaping me into the person I am today, their confidence and advice has pushed me to take the step towards studying in the United States.

Additionally, I want to thank my girlfriend Hannah Jucknischke, with whom I hope to spend many years of life together, for her support and love even though not less than an entire ocean separated us for most of the previous year.

Furthermore, I would like to express my gratitude to my academic advisor Professor Ali Shafqat Akanda. His support and advice during lengthy discussion sessions helped considerably to both improve and finalize this thesis. Accordingly, I would also like to thank the other two member of my defense committee, Prof. Farhad Atash and Prof. Thomas Boving, for their time and effort regarding this project. My graduate study group also deserves reference, as ventures such as this piece of work are more easily carried out together. Additionally, my other course instructors, such as Prof. Peter August, Prof. Vinka Craver and Prof. Reza Hashemi, are deserving of gratitude for their teaching and for sharing their experiences. Lastly, I want to thank Prof. Joerg Gatterman from the Technische Universitt Braunschweig and Prof. Christopher Baxter from the University of Rhode Island for coordinating the dual degree program and thus enabling me to partake in learning experiences from both countries.

Lastly, I want to thank my friends back home in Germany and in the USA for their support and kind words to boost my ongoing motivation to work on this thesis.

TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGMENTS	iii
TABLE OF CONTENTS	iv
LIST OF FIGURES	viii
LIST OF TABLES	xii
LIST OF ACRONYMS	xvi
LIST OF UNITS	xix
CHAPTER	
1 Introduction	1
1.1 Justification for the Study	1
1.1.1 Measuring Sustainability	1
1.1.2 Nexus Applications	11
1.1.3 Pressures posed by Urban Environments	14
1.1.4 Future Trends and Developments	15
1.2 Thesis Objective	20
1.3 Hypotheses	20
1.4 Thesis Structure	21
2 Analysis of Relevant Sectors in Rhode Island	22
2.1 Overview	22
2.2 Climate	26

	Page
2.3 Climate Change Projections	30
2.4 Administrative Boundaries	34
2.5 Statewide and Municipal Planning	35
2.6 Urbanized Areas	36
2.7 Municipalities	39
2.8 Utility Provision and Important Sectors	44
2.8.1 Energy	44
2.8.2 Water and Waste Water	50
2.8.3 Waste Management	56
2.8.4 Transportation System	60
2.8.5 Air Quality Monitoring	66
2.8.6 Land Use and Conservation Lands	69
2.8.7 Economy	73
3 Sustainability Ranking	76
3.1 General Approach	76
3.2 Methods	76
3.2.1 Compilation and Evaluation of the Ranking	77
3.2.2 Derivation of the Indicators	82
3.3 Data Resources	87
3.4 Indicators	90
3.4.1 Social	90
3.4.2 Environment	98
3.4.3 Economy	106

	Page
3.5 Results	111
3.6 Evaluation	117
3.6.1 Spatial Patterns	120
3.6.2 Relation to Municipal Parameters	122
3.7 Ranking Significant Findings	126
4 Urban Water-Energy-Nexus Evaluation	127
4.1 General Approach	127
4.2 Methodology	129
4.2.1 Derivation of Land Surface Temperature	129
4.2.2 Validation of obtained LST values	134
4.2.3 Water Withdrawals for Thermoelectric Power Plants	138
4.2.4 Spatial Analysis of Pollution Sources	140
4.3 Energy for Water	141
4.4 Water for Energy	146
4.5 Urban Interactions	156
4.5.1 Urban Heat Island Implications	157
4.5.2 Point Pollution Sources	164
4.6 Urban-Water-Energy-Nexus Significant Findings	169
5 Evaluation	171
5.1 Summary	171
5.2 Discussion	173
5.3 Limitations of this study	176
5.4 Conclusion	178

	Page
LIST OF REFERENCES	179
 APPENDIX	
A National Ambient Air Quality Standards	193
B Ranking Scores per Category and Segment	195
C Data for Derivation of Municipal Water Demand	206
D Criteria for Derivation of Residential Energy Demand	211
BIBLIOGRAPHY	213

LIST OF FIGURES

Figure		Page
1.1	Sustainability paradigm	3
1.2	Introduction to LEED with rating systems and credit categories	4
1.3	LEED for neighborhood development categories and indicators .	6
1.4	LEED criteria on assessing cities	7
1.5	Number of indicators per category for ISO standard 37120:2014	9
1.6	Distribution of US population by size of incorporated place . . .	10
1.7	Development of US population and share in urban or rural areas from 1800 to 2010	16
1.8	Projected development of global mean temperature till 2100 and assessment of associated risks	18
2.1	Rhode Island municipalities, urbanized areas and population distribution	24
2.2	Rhode Island counties with population figures for 2015	25
2.3	Monthly climate normals 1981 to 2010 NOAA Providence station temperature and precipitation	26
2.4	Comparison of climate normals 1981 to 2010 heating and cooling degree days	27
2.5	Monthly temperature and precipitation Providence and North Foster from 2010 to 2015	28
2.6	Observed and projected annual tidal floods for Providence . . .	31
2.7	Observed and projected temperature change with low and high emission scenario till 2100 for Rhode Island	32
2.8	Expected change in precipitation till 2050 for the entire USA . .	33

Figure		Page
2.9	Urban and rural population of RI municipalities and total population density based on Census 2010 block data	40
2.10	Comparison of electricity, thermal and transportation sector regarding energy demand	45
2.11	Time-line of total monthly electricity generation in Rhode Island 2013 to 2015	46
2.12	Total electricity generation in Rhode Island from 2013 to 2015 and key statistics	47
2.13	Power plants, transmission lines and natural gas pipelines in RI	48
2.14	Water usage in Rhode Island 2010	53
2.15	Water Supply Elements in Rhode Island	55
2.16	RI averages by waste category for RIRRC, other and in total . .	57
2.17	Location of solid waste facilities by type in Rhode Island	58
2.18	Annual municipal solid waste and processing rates 2012 to 2016	60
2.19	Transportation infrastructure features in Rhode Island	62
2.20	Modal split and mean travel time to work for the USA, Rhode Island and four communities for 2015	65
2.21	Percentage of days by AQI status in 2011	67
2.22	Continuous air quality monitoring sites in Rhode Island for AQI	69
2.23	Land Use and Land Cover Rhode Island 2011	71
2.24	Private employment sectors with share on total job figures . . .	73
2.25	Job and GDP growth for USA and Rhode Island 1979 to 2009 .	74
3.1	Hierarchy of applied sustainability ranking approach	80
3.2	Properties of the Excel 2016 box plot visualization	81
3.3	ACS, Hierarchy of geographic entities	88
3.4	Box plot for the six social ranking segments	97

Figure	Page
3.5	Box plot for the six environmental ranking segments 105
3.6	Box plot for the four economic ranking segments 111
3.7	Aggregation of total score for all municipalities along with ranking position per category 112
3.8	Social score for each municipality divided into the six featured categories along with overall ranking position 114
3.9	Environmental score for each municipality divided into the six featured categories along with overall ranking position 115
3.10	Economic score for each municipality divided into the four featured categories along with overall ranking position 116
3.11	Box plot for the social, environmental and economic categories and the overall score 118
3.12	Share on total score by category for each municipality along with partial and total score 119
3.13	Map of overall ranking score by municipalit 120
3.14	Map of ranking score for each municipality divided into social, environmental, economic and total 121
3.15	Linear correlation of population density to sustainability rating performance 124
3.16	Linear correlation of per capita income to sustainability rating performance 125
4.1	Featured aspects of the UWE-Nexus evaluations 128
4.2	Landsat 8 imagery August 2013, NDVI and land surface temperature 135
4.3	Validation of derived LST via comparison to weather stations and interpolation result 137
4.4	Overview of urban water components and resource flows 142
4.5	Impact of ten parameters on energy intensity of water systems . 143

Figure		Page
4.6	Total water use in MGD 2010, share by eight water usage categories and withdrawals for energy generation for selected states	147
4.7	Total water use in MGD from 1990 to 2010, share by eight categories for RI and energy intensity	150
4.8	Monthly generation for the six biggest power plants in Rhode Island and statewide generation for 2015	152
4.9	Relative, monthly distribution of three year averages for Rhode Island's two biggest power plants	155
4.10	Municipal evaluation of people living in areas with 5 K LST thresholds along with ratios of urbanized population, population density and mean LST	160
4.11	Municipal evaluation of land cover type and corresponding LST derived from Landsat imagery	162
4.12	Potential water demand reduction by UHI mitigation per community	164
4.13	Map of pollution sources and protection areas related to public water supply	167
A.1	National ambient air quality standards as monitored by RIDEM	193
C.1	Study regions from RIWRB strategic plan	207
C.2	Public water supply figures as reported by Rhode Island Water 2030	210

LIST OF TABLES

Table	Page
1.1 Share of total U.S. population in incorporated places below or above 100,000 inhabitants	11
2.1 Annual average temperatures and precipitation sums Providence and Foster 2010 to 2015	29
2.2 Total area, length of shoreline and ratio per state	31
2.3 2010 count and population in urban areas, urban clusters and rural areas for the USA and Rhode Island	38
2.4 Parameters for urban areas in Rhode Island as of 2010	39
2.5 Key parameters RI municipalities Barrington to New Shoreham	42
2.6 Key parameters RI municipalities Newport to Woonsocket plus minimum, maximum and statewide values	43
2.7 Capacity by county and technology in MW	50
2.8 Capacity in MW and number of generating facilities for power plants and distributed generation	51
2.9 Total, public and self supplied water average day demand per county	52
2.10 Waste metrics and definitions	59
2.11 LULC coded areas in Rhode Island	70
3.1 Example procedure for ranking score allocation	79
3.2 Methodology for deriving water demand per community as demonstrated for the PWSB	84
3.3 Providence as example for deriving residential energy demand .	85
3.4 Example residential energy demand for five municipalities as examples for derivation procedure	86

Table	Page
3.5	Indicators, social category, education 91
3.6	Indicators, social category, safety 92
3.7	Indicators, social category, health 93
3.8	Indicators, social category, work life balance 94
3.9	Indicators, social category, housing 95
3.10	Indicators, social category, voter participation and equal pay . . 95
3.11	Indicators, environmental category, energy 99
3.12	Indicators, environmental category, transportation 100
3.13	Indicators, environmental category, water 101
3.14	Indicators, environmental category, land use 101
3.15	Indicators, environmental category, air 102
3.16	Indicators, environmental category, waste 103
3.17	Indicators, economic category, income 107
3.18	Indicators, economic category, employment 108
3.19	Indicators, economic category, value 108
3.20	Indicators, economic category, mobility and connectivity 109
3.21	Correlation between demographic parameters and ranking results 123
4.1	Constants for chosen Landsat 8 imagery and correction values . 131
4.2	NDVI thresholds and assigned emissivity values 133
4.3	6th August 2013, Readings from Rhode Island weather stations 136
4.4	Comparison measurements and LST values at weather stations . 138
4.5	Evaluation of energy efficiency for water supply in RI 146
4.6	Water withdrawal and consumption for chosen generation technologies 149

Table	Page
4.7	Six biggest power plants in Rhode Island 151
4.8	Cooling system information for the three biggest power plants in RI 153
4.9	Header abbreviations and units for table 4.10 154
4.10	Three year averages for RISEC and Manchester Street facilities 154
4.11	Minimum, maximum, mean and standard deviation for statewide, urban & rural LST derived from Landsat imagery 158
4.12	Minimum, maximum, mean and standard deviation for by LULC category derived from Landsat imagery 159
4.13	Statewide evaluation of pollution sources and protection areas related to public water supply 168
A.1	Code descriptions for NAAQS from figure A.1 194
B.1	Coding of ranking categories and segments for summary tables . 195
B.2	Overall ranking score and total social score 196
B.3	Total environmental and total economic score 197
B.4	Social category, education and safety score 198
B.5	Social category, health and work life balance score 199
B.6	Social category, housing and participation & equal pay score . . 200
B.7	Environmental category, energy and transportation score 201
B.8	Environmental category, water and land use score 202
B.9	Environmental category, air and waste score 203
B.10	Economic category, income and employment score 204
B.11	Economic category, value and mobility and connectivity score . 205
C.1	Self supply for municipalities in Islands Region 207
C.2	Self supply for municipalities in Northern Region 208

Table	Page
C.3	Self supply for municipalities in Southern Region 209
C.4	Self supply for municipalities in Aquidneck Region 209
D.1	Residential household energy demand for year the structure was built 211
D.2	Residential household energy demand for annual income 212
D.3	Residential household energy demand for tenure 212
D.4	Residential household energy demand for household size 212
D.5	Residential household energy demand for unit type 212

LIST OF ACRONYMS

ACS American Community Survey

AQI Air Quality Index

ASCE American Society of Civil Engineers

COD Coefficient of Determination

DEM Department of Environmental Management

EIA Energy Information Administration

EPA Environmental Protection Agency

FARS Fatality Analysis Reporting System

FBI Federal Bureau of Investigation

GDP Gross Domestic Product

ISO International Organization for Standardization

ISO-NE Independent Systems Operator New England

LEED Leadership in Energy and Environmental Design

LST Land Surface Temperature

LULC Land Use Land Cover

NAAQS National Ambient Air Quality Standards

NDVI Normalized Difference Vegetation Index

NOAA National Oceanic and Atmospheric Administration

PWSB Providence Water Supply Board

RECS Residential Energy Consumption Survey

RIDOH Rhode Island Department of Health

RIDOT Rhode Island Department of Transportation

RIGIS Rhode Island Geographic Information System

RIPTA Rhode Island Public Transit Authority

RIRRC Rhode Island Resource Recovery Corporation

RISEC Rhode Island State Energy Center

RISPP Rhode Island Statewide Planning Program

RIWRB Rhode Island Water Resources Board

SDG Sustainable Development Goals

TIRS Thermal Infrared Sensor

TRI Toxic Release Inventory

UCR Uniform Crime Reporting

UCS United States Census

UHI Urban Heat Island

UN United Nations

USCB United States Census Bureau

USGS United States Geological Survey

USGBC United States Green Building Council

UWE Urban-Water-Energy

WEF Water-Energy-Food

LIST OF UNITS

W	watt
kW	kilowatt
MW	megawatt
GW	gigawatt
kWh	kilowatt-hour
MWh	megawatt-hour
GWh	gigawatt-hour
TWh	terrawatt-hour
BTU	British Thermal Unit
m	meter
km	kilometer
mi	US mile
ft	foot
s	second
min	minute
h	hour
a	year
mi^2	square mile
$\frac{m}{s}$	meter per second
$\frac{km}{h}$	kilometer per hour
$\frac{mi}{h}$	miles per hour
$\$$	US-Dollar
$cents$	US-Dollar cents
dB	Decibel
t	ton
kg	kilogram
g	gram
lb	US-pound

CHAPTER 1

Introduction

In this introductory statement the general objective of the study along with associated research goals and challenges will be discussed. Additionally, the hypotheses, which will be scrutinized later in the paper, are explained.

1.1 Justification for the Study

Overall, this thesis aims to evaluate the communities of Rhode Island regarding their sustainability and assessing connections between energy and water procurement according to the corresponding urban environment. Therefore, the concept of sustainability and the importance of its ongoing progression will first be highlighted in section 1.1.1, where quantification approaches of this highly ambiguous term will be discussed as well. Next, nexus thinking, which generally describes joint management of interdependent resources, will be discussed in section 1.1.2, while particular challenges related to urban areas will be discussed in section 1.1.3. Furthermore, major upcoming challenges of the 21st century, such as urbanization, globalization and climate change, will be outlined in section 1.1.4. Lastly, sections 1.2 to 1.4 state the thesis objective, the hypotheses and the organization of the thesis.

1.1.1 Measuring Sustainability

Ongoing urbanization and climate change are among the key concerns of modern day politics as various scenarios predict a diversity of detrimental effects if these two trends are allowed to remain on their current trajectory. Furthermore, virtually all areas of everyday life such as health, well-being, the natural environment and secure access to food and water may be affected. As those concerns have already persisted for several decades, the concept of sustainability is often featured

as a measure to potentially limit long term detrimental consequences. While its underlying principles have already been thought up centuries ago, political action and public interest have only very recently shifted in its favor with the oil crisis of 1973 being considered a starting point for environmental legislations in many different countries across the globe. [1] [2] A prominent example for the United States of America is the Energy Policy and Conservation Act from 1975, which was established to allow regulation of fuel prices to promote energy conservation. [3] According to this development, the most commonly used definition of sustainability, which is described as the ability to provide for one's needs without compromising future generations to do so, has been defined during the 1987 United Nations (UN) sessions on establishing a global agenda for change. Additionally, according to Portney even this early iteration of modern conferences on joint environmental agendas highlighted the importance of urban sustainability as is evident by the following statement: "cities [in industrialized countries] account for a high share of the worlds resource use, energy consumption and environmental pollution". [4] [5]

While the aforementioned rather ambiguous definition of sustainability allows inclusion of wide ranging issues and sectors, it is abstract in its nature, thus hindering direct applicability and understanding. As a result, creating both palpable and legitimate goals, measures and concepts is paramount for enabling sustainable development and thus advancing the concept overall. [6] In general, sustainability measures shall aim to equally include all relevant sectors, which are nowadays commonly referred to in the modern sustainability paradigm, which is displayed in figure 1.1 as the three pillars or areas of environment, social and economic. This representation emphasizes that sustainability can only be achieved if environmental protection, social equity and economic benefit are considered alike and provides a more tangible approach than the previously discussed definition. [7]

Adapted from (Theis & Tomkin 2012)

Figure 1.1. Sustainability paradigm (Adapted from Theis & Tomkin 2012 [7])

Several methods and efforts to associate this ambiguous term with clear cut figures and tangible measurements have been derived in order to allow directly set targets as well as straight-up monitoring. Conventional approaches range from footprint representations, several modeling systems regarding ratings or indicators to life cycle assessments in order to quantify sustainability. [7] However, urban environments generally present a network of intricate interactions with concealed dependencies and it has been determined that carbon footprints are unsuitable for adequately capturing those complex processes. [8]

In general, no well-founded decisions on future actions can be taken without extensive knowledge of the current situation, which is especially relevant for highly complex issues such as measuring sustainability. In the case of urban areas, the best practice for deriving and using appropriate indicators has been identified to constitute a holistic reporting tool to inform all involved parties such as local government, residents, businesses and other organizations in order to lay a path to achieving urban sustainability. Ideally, the overall endeavor should feature pertinent scoping, a critical review of the chosen indicators and finalization thereof, defining of goals, analysis of results and presentation to the targeted audience followed

up by periodic reassessments. This approach is deemed to give vital information for communities in order to plan for sustainability and to work out constructive policies. [9] [10] Furthermore, planning is the most significant tool for sustainable development at the local level and may be seen as a political process with active public participation, which is said to benefit greatly from palpable goals such as clean air and water. As a result, further incentive is given to formulate sustainability as tangible and quantifiable measures. [11]

As of 2012, there are more than 100 sustainability rating systems, of which the majority focuses on assessments of buildings and only a minority share features neighborhood or infrastructure projects. [12] Therefore, the following paragraphs are going to highlight a few selected rating schemes in order to report about the approaches and featured indicators.

Figure 1.2. Introduction to LEED with rating systems and credit categories (Adapted from Dawn 2014 [13])

One of the most critically acclaimed methodologies is the Leadership in Energy and Environmental Design (LEED) certification, which has been developed in 1993

and is managed by the United States Green Building Council (USGBC). It is the most commonly used rating scheme in the USA and features a checklist evaluation with the results being categorized in different point-based thresholds, of which platinum is the highest attainable level. [12] Figure 1.2 summarizes a majority of the relevant aspects for the LEED program. In general, its different products focus on individual areas such as building and interior design, operation and maintenance, neighborhood development and homes, offering a variety of suitable schemes ranging from new residential buildings to redevelopment of entire city blocks. Additionally, the most significant credit categories, which further consist of individual indicators, cover a variety of topics that can hardly be matched to the aforementioned pillars of sustainability but seem to mostly revolve around environmental issues. Additionally, in most cases the maximum attainable score is 110 points which is then further rated in the four categories of certified, silver, gold and platinum. [13]

Furthermore, neighborhood development is the most suitable area of concern to evaluate communities from the already well established rating schemes, thus it will be discussed in more detail. For that purpose, figure 1.3 lists the credit categories and associated indicators for that specific rating system. It features the five credit categories of smart location and linkage, neighborhood pattern and design, green infrastructure and buildings, innovation design process and regional priority. While the latter category is clearly the least extensive one as it only awards four points in total, neighborhood pattern and design is the most significant one with 44 points in total. In general, the featured indicators are very explicitly devised and thus require extensive effort and attention to detail. However, both social, for instance access to public spaces or recreation facilities, and environmental aspects, such as building water and energy efficiency, are included. Nevertheless, economic considerations are apparently not accounted for in this rating scheme. [14]

The level of detail in the previously discussed LEED product is excessive and may often be too much to work out for rather small communities. Accordingly, the latest LEED project is targeted at evaluating entire cities, which is still in its pilot phase as of June 2017, features fewer and overall less intricate measures as displayed in figure 1.4. This approach is differentiated into nine individual categories that are seemingly much more oriented to match the three areas of environmental, social and economic. In addition, participating cities have to report progress of the featured indicators in an on-line interface, which is open to the public and thus greatly enhances the monitoring and information aspect in relation to sustainable development. [15]

For instance, prosperity focuses on economic aspects with unemployment rate and median household income as individual indicators. Additionally, the three other categories of education, equitability and health and safety are designed to

CATEGORY	METRIC	UNIT
Energy	1. Greenhouse Gas Emissions (CO ₂ equivalent)	Tons/Year/Person
Water	2. Domestic Water Consumption	Amount/Year/Person
Waste	3. Municipal Solid Waste Generated	Amount/Year/Person
	4. Municipal Solid Waste Diverted from Landfill	% of Total Amount Collected
Transportation	5. Distance Traveled in Individual Vehicles Daily	Distance per Day
Human Experience		
Education	6. Population with (at least) a High School Degree	% of Population 25 Years And Over
	7. Population with (at least) a Bachelor's Degree	% of Population 25 Years And Over
Equitability	8. Median Gross Rent as % of Household Income	%
	9. Gini coefficient	Number between zero (0) and one (1)
Prosperity	10. Median Household Income	US Dollars per Year
	11. Unemployment rate	% of Population 16 Years And Over
Health & Safety	12. Median Air Quality Index (AQI)	Number between zero (0) and 500
	13. Air Quality Days Unhealthy for Sensitive Groups	Number of Days between (0) and 365
	14. Violent Crime	Per capita per Year

Adapted from (USGBC 2017)

Figure 1.4. LEED criteria on assessing cities (Adapted from USGBC 2017 [15])

address social issues such as violent crime per capita and year or the share of people with at least a high school degree. Lastly, the remaining areas of energy, water, waste and transportation cover environmental concerns, thus all overarching themes of sustainability are accounted for in this approach.

However, putting these numbers into perspective and interpreting them remains challenging and hinders the comparison of cities against one another. A possible approach to provide concise evaluations is to rank communities amongst a chosen sample size, which has been determined to be a sound procedure to evaluate the current status of development and quality of life. While the extreme values serve as references for the minimum or maximum score allocation, the remaining values are distributed according to their placement within that range. [16] This has been done for instance in the US and Canada Green City Index in 2011, where the featured communities were ranked in accordance with the worst and best performances across nine different categories and 31 individual metrics overall. By featuring

topics such as CO_2 , energy, land use, buildings, transport, waste, water, air and environmental governance, this report, which has determined San Francisco to be the most environmentally sound city across the USA and Canada, primarily focuses on environmental aspects and lacks inclusion of social or economic measures. On the other hand, the inclusion of political aspects by assessing green action plans or management and the level of public participation in the different cities allows to compare the respective political efforts for promoting sustainability, which adds a novel and highly significant aspect to the findings. However, the report focuses on rather big cities as Orlando is the smallest featured community with roughly 240,000 inhabitants. [17] The Sustainable Cities Index 2016 takes a similar approach and compares 100 cities from around the world to one another by determining the best and worst performances for the three categories of people, planet and profit, which are composed of 32 individual indicators in total. Additionally, these metrics are grouped in sub-categories to allow comparison based on different areas of interest such as education, health and affordability, with the latter constituting the indicators of consumer price index and property prices. While this report is seemingly designed to match the areas of sustainability more closely, it is targeted at major population centers of the world, thus severely limiting its transferability to small or rural communities. [18]

Additionally, figure 1.5 gives an overview of the indicators established by the International Organization for Standardization (ISO) standard 37120:2014 Sustainable development of communities to provide a common procedure to evaluate communities and their respective progression related to sustainability. In general, ISO intends to ease international cooperation and trade by establishing commonly applicable methodologies and procedures in relation to specific fields. For instance, the standard 37120:2014 was published in 2014 and features 100 indicators in total,

which are divided into 17 overarching categories. The most prominently featured category is solid waste with 10 indicators, while recreation constitutes only two indicators. Furthermore, the standard puts a heavy emphasis on normalization, for instance via ratios and per capita measures, in order to enable comparisons of differently sized communities. However, it is still targeted at rather large cities as the applied procedure commonly features a normalization to 100,000 people. [19]

Figure 1.5. Number of indicators per category for ISO standard 37120:2014 (Author's own figure, data from ISO 2014 [19])

While the aforementioned principle guidelines of using sustainability indicators in urban areas have been proposed as early as 1996, there are currently no predominant derivation procedures. As a result, already deployed frameworks are usually worked out for specific regions or target certain goals, which hinders possible transfer to other areas. Additionally, existing reports on comparing cities in regards of sustainability have featured population rich metropolitan areas for the most part so far and even the discussed ISO standard uses a normalization to 100,000 inhabitants for all its indicators. As a result, smaller settlements and areas

of lesser popularity may be neglected and not appropriately monitored. However, evaluating the sustainability of these communities is an important issue, as the population distribution per size of incorporated place in the USA, which is displayed in figure 1.6, features more people living in settlements below 100,000 inhabitants than in even more populous areas. Consequently, there is a high potential need for research regarding sustainable development for these relatively small communities even though they have rarely been the focus in appropriate studies so far.

Figure 1.6. Distribution of US population by size of incorporated place (Author's own figure, data from USCB 2015 [20])

Additionally, table 1.1 lists the development regarding the share of people in the USA living in incorporated places above or below 100,000 inhabitants. Even though the ratio of people living in places below 100,000 residents has slightly diminished since 2010, this category still accounts for significantly more inhabitants. This indicates that more people are affected by measures regarding this category, thus highlighting the importance of research and development of appropriate frameworks for the assessment of sustainability. On the other hand, availability of data and spread out settlement distribution may hinder research efforts in this area.

Table 1.1. Share of total U.S. population in incorporated places below or above 100,000 inhabitants (Data from USCB 2015 [20])

Size of Incorporated Place	2000	2010	2013
Overall	61.8%	62.3%	62.8%
Above 100,000	26.8%	27.2%	28.2%
Below 100,000	35.0%	35.1%	34.6%

In conclusion, being able to properly quantify sustainability is crucial step in making this rather ambiguous term more tangible and thus advancing its integration and development. In general, measuring approaches may include rather conventional foot-printing, development of goals and rating systems with incorporated indicators. The latter has been done on numerous occasions and is primarily aimed for application at comparably large cities. However, when focusing on the USA, whose populace is already highly urbanized, the majority of people actually live in incorporated places with less than 100,000 inhabitants. As a result, it can be deduced that researching the suitability of sustainability rating approaches or derivation and application thereof to comparably smaller settlements may yield benefits that potentially affect a majority of the U.S. population.

1.1.2 Nexus Applications

As the secure provision of water, energy and food for all of the world's population has been determined to be a paramount issue, sustainable and resilient supply management frameworks are evermore increasing in importance. One rather recently developed approach to achieve overall increased efficiency of these three vital resources is the Water-Energy-Food (WEF)-Nexus, which was initially discussed during the 2011 Bonn Nexus conference. [21] It aims to promote jointly coordinated measures and policies as well as accounting for interdependencies and relationships between different supply sectors in order to achieve an overall improved use of

resources. For instance, growing food crops requires water for irrigation and the conveyance thereof has an inherent energy demand. Furthermore, electric power generation often takes place in thermoelectric plants, which need water for cooling. Additionally, that may lead to less water availability in the respective area and in turn shortages of water for irrigation and a limited supply of food.

Nexus thinking can be narrowed down to highlight the relationships between individual areas of which the dependencies between water and energy have most often been discussed as of 2015. [22] The connection of these two indispensable resources can be expressed directly, as water is required to provide electricity and energy is required to treat and transfer water, or embodied in other goods and services. For instance, thermoelectric power generation requires 80 liters of water withdrawal and two liters of consumption per provided kilowatt-hour of electricity in average in the United States. On the other hand, water treatment is rather energy intensive as provision of 60 million liters from surface water sources takes up to 60 kilowatt-hours of energy, which does not include distribution and varies with water source and required treatment. [23]

Pressures on sustaining a high quality of life and providing adequate resources are amplified through densely populated environments, thus creating complex supply challenges. [24] Researching and identifying the interactions and implied consequences of individual measures on the overall supply network allows decision-makers to determine the most beneficial course of action. The application of this approach to metropolitan areas is referred to as the urban nexus and its implementation into decision making may improve cross sectoral thinking and in turn help to advance sustainable urban design. [25] Furthermore, integrating and researching interactions of water and energy provision within an urban context is referred to as the Urban-Water-Energy (UWE)-Nexus. [26] Its importance is

highlighted by the fact that water and wastewater utility operators are often the largest energy consumers in American municipalities and may be responsible for up to 40% of a city's total demand. [27]

In addition, water and energy exhibit not directly evident connections in urban environments. For instance, runoff from impervious surfaces, which is the predominant land cover type in cities, contains a higher concentration of pollutants and thus has a lower water quality, which may result in an increased energy demand due to more extensive requirements for water treatment. [28] Another example is the heightened energy demand for cooling due to increased temperatures in downtown areas in comparison to the respective rural surroundings, which is referred to as the Urban Heat Island (UHI) effect. [29] [30] Furthermore, this entails an increased water demand hidden in the required amount for electricity generation. Additionally, higher temperatures lead to accelerated evapotranspiration and, in turn, more water usage for irrigation, whose procurement and conveyance also has an embodied energy demand. [31] Understanding and accounting for those highly intertwined and somewhat concealed relationships will help to improve the overall sustainability of cities.

However, as metropolitan areas may be greatly different from one another, examinations of water and energy provision systems have to be embedded in local conditions and adopt a holistic approach in order to achieve optimal performance. [32] This is emphasized by the substantial range of energy related to water supply systems in different cities, with 10 kilowatt-hours per capita and year for Melbourne, Australia and 372 kilowatt-hours per capita and year for San Diego, USA. [33] As a result, it is recommended that solutions have to be sought out to fit to each individual city, rather than establishing a universally applicable scheme. [34]

1.1.3 Pressures posed by Urban Environments

As mentioned previously, cities have relatively early been identified as major consumers of global resources. Accordingly, the term urban metabolism, which aims to holistically evaluate all the in and out coming resource flows of a city, has been described as early as 1965. [35] Quantification and research thereof requires and advanced understanding of the underlying processes, which has since been determined to be crucial for increasing resource efficiency and for limiting the negative consequences due to high consumption patterns. [36] [37] Not only are cities major focal points for resource allocation with extensively outreaching supply systems, their respective ambient conditions differ greatly in comparison to the surrounding area. Furthermore, cities significantly affect their neighboring areas as they require resources, attract traffic, discharge waste products and emit far spreading pollutants. As a result, they simultaneously heavily depend on and pose pressures on their respective hinterlands. [38]

Accordingly, they significantly influence ambient conditions and quality of life for both the people within their boundaries and beyond. For instance, during the 19th century, in the first modern urban centers in North America, such as New York, inhabitants experienced living conditions that were remarkably inferior in comparison to nowadays predominant situations in the USA. This was largely caused by poor provision of vital services such as access to safe drinking water, which resulted in the widespread occurrence of waterborne diseases such as cholera or typhoid fever, and extremely limited living quarters. However, reforms regarding sanitation, housing and urban open space induced widespread improvements and resulted in the advancement of living conditions in American metropolitan areas. [39] In fact, nowadays cities are considered to be centers for prosperity as they provide numerous benefits to their residents and visitors ranging from an abundance

of available products, public goods and services to enabling the pursuit of personal ambitions and aspirations. [40] However, this development hardly applies to excessively growing mega cities, which are predominantly located in developing countries. In such areas a high portion of the population lacks reliable access to basic services and have to face vastly unfavorable environmental conditions. This observation is especially applicable to rapidly evolving cities in Asia, where half of the world's most polluted cities are located, with Mumbai experiencing the worst air quality worldwide. [41]

Next to sheltering a majority of the worlds inhabitants and providing the basic framework for their ambient conditions and thus shaping their quality of life, cities generate about 80% of the global gross domestic product and are responsible for 70% of worldwide greenhouse gas emissions. As a result they are strongly connected to a majority of global activity and pollution. [42] [43] These figures highlight the ongoing importance of sustainable development in cities as their measures and policies affect a high number of people embedded in a supply system that extensively exceeds the respective municipal confinements.

1.1.4 Future Trends and Developments

Research towards increasing sustainability of urban areas is highly important as ongoing global urbanization keeps enhancing pressures posed on resources and the natural environment. Accordingly, proper management of urban growth has been described as a major challenge for the 21st century. [44] Given this challenge, global sustainability has been determined to be closely linked to urban sustainability, as cities may potentially affect a majority of the global population and define the quality of life for their respective citizens. [45] Additionally, both climate change and globalization further frame the upcoming challenges of the 21st century.

As of 2014, 54% of all people were already living in urban areas, whereas in

1950 this was applicable to only 30% of the worlds population. Furthermore, this trend is projected to continue, leading to an increase in urbanized residency to 66% by 2050. While this ratio varies significantly by region, North America is one of the most highly urbanized regions as 82% of its citizens currently reside in metropolitan areas. [46] Furthermore, as figure 1.7 shows the USA has seen a rapid change in its settlement distribution. While, almost 95% of its citizens lived in rural areas in 1800, this status has almost reversed with over 80% of its current population currently residing in urban areas.

Figure 1.7. Development of US population and share in urban or rural areas from 1800 to 2010 (Author's own figure, data from USCB 2012 [47])

Not only is the world population projected to become increasingly more urbanized, there will also be a higher number of extreme population agglomerations or mega-cities. While there were only two mega-cities, which refers to cities with 10 million or more inhabitants, worldwide in the 1970's, this number has risen to 23 globally in 2013. Furthermore, this development is thought to continue, leading to the projected emergence of 14 additional mega-cities by 2025, which are estimated to house 13.6% of the global population. [48] [49] These extreme agglomerations of urbanized living people pose additional concerns, as the population numbers

often grow rapidly, for instance the city of Dhaka, Bangladesh increases by 400,000 additional people each year, and the associated service infrastructure is often unable to keep up. This in turn leads to manifold problems such as air pollution, congestion of traffic ways and even spreading of epidemic diseases, resulting in a diminishing quality of life. [41] For instance, many of the poorest slum dwellers of Dhaka are highly vulnerable to waterborne and diarrheal diseases such as cholera, dysentery and rotavirus due to a lack of adequately sanitized water and flooding during the precipitation heavy monsoon season and the corresponding spread of pathogens to water bodies. Furthermore, changing weather patterns due to climate change hinder the predictability of said events, highlighting the importance of jointly planned efforts in order to improve resilience. [50]

Climate change, which describes significant long term deviations from recorded weather averages such as temperature or precipitation, will be a major challenge of the upcoming century. Furthermore, the recent and extreme shifts, which especially applies to temperature increases since the beginning of the 20th century, are largely attributed to anthropogenic activities, for instance, the exceedingly high releases of greenhouse gases like carbon-dioxide. [51] [52] Next to rising temperatures, which may exceed 5 °C on average till 2100 under a high emissions pathway according to figure 1.8, the occurrence of extreme weather events and significant shifts in regional climate may change as well. This will culminate in substantial impacts ranging from flooding, sea level rise, altered crop yields and increased water stress amongst many others. Additionally, risks associated with climate change generally increase with the temperature, as for instance a 2 °C average increase is thought to put unique ecosystems such as coral reefs and arctic species under very high threat, while an increase of about 0.5 °C will keep the risks at a medium level. [53]

When focusing on North America, wildfires, loss of property and ecosystems,

Figure 1.8. Projected development of global mean temperature till 2100 and assessment of associated risks (Adapted from Field et al. 2014 [53])

increased human mortality and morbidity due to heat, urban flooding, infrastructure damage and water quality impairment have been identified as the most relevant risks related to climate change. However, most of these factors will only reach high risk levels beginning in 2080 and all have the potential to be reduced to or even below medium risk by adequate adaptation measures. [53]

As mentioned previously, the USA is a highly urbanized country, attributing additional importance to climate change impacts on cities. In general, reliability of service provision and economic stability will be challenged by a changing climate, which is especially true in areas of low elevation in coastal zones, where about 13% of the global urbanized population currently resides. Furthermore, as cities differ greatly in their structure and composition, there can be no universally applicable adaptation strategy and local conditions and potential impacts have to be taken into account for each individual case. However, it has been determined that decision makers should utilize long term urban planning in a timely manner in order to prevent detrimental consequences on the various sectors and demographic groups. [54] Additionally, while mortality in urban areas generally increases with rising

level intense heat during the summer months, certain groups such as elderly people or children may be especially affected. [55] In conclusion, adaptation of urban areas to climate change has to be worked out individually in accordance with the local conditions and should start rather sooner than later. This undertaking is profoundly important, as cities house a high number of people that are reliant on the associated supply infrastructure and may be especially vulnerable to the failure thereof or otherwise dramatically altered conditions.

Globalization describes the increasing level of connection between people from different nations or cultures and is largely driven by international trade or investments and improving information or transportation technology. Although, this process may have far reaching impacts on the environment, economic development, prosperity and standard of living, it is generally thought to globally enhance quality of life. [56] [57] While this development poses an opportunity to raise the living standards for many people around the world, it also entails an increased demand for resources, thus putting further pressures on the associated supply systems. Consequently, the arising discrepancies between globally beneficial progression and environmental protection needs to be carefully evaluated and met by proper management and longterm planning. Furthermore, even though globalization is primarily reported on a national or even broader scale, local decisions can have a tangible impact, and proper determination of the consequences has been deemed crucial to enhance decision-making. [58]

On a global scale, sustainable development is still hindered by challenges affecting all social, environmental and economic aspects. For instance, as of 2013, more than 1 billion people are still living in severe poverty and rising income inequality and unfavorable consumption or production patterns have been identified as major issues. [59] Overall, the three phenomena of globalization, urbanization

and climate change are set to define development during the 21st century, which highlights their inclusion in planning efforts related to sustainable development.

1.2 Thesis Objective

In conclusions to the aforementioned, detailed statements, due to ongoing urbanization, an ever-increasing number of people are going to be affected by the environmental conditions cities have to offer, while also being responsible for a majority of global resources. This renders research of increasing the overall sustainability of urban areas highly important. However, greatly varying local conditions, intricate network interactions, far reaching consequences and uncertainty about future climatic trends are challenges which have to be faced by upcoming sustainable development approaches.

This study will provide a detailed case study for understanding the inherent environmental connections between water and energy provision by examining the current system in Rhode Island. Additionally, a sustainability rating scheme on a municipal level will be worked out in order to determine potentials for further sustainable development. This will involve establishing the current sustainability status of Rhode Island communities by collecting data and creating indicators to rank them according to one another. Furthermore, possible wide ranging benefits, through a joint evaluation of water and energy provision in urbanized areas, will be examined by exploring spatially relevant implications. The study will conclude with evaluating the sustainable development potentials in Rhode Island by identifying major areas for improvement.

1.3 Hypotheses

This paper will evaluate the following two hypotheses, which will be elaborated in chapters 3 and 4, respectively, and reviewed in chapter 5 subsequently to all

necessary assessments.

The primary hypothesis of this study is that a monitoring approach, involving social, environmental and economic indicators, will be useful to assess the sustainability of Rhode Island’s communities. It is believed that this rating of individual municipalities against one another will provide possible knowledge gains in fostering sustainable development in the state.

As mentioned previously, nexus thinking aims at creating more efficient resource management by accounting for the interactions between individual sectors. Accordingly, the secondary hypothesis of this study is that such an approach for the water and energy provisions, with distinct focus on the urbanized areas of Rhode Island, will allow for the identification of sectors and areas where more efficient practices and resource management can be ensued.

1.4 Thesis Structure

Overall, this thesis has two main research objectives, which are as follows:

- Compilation of a comprehensive municipality ranking
- Examination of potentials regarding UWE-Nexus approaches

To begin with, chapter 2 will provide a comprehensive overview to the state of Rhode Island and the relevant sectors such as energy, water, waste, transportation, land use and economy. Subsequently, chapter 3 features the sustainability ranking and explains the applied methodology, featured indicators, results, evaluation and significant findings in detail. Next up, chapter 4 discusses the Urban-Water-Energy-Nexus considerations and states the methods, results and major findings. Lastly, chapter 5 brings both focus areas together and jointly summarizes the results along with a discussion thereof and the overall conclusion of the thesis.

CHAPTER 2

Analysis of Relevant Sectors in Rhode Island

This chapter will feature a general introduction to the relevant sectors of Rhode Island in order to provide a comprehensive basis for both the sustainability ranking in chapter 3 and the Urban-Water-Energy-Nexus examinations in chapter 4. Accordingly, administrative boundaries, relevant state laws and regulations, major state offices, municipalities, urbanized areas, utility provision and other important sectors will be discussed. Additionally, climate change projections for Rhode Island will be discussed to allow for a proper, contextual assessment of major future upcoming challenges.

2.1 Overview

As of 2010, Rhode Island houses about 1.05 million inhabitants, which renders it the 43rd most populous state while being the smallest in regards to total area with 1,545 mi^2 and a land area of about 1,033 mi^2 . As a result, it is the second most densely populated state, next to New Jersey with roughly 1,000 people per square mile. Subsequently, limited space with a dense distribution of its citizens form unique challenges for the entire state. [60] [47]

It is located in the north eastern part of the United States and belongs to the region of New England. Accordingly, its area was a part of the original territory of the USA and was officially recognized as a colony in 1663 when it was granted its own charter as the Colony of Rhode Island and Providence Plantations. Thereafter, it was the 13th of the founding states to acknowledge the constitution of the United States of America and its boundaries have remained largely unchanged since joining the union in 1790. [60] The state is commonly referred to as Rhode Island shortly after its discovery by Dutch explorers due to linings of red clay along the shore.

Its official name is The State of Rhode Island and Providence Plantations and its nickname is The Ocean State as a reference to the vast shoreline along the Narragansett Bay. [61]

In regards to topology the state can be split into a rather hilly western segment and the eastern coastal lowlands. The western two thirds belong to the New England Upland, which reaches elevations of 240 meters above sea level. In comparison, the eastern third is much lower and ranges from about 60 meter above sea level to the flat beaches and plains merging with the sea. Jerimoth Hill is the highest point in the state with an elevation of 247 meters. In general, the landscape was heavily shaped by glacial movements and deposits. Furthermore, about 17,000 years ago glacial influences formed significant parts of Rhode Island's landscape such as Narragansett Bay and the approximately 30 individual islands within it, as well as Block Island, which is located ten miles south of the shore. Additionally, the most noteworthy waterways of the state are the Blackstone, Pawcatuck and Pawtuxet Rivers with the latter having been redirected in order to form the Scituate Reservoir in the 1920's, which has remained a major asset for Rhode Island's drinking water supply till today. [62] [63]

Rhode Island is divided into five counties, which according to section 2.4 are nowadays mere geographic boundaries, and encompasses 39 municipalities, of which eight are cities and 31 are considered towns. Furthermore, there are four urban areas, which will be discussed in more detail in section 2.6, with the metropolitan agglomeration around Providence clearly being the most significant one. All of the aforementioned geographical features, except the allocation to counties, can be seen in figure 2.1. Additionally, it also displays the population distribution, which is clearly centered around Providence or largely along the Narragansett Bay.

Figure 2.1. Rhode Island municipalities, urbanized areas and population distribution (Author's own figure, data from RIGIS 2017 [64])

The extent and location of Bristol, Kent, Newport, Providence and Washington County, the associated municipalities and the 2015 population data can be displayed in figure 2.2. Providence County covers roughly the Northern third of the state and encompasses about 630,000 inhabitants or 57% of the state's population. On the other hand, Bristol County is the smallest one and houses only about 50,000 citizens and encompasses just three municipalities.

Figure 2.2. Rhode Island counties with population figures for 2015 (Author's own figure, data from RIGIS 2017 [64] USCB 2017 [65])

As mentioned previously, counties mainly work as geographic reference in Rhode Island and municipalities function as local government instead. However,

counties remain significant at times, as federal agencies and census reports still commonly refer to them in their publications.

2.2 Climate

Rhode Island’s climate is best described as humid continental and as such has a rather high annual temperature of 50 °F and an average yearly precipitation of 46 inches. There may be extreme weather events such as hurricanes, blizzards, heavy snowfall and periods of uncharacteristic seasonal behavior, but the precipitation pattern is generally well distributed over the course of the year and snowfall is a commonly occurring phenomenon. Furthermore, there are clearly distinguishable differences between coastal and inland locations with the overall main wind direction originating from the west. [62] [66]

Figure 2.3. Monthly climate normals 1981 to 2010 NOAA Providence station temperature and precipitation (Author’s own figure, data from NOAA 2017 [67])

Figure 2.3 shows the minimum, average and maximum temperature for the NOAA Providence station, which is located close to TF Green Airport, retrieved from the monthly normals from 1981 to 2010. In general, climate normals are derived over a long period of time and are used to illustrate average characteristics

for a chosen reference location and to put exceptional values into perspective. [68] [69] [70] Furthermore, their monthly representation allows for determine of long term seasonality. Accordingly, January is in average the coldest month in Rhode Island with 29.2 °F, while July is the hottest with 73.5 °F. The same distribution applies to the daily minimum and maximum values, which results in a total difference of 56.3 °F between the coldest days in January and the hottest days in July. Furthermore, there are about 107 days above 32 °F, resulting in about three months continuously above freezing temperatures. Overall, the annual mean temperature for this location is 51.6 °F.

On the other hand, the precipitation pattern shows a significantly more stable spread around 4 inches per month over the entire year. February and July are equally low with 3.29 inches, while March is the precipitation richest month with 5.01 inches. Over the considered period of time the annual average precipitation was 47.1 inches with almost 72% of it falling as snow. About 1.7 days with more than 5.0 inches of snow were observed, indicating a probability of almost two intense snowfall events per year.

Figure 2.4. Comparison of climate normals 1981 to 2010 heating and cooling degree days (Author's own figure, data from NOAA 2017 [67] Petri & Caldeira 2015 [71])

Additionally, heating and cooling degree days are included within the NOAA climate normals and are commonly used as a basic comparison of different locations regarding housing equipment and the associated energy demand to one another. Accordingly, they describe the amount of time and required effort in order to sustain a set comfortable temperature for indoor environments and are acquired by multiplying the respective timespan by the difference of the outdoor temperature to the reference threshold, which is usually set at 65 °F for the USA. [72] Figure 2.4 shows the degree days for the 1981 to 2010 climate normals for Providence and a selection of other cities. In comparison, the climate of Providence poses similar heating and cooling demands as the nearby city of Boston and a slightly higher heating and lower cooling demand as New York. This methodology allows a concise assessment of different locations and shows significantly varying characteristics to southern cities such as Houston or Phoenix, where adequate provision of cooling is much more important.

Figure 2.5. Monthly temperature and precipitation Providence and North Foster from 2010 to 2015 (Author’s own figure, data from NOAA 2017 [67])

As evident from figure 2.5, which compares the global sums per month from the NOAA stations of Providence and the rurally located town of Foster from 2010 to 2015, local climate can differ on a regional scale even in such a small state as Rhode Island. As expected, the two stations show a quite similar trend, but Foster seems to experience overall lower temperatures while receiving a slightly higher amount of precipitation.

This observation is further backed up by the annual values in table 2.1, as Foster’s annual average temperature is always lower and the yearly precipitation sums are always higher than the respective values of Providence. Furthermore, the temperature for the examined 5 year period is 2.8 °F higher and there were in average 4.8 inches more of total precipitation in Foster than in Providence. However, as the two stations are only about 20 miles apart from each other, they show similar temporal trends and development as evident from figure 2.5.

Table 2.1. Annual average temperatures and precipitation sums Providence and Foster 2010 to 2015 (Data from NOAA 2017 [67])

Year	Providence Mean Tempera- ture in °F	Foster Mean Tempera- ture in °F	Providence Annual Precipi- tation in inch	Foster Annual Precipi- tation in inch
2010	53.7	50.0	53.6	64.8
2011	52.6	50.3	56.8	66.4
2012	53.8	51.7	41.2	43.7
2013	51.9	49.3	45.5	47.9
2014	51.0	48.0	47.0	48.0
2015	51.8	48.9	40.9	42.8
Mean	52.5	49.7	47.5	52.3

Overall, Rhode Island experiences a humid continental climate with temperatures ranging from about 29.2 °F in January to 73.5 °F in July. As a result, heating is the predominant issue with 5,681 degree days, while cooling amounts to only

744 degree days. Furthermore, precipitation is well distributed around the year with annually in average 47.1 inches.

2.3 Climate Change Projections

The particular challenges, projections and vulnerabilities of Rhode Island regarding climate change will be discussed in the following section. Global projections and trends, which include, for instance, changing weather patterns, rising sea levels and temperatures have been discussed in section 1.1.4.

Overall, climate change is a significant challenge for Rhode Island and an average increase of 3 °F, which is projected to accelerate even faster under a high emissions pathway, has been observed over the course of the 20th century. Accordingly, the intensity of heat waves is projected to increase while cold weather periods are decreasing. Furthermore, precipitation has increased as well as the occurrence of associated extreme events, which may lead to a higher frequency of flooding as this trend is projected to continue. Additionally, the town of Newport has experienced a sea level rise of 9 inches since 1930. This trend is above the global average and may culminate in an additional four feet by 2100. [73]

Rhode Island is judged to be particularly susceptible to sea level rise out of the aforementioned developments. This is evident just by the fact that it has the second highest ratio of shoreline, which includes offshore islands, bays and certain sections of streams and creeks, to total area of all states. Its shoreline of 384 miles is heavily shaped by the Narragansett Bay, which reaches about 30 miles inland till Providence as can be seen in figure 2.1. Furthermore, the states most significant urban area, and with it about 88% of its population, is centered around this coastal estuary, resulting in a close proximity of a majority of its citizens and infrastructural assets being located close to the shore.

Accordingly, Rhode Island is generally considered to be severely threatened by

Table 2.2. Total area, length of shoreline and ratio per state (Data from USCB 2012 [47] NOAA 2017 [74])

State	Total Area in mi^2	Shoreline in mi	Ratio	Feet of Shore- line per mi^2
Maryland	12,406	3,190	0.257	1,358
Rhode Island	1,545	384	0.249	1,312
New Jersey	8,723	1,792	0.205	1,085
Delaware	2,489	381	0.153	808
Louisanna	52,378	7,721	0.147	778

climate change and sea level rise in particular. For instance, the annual number of days with tidal flooding in Providence is believed to increase significantly for both the lower and higher emissions scenario as displayed in figure 2.6. Furthermore, the higher trajectory may lead to over 300 days per year with flooding in 2100, which affects a vast majority of the year. Additionally, the figure shows a rapid development after the year 2040 especially in comparison to the rather low numbers of previously observed events in the past century. [73]

Figure 2.6. Observed and projected annual tidal floods for Providence (Adapted from NOAA 2017 [73])

The most prominently discussed consequence of climate change certainly is increasing temperatures. Accordingly, figure 2.7 shows the observed development of

temperature change in Rhode Island and the corresponding trajectory for a low and a high emissions scenario. Naturally, the annually observed values vary drastically from year to year, but still show a distinct upwards trend since the beginning of the 20th century. Accordingly, the projections are displayed as a possible range of values and while the two scenarios overlap for the most part till 2050, they stray further apart from one another during the second half of the 21st century. Overall, the lower emissions scenario ranges from a temperature increase roughly between 2 °F and 8 °F. On the other hand, the higher emissions scenario may result in up to 14 °F higher temperatures and is projected to stay above 7 °F at best. [73] Additionally, Rhode Island has experienced a slightly higher increase of mean temperature, which has risen 1.7 °F from 1905 to 2006, than the North-Eastern regions of the USA in general. [75]

Figure 2.7. Observed and projected temperature change with low and high emission scenario till 2100 for Rhode Island (Adapted from NOAA 2017 [73])

Next to increases in temperature, climate change may potentially affect other meteorological parameters, such as precipitation or the occurrence of extreme events, as well. Accordingly, figure 2.8 displays the projected change in annual

precipitation till 2050 for the entire United States. While the western part of the country is threatened by decreases up to 20% per year, the middle region up to the north western areas are believed to experience an increased amount of precipitation. Furthermore, the entire area of Rhode Island is projected to have an increased mean precipitation in 2050 of 5 to 10% in comparison to current figures. This may enhance the availability of drinking water as the state's entire supply relies upon it, which will be discussed more detailed in section 2.8.2. Furthermore, increase of precipitation has been determined to be around 0.12 inches per year. [75] On the other hand, this increase also puts higher existing infrastructure at risk, as the current build-out of waste water piping may not be able to handle this challenge. [73] In addition, home septic systems, which are used in about 33% of all households in Rhode Island, may not function properly with increasing air temperatures and rising groundwater tables due to sea level rise. [76]

Figure 2.8. Expected change in precipitation till 2050 for the entire USA (Adapted from NOAA 2017 [73])

Furthermore, Rhode Island is significantly more vulnerable to climate change than other states of the USA. Its climate is expected to get warmer with more precipitation, changing seasonal behavior and a higher chance of extreme weather

events such as droughts or storms. On top of that, its ocean ecosystems are under threat by rising air and water temperatures, fisheries are faced with possibly declining livestock and coastal infrastructure may be damaged by erosion and riverine flooding. [77] Additionally, impacts of climate change are not limited to the coastal territory of the Ocean State and will likely affect all aspects of life in its communities. In conclusion, efforts to launch appropriate adaptation strategies and enhancing resilience to the abundant effects of climate change should start rather sooner than later. [78]

2.4 Administrative Boundaries

The state of Rhode Island is divided into five counties and incorporates 39 municipalities, of which 8 are categorized as cities and 31 as towns. [79] In general, counties, of which there are 3040 in the entire USA, are the most common form of local administrative entity of the United States. However, county governance has been abolished in Rhode Island since 1842, rendering it one of only two states, next to Connecticut, where this alteration was implemented in 1958, without counties as the primary local administrative institution. [80] This shift of power was even further enhanced by the implementation of the 13th Amendment to Rhode Island's Constitution in 1951, which grants all cities and towns the right of self government in all local matters. This procedure is commonly referred to as home rule and even allows the creation of original, municipal charters in Rhode Island. Accordingly, a high level of autonomy and authority can be obtained by the individual municipalities, rendering them the most important body for local issues and affairs. [81] Furthermore, as of 2013 only the town of Scituate has not adopted a local charter, which indicates the existence of a high degree of variation regarding localized legislation. [82] As a result, towns and cities in Rhode Island perform tasks and provide services that usually are allocated to county governance. [83]

Thus they are deemed to be the appropriate scope for the following elaborations regarding the sustainability ranking in chapter 3.

The definition criteria for specific geographic entities, which are used for evaluation and assessment of the nation for varying different purposes, and the respective spatial extent are worked out by the USCB. For instance, certain applications may require agglomeration of information per state, while others may focus on school or congressional districts. As a result, the used geographic reference differs according to regional parameters and individual research objectives. Accordingly, county subdivisions, which incorporate all 39 municipalities of Rhode Island and one section of unallocated water area, will be predominantly used for evaluation purposes in this paper. [60] However, as counties remain the prevailing form of local government in all regions of the USA but New England, most federal agencies compile their publications on a county level. Consequently, occasionally counties will be referred to in this thesis instead of the municipalities. [84]

2.5 Statewide and Municipal Planning

Even though Rhode Island is the smallest state of the entire USA, its planning division and further administrative offices, most of which are located in the state capital Providence, cover an array of areas with attention to detail. The following paragraphs constitute an overview of the most relevant offices and planning efforts for this thesis. The Division of Planning of the State Department of Administration, which will be referred to as Rhode Island Statewide Planning Program (RISPP) from this point forward, compiles fact sheets about all 39 municipalities and issues comprehensive plans with a long term planning approach for specific areas such as Rhode Island Water 2030 or Rhode Island Energy 2035. In some cases those state guide plans directly feature data on a municipal level but they are usually concerned with statewide analyses, which renders them outstanding references for

overviews about the entire state. Furthermore, this agency also supervises the status of municipal comprehensive plans, offers guidelines and assistance during the compilation of said plans and reviews them before ratification to ensure accordance with state planning goals. [85]

In comparison to state guide plans, municipal comprehensive plans are to be worked out by the respective communities and focus on issues on a local level. Accordingly, public participation is required during the working process and the functional areas of goals and policies, land use, housing, economic development, natural and cultural resources, services and facilities, open space and recreation, circulation and implementation statement are to be included in each plan. Furthermore, the plans have to be designed with a planning horizon of 20 years and are to be revisited each ten years, which allows municipalities to address issues of each community and promote a positive development. Even though the plans are regulated by state law, they differ in detail and date of origin, thus they are not well suited for comparisons amongst the municipalities. Furthermore, as of May 2017 there are only 14 fully approved and currently valid plans with the rest either expired or denied. In conclusion, while the comprehensive plans are indispensable to ensuring progress and joint development among the communities, they will hardly be referred to in this thesis as they do not offer comprehensive statewide informations. [86] [87]

2.6 Urbanized Areas

In general, urban areas are associated with high population densities as well as a heavily built up environment ranging from industrial or commercial sites, infrastructural assets such as bridges or railroads and residential quarters. Furthermore, they are often centered around specific cities and also encompass the surrounding areas such as suburbs and attached towns. However, the particular definition and

methodology for delineation differs by country. For instance, while communities with 2,500 or more inhabitants are considered urban in the United States, this threshold is set at 30,000 inhabitants in Japan. [88]

In the United States of America the most basic form of a comprehensive community is known as an incorporated place, which requires a local government, a name and legally defined geographic boundaries. In 2013 there were 19,508 incorporated places in the USA and they housed about 198.2 million people or 62.7% of the entire population. [20] Additionally, the USCB delineates comprehensive settlements as an urban area if it incorporates at least more than 2,500 people. Furthermore, urban areas between 2,500 and 50,000 inhabitants are referred to as urban clusters and areas with 50,000 or more inhabitants are referred to as urbanized areas. Accordingly, all areas that do not meet the aforementioned criteria are categorized as rural. Additionally, further parameters such as population density, land use and distance along transportation corridors are taken into account for the actual delineation of the spatial extent for each urban area. [89] The categorization process is revised every ten years and the last iteration results from 2010 regarding number of urban areas and corresponding population are displayed in table 2.3 for the entire USA and Rhode Island. [90]

As mentioned previously in section 1.1.4, the USA is a highly urbanized country with 80.70% of it's inhabitants living in the 3,573 different urban areas and only the remaining 19.30% residing in rural areas. Furthermore, even though there are substantially more urban clusters than urbanized areas, the latter accounts for a significantly higher population share. As table 2.3 shows, this difference is even more pronounced in Rhode Island where 90.66% of its citizens are allocated to urban areas and only about 9.34% live in rural areas. Furthermore, only 0.28% of the state's population resides in urban clusters, which renders urbanized areas the

Table 2.3. 2010 count and population in urban areas, urban clusters and rural areas for the USA and Rhode Island (Data from USCB 2015 [60] USCB 2010 [91])

	Area	Number	Population	Percentage
USA	Urban Areas	3,573	249,253,271	80.70%
	Urbanized Areas	486	219,922,123	71.20%
	Urban Clusters	3,087	29,331,148	9.50%
	Rural	-	59,492,267	19.30%
RI	Urban Areas	4	954,380	90.66%
	Urbanized Areas	3	951,456	90.38%
	Urban Clusters	1	2,924	0.28%
	Rural	-	98,347	9.34%

predominant form of settlement in Rhode Island.

Overall, there are three urbanized areas and one urban cluster in Rhode Island, which are listed in table 2.4. The values have been calculated by apportioning United States Census (UCS) 2010 data to the respective geographic extent and thus differ from the figures for the total urban area. The metropolitan agglomeration around Providence is clearly the most significant urban area in Rhode Island, as it encompasses the highest number of people and accounts for the largest area with nearly 400 mi^2 . This comparison meets the expectations from figure 2.1, where the area related to Providence virtually accounts for almost all of the eastern half of the entire state.

Furthermore, the urban area of Providence even spreads to the neighboring state of Massachusetts and it houses about 1.19 million people and encompasses an area of 545 mi^2 . As a result, as of 2010 it is the 39th largest urban area by population size and the 31st biggest by area. [90] Additionally, with about 666,000 jobs it offers the 38th most employment opportunities overall, which emphasizes it's significance in relation to the entire USA. [92]

Overall, Rhode Island's population is highly urbanized with more than 90%

Table 2.4. Parameters for urban areas in Rhode Island as of 2010 (Data from USCB 2015 [60] RIGIS 2017 [64])

Name	Boston	Charlestown	Norwich	Providence
Category	Urbanized Area	Urban Cluster	Urbanized Area	Urbanized Area
States	MA, NH, RI	RI	CT, RI	MA, RI
Population	271	2,924	21,113	930,071
Area in mi^2	0.39	4.23	15.95	393.27
Population density per mi^2	689.46	690.52	1,323.64	2,364.94
Share on RI land surface	0.04%	0.41%	1.54%	38.04%

residing in urban areas. Furthermore, the urbanized area around Providence is the most significant one for the state and heavily influences its landscape, as it covers about 38% of the total land area and encompasses roughly 88% of the state’s total population. As a result, policies in general and measures for increasing the sustainability of Rhode Island’s urban areas naturally affect a majority of the statewide population.

2.7 Municipalities

The 39 municipalities of Rhode Island are further split into 8 cities and 31 towns. Key parameters for the municipalities can be found in tables 2.5 and 2.6, while their respective location is displayed in figure 2.1. Additionally, figure 2.9 lists the municipalities in regards to population density and the share of people living in urban or rural areas.

Figure 2.9, which has been worked out by apportioning 2010 census blocks to the outline of Rhode Island’s urban areas and municipalities, clearly shows that Providence is by far the most populous community of the state with nearly 180,000 inhabitants. However, it is only the second most densely populated municipality as

Central Falls houses almost 6,000 more people per square mile than Providence. Overall, a declining population density seems to go along with a higher share of people living in a rural environment, which is quite an expected relationship. There are several communities, whose entire populace or at least a high portion thereof lives in urban environments, while there are just about thirteen municipalities with 50% or more of its people living in rural areas. This observation conforms to section 2.6 as more than 90% of the entire state's citizens live in urban areas.

Figure 2.9. Urban and rural share of RI municipalities and total population density based on Census 2010 block data (Author's own figure, data from RIGIS 2017 [64])

Tables 2.5 and 2.6 show an ID, which will be used for following figures, population numbers, share of people living in urban areas, land area, population density, median age and per capita income for all municipalities. Furthermore, the corresponding statewide average, minimum and maximum values are also given. The area and share of residents in urban areas have been determined by overlaying 2010 census blocks with the spatial extent of the municipalities and the

urban areas mentioned in section 2.6. As a result, the area values, and derived population densities, may show slight discrepancies to other sources. On the other hand, population figures and median age were directly retrieved from American Community Survey (ACS) 2015 data.

As mentioned previously, while Providence is the most populous municipality, Central Falls is the most densely populated one as it also covers the smallest area of 1.3 mi^2 . On the other hand, Coventry covers the biggest area with about 62 mi^2 . New Shoreham houses the lowest amount of inhabitants, who also have the highest median age of 55.4 years, while the youngest people live in Central Falls and are in average 28.4 years old. Lastly, the least densely populated community is Foster with only 90 people per square mile. Additionally, only in ten municipalities live more than half of the respective residents in rural areas, resulting in a predominant urban set-up. Central Falls exhibits the lowest average income with only $14,026 \frac{\$}{\text{per capita}}$, while Barrington's citizens have the highest earnings with $55,429 \frac{\$}{\text{per capita}}$.

Rhode Island has an average population density of 1,019.2 people per square mile based on the total land area of $1,033.81 \text{ mi}^2$ and a population of 1,053,661 inhabitants in 2015. Furthermore, 90.7% of its residents, which are in average 39.7 years of age, live in urban areas and have a mean income of $31,118 \frac{\$}{\text{per capita}}$. The state's unique situation is concisely described by it being both the smallest in regards to area and second most densely populated states. Its biggest community is Providence with about 178,000 residents, which is a relatively low figure in context of major US metropolitan areas. However, it poses as the center of the overall 39th largest urban area of the entire USA, which emphasizes its significance both on a regional and national scale. The municipalities will be thoroughly analyzed and evaluated by using the parameters of tables 2.5 and 2.6 and the results of the sustainability ranking in chapter 3.

Table 2.5. Key parameters RI municipalities Barrington to New Shoreham (Data from RIGIS 2017 [64] USCB 2017 [65])

Name	ID	Popul- ation	Ratio Ur- ban	Area in mi^2	Density in $\frac{people}{mi^2}$	Median Age in years	Income in $\frac{\$}{capita}$
Barrington	1	16,280	100.0%	8.51	1,913.0	46.1	55,429
Bristol	2	22,364	99.3%	9.84	2,272.8	42.0	30,445
Burrillville	3	16,170	60.1%	56.96	283.9	45.5	32,581
Central Falls	4	19,378	100.0%	1.29	15,021.7	28.4	14,026
Charlestown	5	7,772	20.2%	37.92	205.0	47.4	36,878
Coventry	6	34,981	80.7%	62.46	560.1	44.5	32,609
Cranston	7	80,761	98.7%	28.93	2,791.6	40.8	29,697
Cumberland	8	34,124	92.9%	28.29	1,206.2	43.6	37,528
East Greenwich	9	13,114	85.2%	16.30	804.5	43.7	55,352
East Providence	10	47,266	100.0%	13.77	3,432.5	41.2	28,000
Exeter	11	6,691	25.7%	58.39	114.6	44.6	35,106
Foster	12	4,671	0.0%	51.97	89.9	47.2	37,621
Glocester	13	9,897	17.7%	56.83	174.2	44.7	33,584
Hopkinton	14	8,123	16.5%	44.14	184.0	47.1	33,862
Jamestown	15	5,464	91.5%	9.53	573.3	49.6	53,845
Johnston	16	29,095	95.4%	24.33	1,195.8	45.0	32,511
Lincoln	17	21,396	100.0%	18.92	1,130.9	41.6	37,211
Little Compton	18	3,504	0.0%	22.49	155.8	52.2	48,787
Middletown	19	16,057	97.6%	13.19	1,217.4	41.0	34,340
Narragansett	20	15,719	98.7%	14.12	1,113.2	43.1	41,737
New Shoreham	21	906	0.0%	9.55	94.9	55.4	43,880

Table 2.6. Key parameters RI municipalities Newport to Woonsocket plus minimum, maximum and statewide values (Data from RIGIS 2017 [64] USCB 2017 [65])

Name	ID	Popul- ation	Ratio Ur- ban	Area in mi^2	Density in $\frac{people}{mi^2}$	Median Age in years	Income in $\frac{\$}{capita}$
Newport	22	24,459	98.7%	8.00	3,057.4	36.3	40,003
North Kingstown	23	26,310	91.9%	44.07	597.0	43.0	40,540
North Providence	24	32,291	100.0%	5.79	5,577.0	43.4	30,966
North Smithfield	25	12,159	84.8%	24.88	488.7	49.3	38,652
Pawtucket	26	71,395	100.0%	8.86	8,058.1	36.3	22,016
Portsmouth	27	17,361	95.6%	23.30	745.1	46.7	43,035
Providence	28	178,680	100.0%	18.76	9,524.5	29.3	22,270
Richmond	29	7,624	0.0%	40.75	187.1	43.3	38,418
Scituate	30	10,450	24.2%	54.80	190.7	48.6	42,668
Smithfield	31	21,513	94.7%	27.61	779.2	41.3	32,099
South Kingstown	32	30,577	76.7%	60.21	507.8	36.6	32,592
Tiverton	33	15,818	70.9%	29.91	528.9	47.9	37,351
Warren	34	10,532	95.9%	6.20	1,698.7	43.5	32,687
Warwick	35	81,855	100.0%	35.73	2,290.9	44.2	35,157
West Greenwich	36	6,117	24.1%	51.22	119.4	42.0	35,842
West Warwick	37	28,891	100.0%	8.10	3,566.8	39.8	27,028
Westerly	38	22,683	86.7%	30.25	749.9	45.1	35,694
Woonsocket	39	41,213	100.0%	7.89	5,223.4	38.0	22,235
Max	-	178,680	90.7%	62.46	15,021.7	55.4	55,429
Min	-	906	0.0%	1.29	89.9	28.4	14,026
Statewide	-	1,053,661	90.7%	1,033.81	1019.2	39.7	31,118

2.8 Utility Provision and Important Sectors

As both main assessments of this paper, namely the sustainability ranking and Urban-Water-Energy-Nexus evaluations, heavily relate to specific features of Rhode Island's environment and service provision, the most significant areas will be highlighted in the following section. This includes energy provision, public water, waste water, solid waste, economic aspects, transportation infrastructure, air quality monitoring and land use.

2.8.1 Energy

This section will provide an overview for the energy sector of Rhode Island, ranging from spatial distribution of major infrastructural assets and generation capacity to time series data for power generation. Furthermore, the state's demand and consumption pattern will briefly be put into a national context.

First of all, figure 2.10 summarizes the state's energy demand for the three major sectors of electricity, thermal and transportation, which all account for roughly the same share on the overall energy demand. However, the individual provision is managed quite differently and as Rhode Island's electricity is predominantly produced in natural gas power plants, it entails the least detrimental environmental consequences while accounting for the same share of overall demand as the other sectors. In comparison, the transportation sector relies heavily on gasoline and thus is responsible for a majority of carbon dioxide emissions. Overall, in 2010 Rhode Island used 190 trillion BTU of energy, while releasing 11 million tons of CO_2 with a inherent cost of \$ 3.6 billion. Additionally, the infrastructure features about 6,000 miles of distribution lines and roughly 2 GW of electricity generation capacity. While Rhode Island is embedded in the New England covering interstate network managed by Independent Systems Operator New England (ISO-NE), there are only three distribution companies in the state itself. Furthermore, National Grid is

clearly the most significant one as it supplies power to roughly 486,000 customers with more than 6,000 miles of distribution lines. As National Grid coordinates distribution of electricity for 99% of the state, the remaining two companies Pascoag Utility District and Block Island Power play only a minor role overall. [93] [94]

Figure 2.10. Comparison of electricity, thermal and transportation sector regarding energy demand (Adapted from RISPP 2015 [93])

As of 2015, Rhode Island has the second lowest generation capacity in comparison to the remaining U.S. states with 1,849 MW and the third lowest annual generation with 6,939 GWh. Therefore, it is responsible for only the fourth lowest total carbon dioxide emissions with 2,874 thousand tons per year. On the other hand, electricity in Rhode Island is rather expensive and the retail price was the fourth highest overall with 17.01 $\frac{\text{cents}}{\text{kWh}}$. [95] The comparatively low energy demand is further emphasized by the fact that Rhode Island's residents had the second lowest energy consumption with 56,856 $\frac{\text{kWh}}{\text{capita}}$ in 2014. In comparison, the people of Louisiana are responsible for the highest average consumption with 270,798 $\frac{\text{kWh}}{\text{capita}}$, which amounts to almost a 500% difference. [96] However, those figures summarize

all usage sectors and thus industry is a significant contributor. But Rhode Island performs well even when comparing residential electricity demands on a national scale, as it's annual total for 2015 was $7,128 \frac{kWh}{capita}$ which is well below the highest consumer of Louisiana with $15,432 \frac{kWh}{capita}$. [97] [94]

As mentioned previously, electricity generation in Rhode Island relies heavily on natural gas, which is further emphasized by the time line of total generation in figure 2.11.

Figure 2.11. Time-line of total monthly energy generation in Rhode Island 2013 to 2015 (Author's own figure, data from EIA 2016 [98])

Even though as six different electricity procurement types are currently being used, natural gas dominates the generation time line with biomass and petroleum accounting for slight additional contributions. Additionally, all three featured years show a distinct seasonality with significantly higher generation during the summer in relation to the winter months. In comparison, generation during the summer, which includes the months of April to August, amounts in average up to about 687 GWh per month, while this value decreases to roughly 395 GWh during the winter. Therefore, the difference in seasonal generation averages 292 GWh or 58%

and signifies a strong disparity depending on the season. Accordingly, the highest recorded generation from 2013 to 2015 took place in August of 2015 with a total sum of almost 1,000 GWh or 1 TWh of generated electricity. Furthermore, the average annual generation amounts to 6,493 GWh, resulting in an average load of 741 MW over an entire year. Additionally, the share on total generation by technology over 2013 to 2015 is displayed in figure 2.12, which further emphasizes the major role of natural gas as it accounts for almost 96% of generated electricity. Furthermore, the renewable technologies of solar thermal and photovoltaic, biomass, wind and hydroelectric only account for 2.73% overall, indicating ample opportunity for improvement. [98]

Figure 2.12. Total energy generation in Rhode Island from 2013 to 2015 and key statistics (Author's own figure, data from EIA 2016 [98])

Moreover, figure 2.13 shows the location of major infrastructural assets related to energy in Rhode Island such as power plants by generation type, major transmission lines and natural gas pipelines. Overall, most power plants are located in the northern part of the state, where as expected the infrastructure, consisting

of transmission lines and natural gas pipelines, is significantly more concentrated than in the remaining areas of state. Additionally, Newport county incorporates the only natural gas power plant outside of Providence county and the highest concentration of wind turbines can be found in Kent county where five of the seven statewide facilities are located.

Figure 2.13. Power plants, transmission lines and natural gas pipelines in RI (Author's own figure, data from RIGIS 2017 [64] EIA 2017 [99])

Furthermore, Block Island houses one of only two petroleum fueled generators, which was also the only generating facility of the island when the EIA power plant

dataset was updated early in 2017. However, the first offshore wind farm of the United States commenced operation in May 2017 and consists of five turbines with 6 MW capacity each. Next to increasing the state's renewable generation as a whole, the wind farm will likely benefit the local residents by reducing the electricity rate significantly from over $60.00 \frac{\text{cents}}{\text{kWh}}$, which was driven up due to fuel prices and the transportation thereof. [99] [100]

Table 2.7 provides the number and generation capacity by energy type and county in order to provide more detailed information about Rhode Island's electricity sector. Providence county houses both the most power plants and distributed generation capacity as a majority of the natural gas power plants are located within its boundaries. Newport County is ranked second respectively, which is mainly due to the Tiverton Power Plant with 268 MW of capacity. A few noteworthy facts regarding renewable technologies include Kent county with the most wind turbines and Providence with the most capacity regarding solar, hydro and biomass. Both distributed generations and power plants amount to 1,965.2 MW of generating capacity in total.

In addition to table 2.7, table 2.8 is further differentiated into power plants and distributed generation and also lists the total number of facilities. While the 26 power plants have by far the higher capacity, the distributed generators, which includes for instance small rooftop photovoltaic arrays, are much more suited to compare the different municipalities to one another. This can be achieved by allocating the 2077 solar power plants, whose combined capacity easily exceeds the six large scale facilities, according to their location. Overall, the technologies of biomass, hydroelectric, solar and wind amount up to 134.4 MW capacity, which leads to a renewable share of 7.15% on the total capacity. However, when accounting for the difference of full load hours per generation type, which describes the annual

Table 2.7. Capacity by county and technology in MW (Data from EIA 2017 [99] Musher 2017 [101])

	County	Bio-mass	Hydro	Natural Gas	Petro-leum	Solar	Wind	Sum
Power Plants	Bristol	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Kent	0.0	0.0	0.0	0.0	1.9	13.5	15.4
	Newport	0.0	0.0	268.0	0.0	0.0	0.0	268.0
	Providence	36.9	2.7	1,522.1	11.6	6.3	4.5	1,584.1
	Washington	0.0	0.0	0.0	7.6	2.0	1.5	11.1
	Sum	36.9	2.7	1,790.1	19.2	10.2	19.5	1,878.6
Distributed	Bristol	0.0	0.0	0.0	0.0	0.9	0.1	1.0
	Kent	0.0	0.6	0.2	0.1	4.7	13.7	19.3
	Newport	0.0	0.0	0.0	0.0	4.9	2.8	7.7
	Providence	0.2	4.2	3.3	5.5	19.5	4.5	37.2
	Washington	0.0	0.0	12.5	0.0	7.3	1.6	21.4
	Sum	0.2	4.8	15.9	5.6	37.4	22.7	86.6

period of output at full capacity, this share diminishes to 2.73% averaged over the period of 2013 to 2015.

Overall, while Rhode Island has a relatively low energy demand in comparison to other U.S. states, the costs for residential consumption are the second highest overall. Its electricity is predominantly produced in natural gas power plants, which account for over 90% of the overall generation capacity and for almost 96% of the total generated power from 2013 to 2015.

2.8.2 Water and Waste Water

This section will discuss the current infrastructure for both water supply and waste water management, as well as overall usage figures. First of all, water suppliers are a highly diverse sector as there are up to 490 individual supply companies. They range from major suppliers, such as the Providence Water Supply Board (PWSB) which manages about 68 MGD on a daily basis to individual systems responsible

Table 2.8. Capacity in MW and number of generating facilities for power plants and distributed generation (Data from EIA 2017 [99] Musher 2017 [101])

Type	Power Plants - Capacity	Power Plants - Number	Distributed - Capacity	Distributed - Number
Biomass	36.9	2	0.2	1
Hydroelectric	2.7	2	4.8	5
Natural Gas	1,790.1	7	15.9	15
Petroleum	19.2	2	5.6	2
Solar	10.2	6	37.4	2,077
Wind	19.5	7	22.7	35
Sum	1,878.6	26	86.6	2,135

for instance remote restaurants. Accordingly, derivation of comprehensive data requires excessive effort and is not worked out and published for each year. The most recent holistic evaluations were carried out by the RISPP, which evaluated the demand from 28 major suppliers that account for about 86.9% of the total daily demand. However, municipal boundaries and the extent of each supplier are not well matched, which hinders the assessments of individual communities considerably. Also, some areas rely on self supply for instance via wells, for which the latest municipal estimates have been determined for 2005 by the Rhode Island Water Resources Board (RIWRB). Table 2.9 displays both segments and the sum thereof by county and the detailed methodology on the derivation procedure of those figures can be found in section 3.2.2. [102] [103]

Overall, municipal water demand is estimated to be at 161.90 MGD, which is composed of 89.99% public and 10.01% self supply. Furthermore, the demand can be expected to increase by 30% during the summertime, resulting in 210.47 MGD. Naturally, Providence County amounts for a majority of the daily demand, as it houses by far the most people, as displayed in figure 2.2. Additionally, most counties rely heavily on public supply and Washington County reaches the highest ratio

Table 2.9. Total, public and self supplied water average day demand per county (Data from RISPP 2012 [103] RIWRB 2012 [102])

Demand Category	Bristol	Kent	New-port	Provid-ence	Wash-ington	State-wide
ADD in MGD Total	4.15	21.03	12.07	107.36	17.29	161.90
ADD in MGD Summer Total	5.40	27.34	15.69	139.57	22.48	210.47
ADD in MGD Public Supply	3.75	19.63	10.47	99.56	12.29	145.70
Ratio on Total	90.36%	93.34%	86.74%	92.73%	71.08%	89.99%
ADD in MGD Self Supply	0.40	1.40	1.60	7.80	5.00	16.20
Ratio on Total	9.64%	6.66%	13.26%	7.27%	28.92%	10.01%

of self supply with almost 30%. However, there are consumers that do not show up in municipal evaluations such as large industrial facilities and thermoelectric power plants. The sustainable withdrawal for Rhode Island, as determined by the RIWRB at about 156 MGD, is already being exceeded, which may be due to a lack of combining different data sources or exclusion of other water procurement opportunities such as purchased water. It is advised to launch further examinations as there is additional water stress during the summer months, which may impair the natural environment.

One of the few nation-wide reports to compare water usage is carried by the United States Geological Survey (USGS) every five years. Those publications feature eight water usage categories and list a total statewide demand of 375 MGD for Rhode Island in 2010. This value constitutes the estimated total of water withdrawals on an average, daily basis across all usage categories. Additionally, it can be further differentiated into withdrawals and consumptive use, which describes processes that alter the availability of water for instance via evaporation or temporal

embodiment in products e.g. crops or livestock. However, limited data availability does not allow for more detailed nation-wide reporting on this matter, rendering appropriate assessments for the individual sectors even more important. The composition between the usage categories is displayed in figure 2.14, which reveals Thermoelectric Power as the most significant sector as it accounts for almost two thirds of the overall demand. Due to its small size and population, Rhode Island has the second lowest overall water demand of all states next to the District of Columbia and the third lowest overall on a per capita basis with $358 \frac{\text{gallons}}{\text{day capita}}$. However, when taking only self and public supply into account, Rhode Island ranks tenth overall with about $110,50 \frac{\text{gallons}}{\text{day capita}}$. [104]

Figure 2.14. Water usage in Rhode Island 2010 (Author's own figure, data from USGS 2014 [104])

The most important sources of drinking water are the Scituate Reservoir, the Big River Management Area and four sole source aquifers. Overall, precipitation ensures the supply for all drinking water in the state and thus surface water reservoirs are used for about 85% of all public water with the remaining 15%

being primarily sourced from groundwater wells. The Scituate watershed alone accounts for up to 50% of all surface water withdrawals and is the primary source of water for about 600,000 people, highlighting the importance of management and environmental protection. Proper supervision of wells should be taken into consideration, as about 150,000 residents or about 26% of the state's population rely on it. Figure 2.15 displays relevant aspects of water supply elements such as protection areas and reservoirs. The surface water protection areas largely follow the outline of the major reservoirs with the Scituate Reservoir, which is located in the North-Western part of the state, centering the biggest continuous area. Furthermore, the occurrence of wellhead protection areas is most pronounced in the southern part of the state and its rural locations overall, indicating an overall higher groundwater dependency. [102] [103]

Treatment of waste water is equally separated across the state as the provision of drinking water and can generally be divided into on-site treatment and processing in treatment plants. Overall, the Department of Environmental Management (DEM) supervises licensing, defines guidelines for plant design and maintenances and publishes overviews regarding the treatment of waste water in Rhode Island. As of 2017, the latter includes eight industrial, one packaged and 20 municipal facilities, which served approximately 775,000 residents in 2015 and, thus about three quarters of the state's population. The municipal treatment facilities combine for an average flow of 130 MGD, which cover about 80% of daily used water when taking the figures from table 2.9 into account. As daily demand and the amount of treated water may differ on a daily basis, official records state that 100 MGD are treated in 19 major facilities from both industrial and residential sources per day. [105] Hence, the remaining sewage is treated with on-site facilities such as septic tanks, which is in comparison hard to supervise and to quantify for the entire state. The DEM

Figure 2.15. Water Supply Elements in Rhode Island (Author’s own figure, data from RIGIS 2017 [64])

supports communities to develop management plans and loan systems for septic systems in order to enhance on-site facilities and ensure a high quality of treatment. As of 2014, 18 municipalities have a management plan for on-site wastewater treatment, 14 have a septic system loan program and 11 are primarily served by sewers and thus participate in neither of these programs. [106] Overall, about one third of Rhode Island’s households are estimated to use a septic system, which highlights the importance of regulation thereof. [76] Additionally, the location of

sewered areas, which have been derived by the distribution of piping and land reserved for water and sewage treatment are displayed in figure 2.15. Overall, the associated infrastructure seems to be concentrated around Providence, indicating that this area is primarily served by sewers. [64]

A large portion of the water supply infrastructure has been determined to be near the end of its life cycle with the last major installments having been done to accommodate suburban development beginning roughly in 1950. [103] Accordingly, the most recent estimates for infrastructure investments by the American Society of Civil Engineers (ASCE) include \$ 148.2 million for drinking water and \$ 1.92 billion till 2037, which indicate the latter as the major area of improvement in comparison to the procurement of water. [107]

In summary, municipal water demand amounts up to ca. 160 MGD with the total figure being significantly higher with 375 MGD, which places Rhode Island the second lowest consumer of all states. Fresh surface water supplies with 85%, while groundwater wells account for the rest and are predominantly used in the southern region and rural areas in general. Official facilities treat about 100 MGD of sewage, with the rest being processed in hard to quantify on-site facilities such as septic tanks.

2.8.3 Waste Management

This section gives a concise overview of the generation of waste and the disposal thereof in Rhode Island. Accordingly, figure 2.17 displays the locations of processing facilities, while figure 2.18 shows annual metrics for the municipal sector from 2012 to 2016 with table 2.10 giving the required definitions.

Overall, it is estimated that about 1.5 million tons of solid waste is produced per year, for which the distribution by origin and operator is displayed in figure 2.16. The majority thereof is disposed in the central landfill in Johnston, which is operated

Figure 2.16. RI averages by waste category for RIRRC, other and in total (Author's own figure, data from RISPP 2015 [108])

by the Rhode Island Resource Recovery Corporation (RIRRC) and can be seen in figure 2.17, while some of it is recycled or otherwise reused for example in waste-to-energy facilities in the neighboring states. Alike the supply of public water, waste management in Rhode Island may differ greatly for the individual municipalities. However, the RIRRC, which is established by state law chapter 23-19 in order to provide a central operator for this crucial service, processes more than 70% of all solid waste and more than 75% of recyclable materials. As a result, it can be considered to be the major provider and, thus its municipal metrics provide a comprehensive overview on which to compare the communities. [108] [109]

However, there are further operators next to RIRRC managed facilities and services, all of which are displayed in figure 2.17. Overall, there are 30 residential drop-off locations, which include facilities for general waste and recyclable materials and are overall well dispersed across the state. Waste from those facilities is

Figure 2.17. Location of solid waste facilities by type in Rhode Island (Author's own figure, data from RIGIS 2017 [64])

transported to transfer stations where it is diverted for further processing such as recycling or landfiling. Subsequently, it is transported to either the landfill in Johnston or in Tiverton, which handles only a minor percentage of the overall amount and is the last remaining municipal landfill, or transported for further processing elsewhere. Additionally, there are 18 composting facilities for yard or leaf debris and one location for handling construction and demolition remains.

Measures including total amount of waste generated and the processing such

as landfilling or recycling are paramount for assessing the performance and long term planning or designing of associated facilities. Accordingly, table 2.10 shows commonly used specifications which will be used for subsequent evaluations. There are several processing rates, which largely improve upon another. For instance, while the MRF recycling rate incorporates recyclable materials, the mandatory recycling rate goes one step further and also includes other salvageable items such as leaf and yard debris. The diversion rate is the most comprehensive measure in terms of waste disposal, as it describes the ratio of total waste that is not disposed of in a landfill but otherwise processed. Therefore, a higher diversion rate allows to operate the corresponding landfills longer and thus indicates a higher useful facility lifetime and return of investment.

Table 2.10. Waste metrics and definitions (Data from RISPP 2015 [108])

Category	Description
Solid Waste	entire non-hazardous waste collected for recycling and disposal
Diversion Rate	ratio of waste diverted from landfilled amount to total waste
Mandatory Recycling Rate	ratio of recyclables plus further materials e.g. leaf and yard debris to total collected waste
MRF Recycling Rate	ratio of recyclable materials collected to total waste

Figure 2.18 shows the total amount of solid waste, the diversion rate, the mandatory recycling rate and the MRF recycling rate for Rhode Island from 2012 to 2016 in order to gain more insight into the state's development and overall magnitude. In general, all four measures show positive development since 2013, when the total amount of solid waste peaked with slightly more than 490,000 thousand tons. Furthermore, all processing rates have increased steadily since 2012 and about 38% of all waste is currently being diverted from landfilling. The MRF recycling rate is the smallest one of the featured measures, indicating a significant

difference in included materials in comparison to the mandatory recycling rate and the diversion rate.

Figure 2.18. Annual municipal solid waste and processing rates 2012 to 2016 (Author’s own figure, data from RIRRC 2016 [110])

Overall, in average about 1,478 thousand tons of solid waste have to be disposed of in Rhode Island and about two thirds of that amount is processed by RIRRC. This share is even higher regarding municipal waste, where this corporation processes more than 90% of the total 506 thousand tons. Accordingly, their annually published metrics for all communities, which have been used to work out figure 2.18, are an excellent source of information for detailed comparison. Figure 2.18 indicates a positive trend, both for total amount of municipal waste and processing rates. This development should be further encouraged to extent the useful life cycle of the central landfill in Johnston, which has been projected to close in 2038. [110]

2.8.4 Transportation System

This section will constitute an overview of the states most important traffic systems which include highways, train connections, public transportation and

airports. A general overview about the current rail ways, bus routes, bike trails and alternative fueling stations is displayed in figure 2.19. The area of Providence clearly serves as a major node for all traffic systems as the network of routes and tracks seem to heavily concentrate around it. Furthermore, of all of the three interstates which connect between New York and Boston, Interstate 95 is the most significant. It lead towards the city, thus further emphasizing its role as a transportation hub for the state. The same observation can be made for the alternative fueling stations, which are primarily located near major traffic ways and cluster around Providence and Newport. [111]

Even though the interstates only amount to 1.2% of total road mileage in the state, about 35% of all vehicular motorized traffic passes through them, resulting in occurring congestion on a regular basis. The overall road network encompasses more than 6,700 miles with local roads accounting for almost 60% of it. Additionally, 4,400 miles of the road network were built before 1962, which together with salt exposure and unfavorable weather conditions lead to a higher than average deterioration of infrastructure. The same conditions apply to pavement and bridges, of which there are more than 700 in the state, further highlighting the importance of proper maintenance. Additionally, there are over 60 miles of designated bike lanes in the state and further enhancements are already underway to promote cycling. [111]

The Rhode Island Public Transit Authority (RIPTA) maintain and operate all public transportation services on a local in the state, which includes both fixed bus route and flex service. As of 2016, the network of bus routes, which is displayed in figure 2.19 and encompasses 1,019 miles, resulting in a line density of $0.95 \frac{mi}{mi^2}$ in relation to the state's land area. Additionally, there are slightly over 5,000 stops, which lead to an available stopover about every 1,000 feet in average for all lines. [64] Flex service is employed on demand to enhance the accessibility of

Figure 2.19. Transportation infrastructure features in Rhode Island (Author's own figure, data from RIGIS 2017 [64] U.S. Department of Transportation 2017 [112])

remote locations with public transportation and is primarily targeted at suburban or rural areas. [113] During an average weekday about 66,000 single public transit trips are taken with 308 vehicles in operation during maximum service. In 2014 21.6 million unlinked passenger trips were recorded for RIPTA and the associated urbanized area, ranking it 38th overall in the nation. [114] [115] In addition, long range public services include commuter rail to Boston with approximately 2,000 passengers per weekday, Amtrak rail to New York and Boston and motor coaches

like Greyhound and Megabus with a variety of destination across New England and beyond. In addition there are eleven airports in Rhode Island, from which six are state owned and annually attract up to 6 million passengers. The respective locations are displayed in figure 2.19, where T.F. Green Airport in Warwick is highlighted as it is the most important aviation center for the state with seven commercial airlines total. [111]

Providence also serves as a major node for freight conveyance as it houses a majority of trucking terminals and the state's main commercial port where up to 2.7 million tons of cargo are shipped on an annual basis. However, rail infrastructure is highly important on a regional context as it provides many convenient connections within the state and to other areas of New England. Additionally, a functional highway system with reduced congestion has been determined to be crucial for ensuring an adequate movement of freight. [111]

Next to taking stock of inventory, a commonly used method to assess mobility patterns is to display the modal share on total or the commuting traffic. The ACS reports commuting characteristics for the seven different modes of single car driver, carpooling, public transportation, bicycling, walking, working from home and other means of transportations such as taxicabs and motorcycles and thus provides an excellent basis for working out modal splits as a means of comparing communities or regions. Additionally, the mean travel time in minutes is also supplied, which further helps to evaluate the local situation. [65]

Accordingly, the modal split has been worked out in relation to the entire USA, Rhode Island and four of its municipalities and is visualized along with the mean travel time in figure 2.20. In general, the state of Rhode Island commuting modes are quite similarly distributed as for the entire country with individual car use accounting for a marginally higher share, while the mean travel is slightly

lower. However, the statewide characteristics can not be easily transferred to its individual communities, as the distributions differ vastly from one another. For instance, Providence has both the highest commuting share by walking and public transportation, while both Cranston and Foster rely much more heavily on individual car usage. Even though the commuting shares of these two municipalities are very similar to one another, Foster exhibits a significantly higher mean travel time possibly due to its rather remote location. On the other hand, New Shoreham, which is easily the state's most isolated municipality, shows the lowest mean travel time overall as a high portion of its residents work from home rather than commuting on a daily basis. In conclusion, the travel characteristics of the individual communities may differ greatly from one another with different impacts on sustainability. For instance, a high share of public transportation is considered to be more sustainable as the amount of emissions are significantly reduced in comparison to single car usage. [65] [116]

A sustained effort to maintain an invest in transportation infrastructure has been determined as a main agenda to ensure a safely and adequately usable network. While the minimum scenario has been estimated to require \$ 454 million for that purpose, the most favorable case with a high number of beneficial projects such as walkable communities, streetcars and bicycle accommodations may require up to \$ 1,150 million. However, both scenarios are plagued by uncertainty due to a rather outdated financing support structure, for which especially stagnant revenues from fuel taxes are problematic. [111] According to the most recent estimates of the ASCE, about a quarter of Rhode Island's 772 bridges are structurally deficient, even though about \$ 99 million were spent on related maintenance projects in 2013. This situation is the worst among all states, highlighting the upkeep of projects and funding to ensure safe usage of traffic ways. [117] Furthermore, about 54% of

Figure 2.20. Modal split and mean travel time to work for the USA, Rhode Island and four communities for 2015 (Author's own figure, data from USCB 2017 [65])

all roads, which amount up to over 6,700 miles, are in inadequate condition and cause costs up to \$ 810 per user and year. Overall, it is strongly recommended to start investing in infrastructure sooner rather than later in order to keep risks to a minimum level and enhance economic competitiveness. [107] [111]

In summary, Rhode Island encompasses over 6,700 miles of roads and 1,000 miles of public bus routes and both its ports and rail infrastructure are of high importance for freight movement. Car use still accounts for the highest share of commuter traffic with over 85% statewide, which may differ greatly depending on the location. Lastly, there is a high projected need of investment in infrastructure to ensure a safe and adequate transportation system.

2.8.5 Air Quality Monitoring

This section will feature a concise introduction to air quality monitoring, the related targets and purposes as well as the current status of both air quality and the related monitoring network in Rhode Island. In the past, worsening ambient air conditions have been viewed as a necessary byproduct to industrial progress, largely due to a lack of understanding of the consequences to the natural environment and health and well being of the affected population. [7] However, extreme events such as the great smog in London of 1952, where extreme agglomerations of air pollutants over several days caused the deaths of over 4,000 people, have sparked research incentives. This results in modern monitoring frameworks aiming to prevent increased mortality due to respiratory or cardiovascular illnesses because of high exposure to detrimental air conditions. [118] The main regulation in the USA is the Clean Air Act of 1970, which has undergone major amendments in 1990 with a focus on acid rain, urban air quality, stratospheric ozone depletion and toxic air emissions. It is managed and enforced by the Environmental Protection Agency (EPA) and the locally assigned authorities. Even though there have been major improvements since 1990, there are still significant areas for concern in regards to ground level ozone receiving increasing attention. In 2015 about 127 million people resided in counties with concentrations above the respective national standards. [119] [120]

Proper monitoring of air quality is highly important but at the same time requires an extensive amount of resources. In Rhode Island, the DEM is tasked with planning, management and operation of monitoring and therefore is the primary contact point for that matter. Since 1968, its office of air resources has been observing the state's air quality in a joint effort with the Rhode Island Department of Health (RIDOH) and features seven monitoring locations, five of

which are used for daily Air Quality Index (AQI) reporting, in total. [121] Its work is focused on the six criteria air pollutants from the National Ambient Air Quality Standards (NAAQS) established by the Clean Air Act, which can be found on page 193 in the appendix.

Figure 2.21. Percentage of days by AQI status in 2011 (Author's own figure, data from RI DEM 2011 [122])

Figure 2.21 displays the air quality summary by showing the percentage of days with the respective AQI, which is an aggregation of various ambient air parameters, for Rhode Island in 2011. The AQI is designed to serve as a single value representation for atmospheric conditions and the associated health impacts and ranges on a scale from 0 to 500 with higher scores indicating more potentially harmful conditions. In Rhode Island the significant contributing air pollutants differ on a seasonal basis with ozone (O_3) and 2.5 micron particulate matter ($PM_{2.5}$) being more relevant in the summertime, while sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) along with $PM_{2.5}$ are major contributors during winter. However, as figure 2.21 indicates, the annual air quality reaches unhealthy conditions only for two percent of the entire year or about seven to eight days in total. Accordingly,

air quality is not a major concern and only certain pollutants have been described as worrisome overall. [122]

The aforementioned AQI monitoring is carried out on a daily basis and delivers almost instantaneous results. In 2011, the continuous reporting network, which is displayed in figure 2.22, featured five sites overall of which two are located in Providence, one in East Providence and the remaining two are in the rather rural environments of West Greenwich and Narragansett. The overall monitoring network may differ from figure 2.22 for measuring specific pollutants and is in general designed to provide the best spatial coverage in the most populous areas of the state. For that purpose, the current status of the network is revised every year in order to adapt to recent trends and to achieve the best possible results. [123]

Overall, monitoring sites are concentrated around Providence next to two locations in rather rural or background areas of the state, as displayed in figure 2.22. Such a set-up may be suitable to report on the situation in the state as a whole, but is inadequate to draw conclusions for every single remote location, which would regardless require an unnecessary amount of resources and effort. Accordingly, the AQI is reported and forecasted only for three separate locations in Rhode Island, which may allow to detect trends in nearby communities but is rather unsuitable for in depth comparisons. As a result, there are complimentary actions to assess impacts on air quality such as tracking stock of emission and especially harmful pollutants and regulation of disadvantageous technologies such as diesel engines. On a national scale, toxic emissions are recorded and published in the Toxic Release Inventory (TRI), which is maintained by the EPA and included 88 facilities for Rhode Island in 2015. Overall, on site toxic air releases amounted to 293.2 thousand lb in that year, which is equivalent to almost the entirety of records in that category. [124] Furthermore, this task is also carried out by the DEM on a

Figure 2.22. Continuous air quality monitoring sites in Rhode Island for AQI (Adapted from RI DEM 2011 [122])

local scale regarding the release of criteria and toxic or hazardous pollutants with the last at length inventory having been conducted in 2014. [125]

2.8.6 Land Use and Conservation Lands

Land use is a key component of municipal planning as it allows to manage land resources and spatial development, which is especially important for Rhode Island and its overall rather limited land area of about $1,000 \text{ mi}^2$. In general, land use planning may focus on detailed areas, for instance zoning ordinance of town

areas and even individual lots, or take a comprehensive approach and evaluate big areas in regards to the current status and projected development. The most recent assessment has been carried out in 2011 by reviewing orthophotography in order to derive land patches with a minimum size of 0.5 acres depending on the use and resulting coverage type. Subsequently, the results are then classified into Land Use Land Cover (LULC) coding, for which the seven overarching categories and the respective area and overall share for Rhode Island can be found in table 2.11. With about 58.03% most of the state's land surface is covered by forest and the second biggest share is achieved by development such as residential, commercial and industrial sites or infrastructural assets such as roads and power lines. [64]

Table 2.11. LULC coded areas in Rhode Island (Data from RIGIS 2017 [64])

LULC Code	Type	Examples	Area in mi^2	Ratio
100	Developed	residential, commercial, industrial, roads, power lines, cemeteries	327.0	30.44%
200	Agriculture	pasture, cropland, orchards, feeding operations, idle land	36.6	3.41%
300	Brushland	shrub or brushlands and areas for reforestation	12.2	1.14%
400	Forest	deciduous, softwood and mixed forest	623.2	58.03%
500	Water	lakes, streams, ponds	41.2	3.84%
600	Wetland	swamps, marches and fens	19.6	1.82%
700	Other	beaches, rock outcrops, mines, transitional and mixed barren areas	14.2	1.32%

Additionally, figure 2.23 displays the distribution of top level LULC coding categories from the 2011 dataset. Prominent features, such as the Scituate Reservoir and the outline of urbanized areas are clearly discernible. In general, forested areas are most common and take up the majority of the north western portion of the

state with a few spots of brush- and wetlands in between. Furthermore, most of the state's agriculture is located in the southern region in Washington County.

Figure 2.23. Land Use and Land Cover Rhode Island 2011 (Author's own figure, data from RIGIS 2017 [64])

As of 2014, there are 273.54 mi^2 of conservation land in Rhode Island, which may include wildlife management areas, drinking water supply watersheds, state parks, beaches, bike paths, fishing access areas, local parks and recreation facilities. This area is split almost evenly into state owned lands, of which there are 136.67 mi^2 , and otherwise protected areas for instance by the Audobon Society of Rhode Island,

nature conservancies, municipal governments, the United States Fish and Wildlife Service and by voluntary conservatory intent. The largest object of the latter category is the protected area belonging to the Scituate Reservoir, which is owned by the PWSB and covers an area of 19.40 mi^2 . The largest state protected object belongs to the Big River Management Area and encompasses 13.09 mi^2 . [64]

Additionally, impervious land cover is frequently associated with detrimental consequences. It causes higher and more frequent runoffs, thus conveying more pollutants to nearby watersheds and increases the land surface temperature in close vicinity. As a result, it is associated with lower water quality, higher temperatures in the summertime and negative influence on aquatic terrestrial habitats. [126] The share of impervious surface to overall area is a concise indicator to assess potential risks associated with it. As of 2013, Rhode Island encompasses 138.94 mi^2 of impervious surfaces, which amounts to 12.94% in relation to its land area. [64] As this value is significantly higher than both the worldwide average with 0.43% and for the United States with 1.05%, Rhode Islands limited land area and thus closely confined development demand special attention to changes in its land use and surface. [127] On the other hand, as table 2.11 shows, about 60% of the state's area is still forested and both state and other conservation lands cover roughly a quarter of its land area. Accordingly, Rhode Island has managed to preserve a strong rural character and many of its natural assets such as beaches, bays, forests, farms and rivers even though it is one of the most densely populated states in general. [128] Therefore, the statewide land use development plan, which is targeted at the year 2025, has identified preservation of rural areas while promoting growth of urban centers as a guideline with acute priority. Additionally, underutilized urban neighborhoods, highway interchange infrastructure and waterfront areas have been identified as major areas of concern moving forward. [129]

2.8.7 Economy

This section will provide a short introduction to Rhode Islands economic assets in order to provide a frame of reference for the economic section of the sustainability ranking. Accordingly, major employment sectors, metrics and other relevant areas will be discussed.

Figure 2.24. Private employment sectors with share on total job figures (Author's own figure, data from RISPP 2014 [130])

In 2012 Rhode Island offered 451,357 employment opportunities, of which 392,278 belong to the private sector and 58,599 to government employment. The top ten private categories are displayed in figure 2.24 with health care and social assistance clearly accounting for the most jobs. Subsequently, retail and trade, accommodation and food services and manufacturing were the only other three sectors that individually account for more than 10% of private employment. Afterwards, the six sectors of administrative and waste services, finance and insurance, professional and technical services, educational services, wholesale trade and construction jointly account for about 31% of private jobs. The remaining minor sectors such as information or mining are summed up under other services, which account for

the remaining sixteen percent of private sector employment. Lastly, the 58,599 government jobs are distributed 55% local, 27% state and 18% federal, naturally resulting in local government work being most significant within the state. [130]

Figure 2.25 shows the relative development of jobs and the Gross Domestic Product (GDP), which summarizes all the value of goods and services for the referenced area, for both the entire USA and Rhode Island, which reveals a closer connection for the GDP than the employment figures. In fact, Rhode Island faced its all-time highest unemployment rate of over 11% in 2011, from which it has recovered somewhat as this value has decreased to 8.5% in 2015. This ranks Rhode Island 35th in comparison to all states of the USA and second worst amongst the states of New England. On the other hand, as of 2015 Rhode Island has the 14th highest per capita income with \$ 31,118, which represents the 4th highest value in New England. [130] [65] Furthermore, Rhode Island achieved the sixth lowest GDP overall with \$ 55.6 billion in 2015, which is largely due to its small size and population. However, on a per capita basis it has the 25th highest value with $55,432 \frac{\$}{\text{per capita}}$, which indicates an overall average economic activity. [131]

Figure 2.25. Job and GDP growth for USA and Rhode Island 1979 to 2009 (Adapted from RISPP 2014 [130])

Next to evaluating economic activity via the aforementioned, determining the ease of commencing business may supply further insight into the state's economic

situation. While Rhode Island has offered one of the most unfavorable situation regarding taxes and, thus a high cost of doing business, this condition has improved recently. For instance labor is now available at competitive rates in comparison to neighboring states. However, New England in general has exceedingly high costs for services such as housing, utilities and childcare, prohibiting the area from becoming overall more attractive for potential employees or companies. Additionally, most jobs can be reached with only a thirty minute car ride due to the state's compact layout. Thus, this high personal mobility indicates a good workplace accessibility. Alternative modes should be promoted to prevent environmental consequences, such as deteriorating air quality, and to alleviate congestion of highways. Lastly, communication technologies are also deemed crucial in regards to economic aptitude. Rhode Island is generally in a good position, as wireless broadband is available in all locations and 63.4% of the state's citizen have fiber service available. While this places Rhode Island in the top twelve of all states for both available service and connection speed, the development of other states has been progressing faster recently. As a result, continuing investments are required to ensure a favorable position regarding connectivity. [130]

As of 2014, uneven wage development, diminishing middle class, racial gaps in income, health and employment opportunity have been determined as major upcoming challenges. Furthermore, the population is getting considerably older on average, which leaves jobs to be replaced by young professionals. Therefore, the goals of the long range planning effort include promotion of proper education, an inclusive and more diverse workforce and creation of financially competitive and attractive locations. The goals are expected to be completed by 2035 and require investments in economic sectors, housing and transportation. [130]

CHAPTER 3

Sustainability Ranking

This chapter will feature the methodology for working out the sustainability ranking and the individual sectors as well as evaluations on a spatial scale and by using chosen municipal parameters. Additionally, noteworthy divergent areas per community will be identified and discussed accordingly. Eventually, the most sustainable municipalities and most unfavorably performing ones will be determined and a recommendation for future assessments will be worked out.

3.1 General Approach

As discussed in section 1.1.1, actually measuring sustainability is no small feat due to its ambiguous nature and applicability across various intertwined sectors. However, this endeavor may reap tremendous benefits as creating clear and understandable labels is crucial to reach the people whose actions induce tangible outcomes. Furthermore, establishing a framework with distinct local connections may help to create additional motivation and incentive for the respective populace. Therefore, this study aims to establish a sustainability rating for the municipalities of Rhode Island in order to give a comprehensive overview of the current status as well as identifying areas for further improvement. As scrutinizing rather small individual municipalities regarding such a rating scheme is a novel approach, this iteration may not be entirely free of flaws. However, there is substantial insight to be gained, which renders research in this area highly important.

3.2 Methods

This section will discuss the overall ranking approach and methodology regarding the derivation of certain measures. Additionally, section 3.3 will discuss the

data sources, while section 3.4 will state the intent of each individual indicator in detail.

3.2.1 Compilation and Evaluation of the Ranking

Overall, there is an abundance of existing frameworks and set of indicators, which are usually tailored to fit the resources, parameters and conditions of the city or research area of interest. [132] As a result, there is no commonly accepted or generally applicable methodology for assessing sustainability of cities on a global scale without requiring extensive work for data acquisition and processing. For instance, the framework developed to assess progress and provide objectives for the Sustainable Development Goals (SDG) features 232 indicators in total, which may often be too detailed and inappropriate for comparably small settlements. [133] In addition, the choice of indicators and the significance thereof may vary with regional characteristics or challenges, leading to different points of emphasis. For instance, reporting on the number of people living in slums or suffering from malaria may be a much more pressing concern in rapidly evolving Asian mega cities rather than a decently sized and wealthy European city. As a result, the applied approach for this paper was modeled after a few existing examples and suited as best as possible in order to provide a holistic comparison while also accounting for availability of data. However, mainly due to time constraints, the chosen indicators were worked out with already existing data or rather easily elaborated parameters. Therefore, potential future iterations may benefit greatly from improved data acquisition and well planned collaborations with appropriate state offices or otherwise affected parties.

In general, the finalized ranking intends to cover all aspects of sustainability or likewise its three pillars of environment, economic and social. As those categories are thought to be part of a highly intertwined and cohesive system,

comprehensive evaluations instead of focused examinations on individual aspects is strongly recommended. [7] Furthermore, differentiating the ranking further into individual segments, such as energy, water and transportation amongst others for the environmental category, allows for the identification of exceptionally performing areas for the communities. As mentioned previously, the methodology has been modeled after a few already existing systems, which are discussed in section 1.1.1. As a result, the approach of this elaboration does not feature novel methods for assessing sustainability but explores the applicability to rather small communities in great detail for the state of Rhode Island.

Given the lack of definitive values on which to base goals or otherwise related measures for quantification, it was decided to compare the municipalities amongst each other according to the respective best and worst performances for each indicator. Furthermore, all values scattered in between those two thresholds have been allotted a score according to their placement amongst the range between the minimum and maximum values. Additionally, depending on how the indicators have been interpreted, each score has been distributed from low to high values or vice versa. This approach allows for the derivation of a ranking in respect to all featured municipalities, while achieving a high level of detail in a regional context and clearly identifying overly positive or negative performances. All indicators are listed in tables in section 3.4, where the methodology and reasoning for each case is also explained in detail along with the assigned score, data source and year of origin.

Table 3.1 displays the allocation of points for two indicators and five chosen communities. In the first case, Providence has overall the highest unemployment rate and thus receives zero points, while Cumberland receives the maximum score as it has the lowest overall value. Meanwhile, the remaining municipalities are accredited points according to their placement within the range of 9.2% between

Table 3.1. Example procedure for ranking score allocation

Municipality	Providence	Johnston	Warwick	New Shoreham	Cumberland
Indicator	Unemployment rate in % - low - 2.5 points				
Value	12.7	5.6	8	6.9	3.5
Range	0.00%	77.17%	51.09%	63.04%	100.00%
Score	0.0	1.9	1.3	1.6	2.5
Indicator	Bus lines per area of municipality in $\frac{mi}{mi^2}$ - high - 0.5 points				
Value	11.86	0.99	3.94	0.00	0.15
Range	100.00%	8.31%	33.26%	0.00%	1.30%
Score	0.50	0.04	0.17	0.00	0.01

Providence and Cumberland. The second case compares the communities according to the mileage of bus line normalized to their respective area, thus high values indicating good availability of public transportation services. Therefore, the highest value, which belongs to Providence with $11.86 \frac{mi}{mi^2}$, has received maximum score, while New Shoreham has been allotted zero points as it does not have any bus lines within its boundaries. This procedure was conducted for all 75 indicators and each municipalities for which the specific values and accredited points can be found in appendix B beginning on page 195.

The general structure of the ranking procedure is displayed in figure 3.1 and is split into the three categories of social, environmental and economic aspects. Additionally, these categories further consist of themed segments such as education, safety amongst others in order to recognize different points of interest or emphasis. Next up, the segments are made up by the actual indicators with the featured number varying according to data availability and thus the possible level of detail during the working process. While the number of indicators per segment ranges from three to seven, the awarded score per segment always amounts to ten in total in order to allow comparison on an equal basis within the categories.

Figure 3.1. Hierarchy of applied sustainability ranking approach (Author's own figure)

Furthermore, the scores per category are visualized as bar charts, which are also split up into the individual segments in order to provide a clearly arranged overview and allow for identification of the composition of each community's score. Lastly, the overall results are arranged as bar charts too, but the composition consists only of the three overarching categories as more in depth visualization would have been to cluttered.

In addition, the results are analyzed by using box plots, which are worked out for all 20 featured categories, in order to analyze the distribution of values and to identify outliers. The box plots have been worked out in Excel 2016, which

allows for direct processing from the results without the need for intermediate steps. In general, each section from beginning of the first whisker, the bottom and top sections of the box and the following whisker encompass a quarter of the featured values. This allows concise visualization of variance within the dataset, as the figure and its individual sections increase in size the further spread out the data points are. Furthermore, there may be outlying values, which are defined as being outside the 1.5 interquartile range beginning from each end of the box, as the whiskers are set to local minimum or maximum values. Additionally, the median value is represented by the mid line of the box, while the mean value has been added as a x-shaped marker. [134] Overall, box plots are considered to be standard procedure for visualizing the distribution of data points and thus allowing clearly arranged comparisons between different sets. [135]

Figure 3.2. Properties of the Excel 2016 box plot visualization (Adapted from Excel Team 2017 [134])

Additionally, subsequent evaluations include assessments of spatial patterns by mapping the results and examination of correlation to demographic parameters by applying a simple linear regression approach. In conclusion, the aforementioned

methodology allows for comparison of the different municipalities in detail while achieving clearly arranged figures for concise analysis and in-depth evaluation of the results.

3.2.2 Derivation of the Indicators

In comparison to, the required amount of effort to derive the indicators may vary significantly. While some sources, for instance the ACS reports and waste related measures as supplied by RIRRC, publish their data already in relation to the municipalities, most information has to be edited in order to fit to the referenced communities. Furthermore, a few indicators such as water and residential energy demand per capita had to be generated almost entirely from the ground up, resulting in an excessive increase of work for those areas. Accordingly, the next few paragraphs will highlight the used methodology for chosen indicators.

Several of the measures have been derived using spatial analysis methods in ArcGIS, which includes share of people or structures living within a certain distance of a facility or other point of interest, average distances and determination of share of distinct areas such as LULC to the overall municipal area in addition to other factors. Accordingly, the following paragraph will describe the applied methodology and procedures in detail in order to make the derived indicators thereof more accessible and better to work with. [136] [137]

Average distances have been computed to evaluate accessibility of services, e.g. fire stations or alternative fueling stations and have been determined as euclidean distance rasters with a 30 foot cell size, which was then averaged via zonal statistics as a table over the respective areas of the communities. Next, proportion of areas, for instance ratio of developed land, has been computed by unifying the polygon dataset of interest with the areas of the municipalities and then retrieving the applicable areas via summary statistics, which was then exported to excel for

subsequent evaluations. Determining the share of people follows largely the same work flow, which starts off by calculating the population density per 2010 census block by dividing the reported population figure by the respective area. Afterwards, the census blocks were unified with the municipal boundaries and areas of interest, for example, a half mile buffer around bus stops. Subsequently, the new population distribution was determined by multiplying the population density with the areas of the new shapes, which was then exported to excel for follow up evaluations. All population based spatial procedures were carried out with 2010 block data, as it is freely available on RIGIS, while more recent datasets related to the ACS are only accessible on block group level. While the latter offers more recent information, it was decided to work with census blocks as they allow evaluations on a much more detailed spatial scale. However, as block groups are the finest spatial feature of ACS publications, which is supposed to supplant the decennial census procedure, future elaboration may have to focus on using them instead. This would also enable to better match demographic information to the year of origin of the spatial dataset. Accordingly, this work compromises for some minor discrepancies as for instance TRI facilities stem from 2015, while the population distribution originates from the 2010 census. [64] [138] [139]

As mentioned previously, the indicators related to water and energy demand required a comparably high amount of work and thus their derivation will be described in detail during the next few paragraphs. According to section 2.8.2, there are almost up to 500 different suppliers in Rhode Island rendering comprehensive data gathering an excessively complicated task. As a result, the here derived indicator used for comparing the communities water demand on a per capita basis may benefit greatly from future work regarding data collection. For this thesis, a number of reports from the RISPP and the RIWRB were consulted, for which the

most significant specifications can be found in appendix C, to obtain figures on water demand.

Table 3.2. Methodology for deriving water demand per community as demonstrated for the PWSB (Data from RISPP 2012 [103] RIWRB 2012 [102])

Category	Area of Providence Water Supply Board			
	Cranston	Johnston	North Providence	Providence
Public supply in MGD	68.14			
Total structures within area	94,428			
Structures per municipality	29,164	7,175	10,251	47,838
Apportioned public supply	21.04	5.18	7.40	34.52
Self supply in MGD	0.1	0.3	0	0
Total demand in MGD	21.14	6.09	7.63	34.52
Population in 2015	80,761	29,095	32,291	178,680
Total demand in $\frac{gal}{capita}$	261.82	219.55	236.20	193.20

In general, each municipal water demand may consist of public and self supply and the sum thereof composes the entire consumption. The public supply was apportioned per supplier according to the number of encompassed structures per municipality as displayed for the Providence Water Supply Board in table 3.2. The area of this supplier covers the four municipalities of Cranston, Johnston, North Providence and Providence, whose water demands amounts to 68.14 MGD in total. [103] This figure is then split according to the ratio of structures per municipality and structures per supplier, resulting in Providence being allocated the majority of the public supply figure. Next, the direct supply, as reported by the Rhode Island

Water Resources Board for 2005, is added, leading to the total demand. [102] Furthermore, normalizing to the number of residents results in the final measure by which the communities will be compared later on. This approach neglects water transferrals between the suppliers and thus may underestimate the overall demand for communities that rely heavily on this procedure. However, as no other figures on municipal water demand were available, the derived measures are going to be used nonetheless. Accordingly, establishing a comprehensive reporting scheme to achieve a higher quality of data regarding water usage of Rhode Island’s communities proofs to be an advisable future goal.

Table 3.3. Providence as example for deriving residential energy demand (Data from EIA 2017 [140])

Size of household	Energy in kWh per size of household	Number of households	Energy per category in GWh
1 person	23,768	19,477	462,931
2 people	31,271	15,884	496,704
3 people	34,582	9,286	321,132
4 people	36,224	7,481	270,989
5 people	42,261	4,443	187,765
6 or more	44,107	2,785	122,839
Sum	-	59,356	1,862,358

Subsequently, the derivation procedure for the residential per capita energy demand will be discussed in detail. No comprehensive source of information regarding municipal energy demand could be found during the research phase of this project. Therefore, figures had to be derived manually, using estimates from the 2009 iteration of the Residential Energy Consumption Survey (RECS) as conducted by the EIA for the Northeast region of the United States. The RECS enables the derivation of estimates for annual energy demand based on structural and demographic attributes. The listed criteria, which can be found in appendix D,

were compared to the household demographics of the municipalities and then divided by the 2009 population figures to obtain the per capita energy demand. In total, five different attributes were used and subsequently averaged to obtain the energy demand for each community. This includes the year the structure was built, household income, tenure, household size and unit type. [140] [65]

Table 3.4. Example residential energy demand for five municipalities as examples for derivation procedure (Data from EIA 2017 [140])

	Residential energy demand in $\frac{kWh}{per\ capita}$				
Derivation method	Central Falls	Foster	Newport	Providence	Warren
Year structure was built	10,430	11,172	15,019	11,788	13,413
Household income	17,646	18,026	24,192	19,442	22,031
Tenure	8,718	12,615	14,086	10,542	13,434
Household size	10,694	11,677	14,087	11,677	13,004
Unit type	7,936	13,154	16,765	9,738	12,855
Average	11,085	13,329	16,830	12,638	14,947

As Providence housed 159,483 residents in 59,536 housing units in 2009 and had a total residential energy demand of 1,862,358 GWh according to the RECS derived values, the per capita demand amounts to 12,638 kWh. In addition, table 3.4 displays the five intermediate steps and the averaged per capita demand for five chosen municipalities. Central Fall has the lowest energy demand of all communities with $11,085 \frac{kWh}{per\ capita}$, while Newport has the highest demand with $16,830 \frac{kWh}{per\ capita}$. Additionally, the criteria of tenure and unit type generally result in the lowest figures, while household income culminates in significantly higher values. Therefore, the averaged value was used instead of figures derived from a singular criterion.

This procedure was executed for all 39 municipalities and five criteria, resulting in an averaged residential energy demand per capita and year for all communities. Furthermore, the applied methods result in a statewide average residential consumption of $12,309 \frac{kWh}{per\ capita}$. Naturally, this estimate can not be as accurate as figures measured by the utility provider, which is in this case National Grid, but still adequately matches the statewide averages as discussed in section 2.8.1 for 2015, especially as the derived figures account for all usage categories instead of just accounting for electricity. Furthermore, this methodology features a linear approach, which may be improved upon by accounting for interactions between the parameters and with the ambient conditions in order to achieve more realistic estimates. [141]

Overall, the methodology for deriving the indicators has been profoundly discussed in the prior section and major areas for improvement have been mentioned. This includes a lack of data regarding economic figures and water or energy demand per municipality. This procedure can be seen as a crucial step to enable enhancements in future iterations.

3.3 Data Resources

In general the used data comes from a variety of sources from within Rhode Island and federal agencies, which in some cases offer datasets with a fitting resolution to work on a municipal level. The US Census Bureau is tasked with providing in depth information about the United State’s population with the decennial census being its most popular and widely used publication. Its first iteration was carried out in 1790, as required even by the very first version of the U.S. Constitution, to establish an informative basis to enhance political decision making in communities. From that point forward the census survey has been used to acquire population counts and detailed demographic information every ten

years till 2000, when the latter function was assigned to the newly developed ACS. The main objective of this alteration was to provide figures on an annual rather than a decennial cycle, which is more suitable in the rapidly changing information technology age. The geographic levels, for which the ACS results are compiled and published, can be seen in figure 3.3 with state, county and county subdivision areas being most often referred to in this paper. [142] [143]

Figure 3.3. ACS, Hierarchy of geographic entities (Adapted from USCB 2016 [138])

Furthermore, the 5-year estimates datasets provide the most consistent information and thus will be used in most analyses. About the only exception are distribution of population examinations, e.g. number of people within a buffer around a point of interest. For this goal, the 2010 Census Block data will be used, as the detailed information of the ACS is not publicly available for that spatial resolution in order to prevent privacy intrusions of individual households or companies. However, from Census Tract level upwards the ACS provides extensive information such as mean travel time to work, median age or household income. As

the level of accuracy of the survey estimations have been deemed to be questionable from the tract level downward, county subdivision data will be predominantly used in this paper. [141]

Occasionally, federal data sources have been used, which include the Toxic Release Inventory for Rhode Island in 2015 and the Fatality Analysis Reporting System (FARS) database regarding accidents with fatalities and datasets from the geospatial data inventory from the U.S. Department of Transportation. As of 2015, the TRI incorporates 88 facilities, whose reported emissions have been used to derive indicators related to health. [124] Data from FARS has been used to measure sustainable transportation, while the featured noise levels from the U.S. Department of Transportation have been applied for health related indicators. [144] [112] Additionally, Rhode Island based projects have been retrieved from the total list of LEED certifications as published by the United States Green Building Council and serve as a measure for sustainable energy consumption in this paper. [145] Additionally, figures from RECS 2009 have been used to derive the residential energy demand per community, for which the detailed methodology can be found in section 3.2.2. [140] Additionally, data, including air emissions for 2014, were supplied by state agencies or initiatives such as DEM or RIGIS. Occasionally, specific programs regarding housing information or health statistics, were incorporated in the rating. [64] [125] [146]

Overall, a majority of the indicators were derived from ACS data. However, figures published by entities within the state of Rhode Island were used over the aforementioned source when available, as those reports promise more accuracy in comparison to the nationwide survey. On the other hand, the annual publishing cycle of the ACS poses as a great basis for reiterations, which should be considered by future research efforts for this kind of evaluation. Nonetheless, section 3.4 gives

more detailed information on the processing of the retrieved data by describing the derivation process and purpose of all 75 indicators along with statements regarding the respective data sources.

3.4 Indicators

In this section the procedure for deriving the individual indicators along with a description of the three overarching categories of social, environment and economy will be discussed. Overall, 75 indicators have been derived, which are listed for each segment in individual tables along with the associated unit, minimum and maximum values, score, order on which the score has been apportioned and the year of the respective dataset. The scores have been allocated based on the range within each indicator and measures where high values are judged to be more beneficial have been declared as high. Thus the highest values obtain the highest score, while the opposing case has been declared as low. Additionally, each subsequent section features a box plot in order to give an clearly arranged overview for each set of indicators per segment for the three categories. However, the actual scores per municipality along with a detailed analysis are first comprehensively stated in section 3.5. Background information on the state of Rhode Island can be found in chapter 2, while a general discussion on measuring sustainability and ranking approaches can be found in section 1.1.1.

3.4.1 Social

The social indicators are distributed over the following six categories of education, safety, health, work life balance, housing and voter participation and equality. All individual segments have been allotted ten points in total but the number of featured indicators ranges from seven for safety and health to two for voter participation and equality.

To begin with, table 3.5 features measures on which to evaluate the status of educational attainment in the municipalities. Four different indicators have been derived from ACS 2015 data and weighed equally within this segment. While the first two indicators intend to report on the current status of education via the percentage of population with at least a high school or a bachelor degree, the latter two compare the communities regarding school eligibility and current enrollment for the two age thresholds between 5 and 17 and between 18 and 24 years of age. All four measurements have been judged to indicate a more beneficial situation with increasing values, thus ranking them from low to high. [65]

Table 3.5. Indicators, social category, education

Description	Unit	Min	Max	Score	Order	Year
Share of people with high school degree or higher	%	55.50	98.10	2.5	high	2015 [65]
Share of people with bachelor degree or higher	%	8.90	67.20	2.5	high	2015 [65]
Share of population 5 to 17 years enrolled in school	%	94.12	100.00	2.5	high	2015 [65]
Share of population 18 to 24 years enrolled in school	%	26.38	91.39	2.5	high	2015 [65]

Table 3.6 displays the indicators related to safety, which is intended to deliver data on crime as well as response capability via distance to relevant services and personnel figures. The crime related measures have been retrieved from the Uniform Crime Reporting (UCR) website of the Federal Bureau of Investigation (FBI), where data for 18,000 geographical entities is available going back to 1995. This has been normalized to ACS 2015 population figures in order to achieve a common basis for comparison among the communities. Unfortunately, the town of Exeter is not featured in those publications as it does not possess its own police station. As a result, it could not be considered for the respective indicators thus preemptively receiving zero points. However, this is the only case for the entire ranking where

such a procedure was necessary. [147] The number of firefighters has been retrieved from ACS 2015 data, while the mean distances have been determined with RIGIS datasets, from which all listed facilities have been used, and averaged over the respective municipal areas. [65] [64]

Table 3.6. Indicators, social category, safety

Description	Unit	Min	Max	Score	Order	Year
Number of law enforcement employees per 10,000 people	$\frac{number}{10,000}$	15.53	88.30	1	high	2015 [147]
Number of firefighters per 10,000 inhabitants	$\frac{number}{10,000}$	0.00	191.98	1	high	2015 [65]
Crime rate per 10,000 inhabitants	$\frac{crimes}{10,000}$	110.13	1,147.90	4	low	2015 [147]
Offenses per law enforcement officer	$\frac{crimes}{officer}$	3.143	27.843	1	low	2015 [147]
Average distance to a police station in miles	mi	0.452	3.815	1	low	2014 [64]
Average distance to a fire station in miles	mi	0.411	2.293	1	low	2017 [64]
Average distance to a hospital in miles	mi	0.928	17.743	1	low	2013 [64]

The indicators categorized under health, which are listed in table 3.7 have been derived from three different data sources. First of all, the share of people without health insurance has been retrieved from ACS 2015 data and has been allocated 4 points as it is from a rather recent year and concisely summarizes the accessibility of health services. [65] In comparison, the indicators related to births and deaths stem from the year 2005. Even though this dataset is comparatively old, it was still used here as no other comprehensive report could be acquired. All figures were already worked out in the report besides the infant mortality rate, which has been determined by dividing the number of deceased infants by the number of births for each municipality. [148] The noise related indicators were derived from the national aviation and road image services as published by the U.S. Department

of Transportation and reduced to the area of Rhode Island. Additionally, these raster datasets were averaged over each municipality to attain mean noise levels in decibel and the spatial distribution was superimposed on 2010 census block groups to determine the share of potentially affected people. [112]

Table 3.7. Indicators, social category, health

Description	Unit	Min	Max	Score	Order	Year
Share of people without health insurance	%	2.70	27.70	4	low	2015 [65]
Births per 1,000 inhabitants 2005	$\frac{number}{1,000}$	7.10	21.00	1	high	2005 [148]
Deaths per 1,000 inhabitants 2005	$\frac{number}{1,000}$	5.10	13.20	1	low	2005 [148]
Low weight infants per 1,000 live births	$\frac{number}{1,000}$	41.28	118.34	1	low	2005 [148]
Infant mortality rate per 1,000 births 2005	$\frac{number}{1,000}$	0.00	11.96	1	low	2005 [148]
Average noise level due to major roads and aviation	dB	39.49	47.91	1	low	2017 [112]
Share of population affected by road and aviation noise	%	6.41	99.43	1	low	2017 [112]

Next, table 3.8 displays the four indicators representing the work life balance of the communities with more time for leisure and opportunities to spend it at appropriate facilities being interpreted as being more sustainable overall. To begin with, the average hours per week work has been obtained from ACS 2015 data and allocated four points, as it indicates the available time besides work while the other featured datasets focus on the availability of facilities. [65] Subsequently, the acres of public outdoor recreation area and share of people living in close vicinity thereof has been gathered from the website RI DataHUB, which aims to gather information from various official sources such as the Rhode Island departments for labor or health and make it available in one place. Along with the share of developed recreation area of the LULC-data from RIGIS, these three measures

enable comparisons for variety and accessibility of recreation offers between the communities. [149] [64]

Table 3.8. Indicators, social category, work life balance

Description	Unit	Min	Max	Score	Order	Year
Average hours per week worked	hours	33.30	39.10	4	low	2015 [65]
Acres of public outdoor recreation area per 10,000 people	$\frac{acres}{10,00}$	0.3	227.5	1.5	high	2011 [149]
Share of people living close to an outdoor recreation facility	%	34.67	100.00	3	high	2011 [149]
Share of area as developed recreation area	%	0.18	9.96	1.5	high	2011 [64]

The indicators related to the affordability of housing, which are displayed in table 3.9, have been largely derived from the annually published report of HousingWorksRI. This program is a collaborative effort to comprehensively collect information about housing in Rhode Island and provides in depth data for all municipalities. The three measures of cost burdened owner or renter households and the ratio of affordable housing on the overall housing stock have been adopted to reflect upon the respective status of housing and the associated costs. Those measures concisely summarize the ratio of income spent for accommodation and the overall lesser portion has been judged to be more sustainable. In that sense, while housing is considered affordable if less than 30% of a household’s income is used for it, it is considered cost burdened if the latter case is exceeded. Additionally, the median housing affordability gap has been determined by subtracting the median household income as reported in the ACS 2015 from the required income to own a single family house in the respective community as listed in the Housing Fact Book of 2015 by HousingWorksRI. This results in negative values when the actual income exceeds the required amount, thus low values were ranked more favorably than higher ones. As all four worked out indicators report on the same issue and

have been judged to be roughly equally significant, they have been allocated the same amount of points. [146] [65]

Table 3.9. Indicators, social category, housing

Description	Unit	Min	Max	Score	Order	Year
Share of owner household as cost burdened	%	25.00	63.00	2.5	low	2014 [146]
Share of renter households as cost burdened	%	13.00	64.00	2.5	low	2014 [146]
Ratio of affordable housing on overall housing stock	%	0.60	17.10	2.5	high	2014 [146]
Median housing affordability gap	\$	-20,091	212,113	2.5	low	2015 [65]

Lastly, table 3.10 displays the two measures which compose the segment of voter participation and equal pay. Both report on significant social issues with a high potential to influence sustainable development as for instance high voter participation, which has been determined by dividing the total number of casted votes by the number of eligible residents of each community for the 2016 statewide primary as published by the Rhode Island Board of Elections, may entail strong communal engagement and thus serves as an indicator for political awareness. [150] Next up, the mean difference in wages for male and female full time workers has been derived from ACS 2015 data by subtracting the mean earnings for women from the mean earnings for men. [65]

Table 3.10. Indicators, social category, voter participation and equal pay

Description	Unit	Min	Max	Score	Order	Year
Voter participation 2016 primary election	%	17.50	39.10	5	high	2016 [150]
Difference in earnings male and female	\$	895	70,585	5	low	2015 [65]

Additionally, figure 3.4 displays the spread of results for the six featured social

segments, of which work life balance has the lowest mean value while safety has the highest one with a slight edge over health and education. The latter also exhibits the furthest spread results ranging from 8.87 to 3.50 points with two even lower outlying values, which are constituted by the towns of Central Falls and Pawtucket. Accordingly, both cities perform rather negatively in the education sector as, for instance, Central Falls steadily ranks last in all four featured indicators but for the share of children from 5 to 17 years enrolled in school. Additionally, the community's unfavorable situation is further emphasized by some key facts as 55.5% of its inhabitants are currently without a high school degree. For safety there are three significantly worse scoring communities due to varying reasons. Exeter achieves the lowest score because it does not possess an individual police department and thus is not included in FBI crime statistics. Accordingly, it did not qualify for three of the seven indicators which translates to a loss of 6 total points. This was the only time for the entire working process when a community could not be included in the ranking, thus resulting in a considerably lowered score. Both Providence and New Shoreham exhibit high crime rates, the latter largely due to its low population count leading to high values when projected the number of reported crimes to the common denominator of 10,000 people. Additionally, its remote location hinders the accessibility to certain institutions e.g. hospitals. Central Falls also performs significantly below average regarding health largely due to the fact that 27.7% of its inhabitants are currently without health insurance. Johnston achieves the lowest score for work life balance as its residents work the second most hours per week and there are limited opportunities for recreation. Newport achieves a significantly higher housing score, as it regularly performs above average for all related indicators and even has the highest share of affordable housing on the overall housing stock. East Greenwich is noteworthy regarding voting and equality

as it shows an average voter participation and the highest average salary difference for men and women with about \$ 70,500.

Figure 3.4. Box plot for the six social ranking segments (Author's own figure)

Altogether, the aforementioned indicators intend to cover an array of social issues and could largely have stemmed from the ACS of 2015, but local data sources, for instance HousingWorksRI or RIDOH, have been used preferably if available. For example, both the ACS and RIDOH report births and the number of law enforcement employees is also reported locally or in census data. Overall, the working process revealed two main difference between Census reports and local sources. While the latter may potentially capture the situation in the state more precisely, the former is available on an annual basis and thus allows the derivation of periodic rating iterations as a next step. However, this principal elaboration has first to establish a current evaluation and thus the more precise data has been used if available.

Unfortunately, some important issues could not be considered for this thesis due to a lack of available data for all municipalities. This is especially true for the segment of health, as detailed information for example obesity rates or other

significant health concerns are simply not reported on the required spatial scale. However, worked out indicators still are deemed to cover most issues in appropriate detail and even allow for identification of exceptional situations as visualized in figure 3.4. Additionally, the performance of each community is reported for all social segments in figure 3.8 on page 114.

3.4.2 Environment

The environmental indicators are split into the six categories of energy, water, land use, transportation, air and waste, for which transportation features the most indicators with seven and energy features the lowest number with three indicators. In comparison, the required effort to derive the measures for the individual segments varies vastly within the environmental category. For example, all measures related to waste could be directly transferred while both energy and water required extensive effort to substitute for lack of available data.

First of all, table 3.11 displays the indicators for energy, of which the latter two are the more significant ones as they characterize the usage of renewable energies and residential energy demand. In comparison, the number of LEED projects, which has been obtained from the website of the USGBC and matched to the municipalities of Rhode Island, serves rather as supporting information and therefore was attributed only with 2 points. In order to achieve the biggest sample size as possible, all listed projects, even if no certification has been issued yet, have been included. Furthermore, no differentiation of the different rating thresholds has been established. [145] The share of distributed renewable energy has been determined by allocating the facilities as supplied by the Rhode Island Office of Energy Resources to the individual municipalities and computing the ratio to the total capacity of this dataset. [101] Unfortunately, no official records were available regarding overall energy demand. As a result, the residential per capita energy

consumption was derived from EIA resources and demographic parameters of the communities as described in detail in section 3.2.2. [140] [65]

Table 3.11. Indicators, environmental category, energy

Description	Unit	Min	Max	Score	Order	Year
Number of LEED projects per 10,000 structures	$\frac{\text{number}}{10,000}$	0	14.92	2	high	2017 [145]
Share on total statewide distributed renewable energy	%	0.00	21.70	4	high	2017 [101]
Energy demand from residential buildings per capita	$\frac{kWh}{\text{capita}}$	11,085	16,830	4	low	2009 [140]

In order to properly rate the transportation sector of each municipality several measure have been manually derived such as ratio of populace living within certain distance of a bus stop, length of public transportation routes or bike lanes per municipal area and the average distance to alternative fueling stations. Only the share of commuters using their own car, without considering car pooling, and the number of accidents with fatalities from 2005 to 2015 have been retrieved from official sources and only had to be allotted to the municipalities. [65] All other measures were derived by spatial evaluations of the existing transportation infrastructure. [64] [112]

Table 3.13 displays the environmental indicators related to water, of which the daily water demand has received the most points as it is judged to be the most meaningful one within this segment. However, as described in detail in section 2.8.2 the high number of individual suppliers renders reporting on municipal water demand a time and resource consuming endeavor. This issue is made even more complicated due to the fact that the extent of individual supply companies, for which consumption figures are generally computed, is not well matched to municipal boundaries. In order to obtain figures for each community, the reported consumption by supplier as listed in the report Rhode Island Water 2030 were

Table 3.12. Indicators, environmental category, transportation

Description	Unit	Min	Max	Score	Order	Year
Number of accidents with fatalities per 10,000 people	$\frac{\text{number}}{10,000}$	0.52	27.83	2	low	2015 [144]
Ratio of people living within quarter mile of bus stop	%	0.00	96.67	0.5	high	2016 [64]
Ratio of people living within half mile of bus stop	%	0.00	100.00	0.5	high	2016 [64]
Bus lines per area of municipality	$\frac{\text{mi}}{\text{mi}^2}$	0.00	11.86	0.5	high	2016 [64]
Bike lanes per area of municipality	$\frac{\text{mi}}{\text{mi}^2}$	0.00	1.31	0.5	high	2016 [64]
Average distance to an alternative fueling station	mi	0.66	14.02	2	low	2015 [112]
Share own car single driver on commuting modal split	%	55.30	89.80	4	low	2015 [65]

apportioned to the respective communities and added to self supply figures as described in detail in section 3.2.2. [103] [102] The next two indicators characterize the respective situations regarding wastewater and the higher share of households with complete plumbing facilities, which has been obtained from ACS 2015 data, or structures within sewerred areas the more points have been accredited. The latter has been determined by evaluating the dataset of E-911 structures and sewerred areas from RIGIS and interprets comprehensively managed and supervised treatment of waste water to be more sustainable in comparison to individual systems such as septic tanks. [65] [64] Lastly, the ratio of unaccounted for water, which describes losses during conveyance, is a crucial measure for assessing the sustainability of water supply infrastructure. However, as it was only available as median value per county, it was only accredited with one point as the data hardly enables municipal comparisons. [151]

The indicators related to land use, which are displayed in table 3.14, give information about the share of municipal areas covered with impervious materials

Table 3.13. Indicators, environmental category, water

Description	Unit	Min	Max	Score	Order	Year
Water demand per day and capita in gallons	$\frac{gal}{d \text{ capita}}$	40.42	331.13	7	low	2010 [103]
Share housing units without complete plumbing facilities	%	0.00	4.31	1	low	2015 [65]
Share of structures within sewerred areas	%	0.00	100.00	1	high	2012 [64]
Percentage of unaccounted for water	%	4.00	10.00	1	low	2015 [151]

and the share of natural space. The latter is represented by the ratios of land with 300 to 600 LULC coding, which incorporates brushlands, forests, water and wetlands as explained in more detail in section 2.8.6, and state or other conservation lands to the total municipal area. All measures have been derived from RIGIS datasets and apportioned to the respective communities. Furthermore, the indicator for impervious surfaces has been accredited with the most points as it gives a different perspective than the remaining ones, which largely measure the existence of natural land. [64]

Table 3.14. Indicators, environmental category, land use

Description	Unit	Min	Max	Score	Order	Year
Share of area as impervious surface	%	2.91	66.40	5	low	2011 [64]
Share of area 300 to 600 LULC	%	8.53	88.09	3	high	2011 [64]
Share of area as state conservation land	%	0.51	40.67	1	high	2014 [64]
Share of area as other conservation land	%	3.10	31.84	1	high	2014 [64]

Table 3.15 shows the indicators related to air quality. Overall, as discussed in section 2.8.5, monitoring is an extensive field of work and is carried out on a daily basis for Rhode Island with five stations for continuous reporting of the AQI. As

a result, spatial coverage is judged to be insufficient for reliably determining the AQI for all municipalities. Therefore, instead of directly analyzing local conditions with recorded or derived data, each municipality's contribution via comparison of emissions per capita have been worked out. [125] Additionally, exposure to detrimental ambient air circumstances was evaluated by determining the share of people living close to major roads, for which the roads dataset by Rhode Island Department of Transportation (RIDOT) from 2016 as supplied by RIGIS was used, and TRI facilities with recorded air emissions. [64] [124] Additionally, as wood stoves pose potential health risks and are closely link to particulate matter emissions, an increasing share of households with usage thereof has been judged to be more unsustainable. [152] [65]

Table 3.15. Indicators, environmental category, air

Description	Unit	Min	Max	Score	Order	Year
Emissions in kg per person for 2014	$\frac{kg}{person}$	0.00	91.53	5	low	2014 [125]
TRI air emissions in kg per person for 2015	$\frac{kg}{person}$	0.00	7.94	2	low	2015 [124]
Ratio of population within 2 mi of TRI Air Site	%	0.00	99.92	1	low	2015 [124]
Ratio of population within 1 mi of major road	%	0.00	99.79	1	low	2010 [64]
Ratio of housing units with wood as primary heating	%	0.06	19.94	1	low	2015 [65]

The communities were compared regarding generation of solid waste and processing thereof by using the annual metrics for 2015 published by the RIRRC. The publications include the figures of overall produced waste, which were normalized with the 2015 ACS population numbers, as well as recycling and diversion rates. Details and explanations regarding the metrics can be found in table 2.10. [110]

In order to easily evaluate all environmental indicators, the distribution of

Table 3.16. Indicators, environmental category, waste

Description	Unit	Min	Max	Score	Order	Year
Total generated waste in kg per person for 2015	$\frac{kg}{person}$	147.71	3,881.90	5	low	2015 [110]
MRF recycling rate in 2015	%	10.00	41.20	2	high	2015 [110]
Mandatory recycling rate in 2015	%	15.20	55.50	2	high	2015 [110]
Overall landfill diversion rate in 2015	%	15.70	55.70	1	high	2015 [110]

scores has been arranged in a box plot as displayed in figure 3.5. In comparison to the social segments, which are displayed in figure 3.4, the environmental aspects vary considerably in their distribution and exhibit a higher number of outliers, indicating a less cohesive composition or more drastic differences within the segments. For instance, the indicators related to land use cover almost the whole range of possible scores, while a majority of air related ratings is between eight and nine points.

Regarding the energy segment, while a majority of the municipalities receives scores below three points, North Kingstown, Coventry and Providence are especially favorably rated. While Coventry receives a majority of its energy score due to it encompassing 21.70% of Rhode Island's distributed renewable energy generation, North Kingstown and Providence perform well due to the respective low figures on estimated residential energy demand and a high number of LEED projects in relation to the overall structures.

The transportation segment features the rather urbanized communities of Central Falls, Providence and Newport as above average performers. They tend to feature a high share of commuters using public transportation, a close proximity to alternative fueling stations and a high accessibility to public transit facilities. The latter is notably true for Central Falls and Providence as almost all of the respective citizens live within half a mile of a bus stops and the amount of bus

routes per area, for instance there are $11.86 \frac{mi}{mi^2}$ in Providence, is especially high.

Overall, the municipalities tend to receive rather high scores in the water segment. This is most likely due to the sole indicator of water demand being apportioned seven points, however there are a communities with significantly heightened figures. For instance, New Shoreham has a demand of 331.13 MGD, while the statewide average has been determined to be around 161.90 MGD as described in detail in section 2.8.2. Accordingly, such a considerably higher demand has also been worked out for Burrillville and Cranston. In comparison, the three remaining indicators regarding plumbing facilities, sewerage areas and unaccounted for water have a low influence as they are only attributed with one point each.

As previously described, the land use segment features a variability of scores and no drastically different values were identified. This is largely due to the somewhat mutually excluding set-up of the indicators, as a high share of impervious surfaces is likely to entail a low share of conservation values. However, the highest score of 9.4 points belongs to West Greenwich as it exhibits the third lowest share of impervious surfaces and the highest share regarding 300 to 600 LULC coded areas and state conservation areas. On the other hand, Central Falls receives the lowest score in this segment as its densely structured set-up entails a low share of natural areas and leads to the highest overall share of impervious surfaces.

The indicators related to air lead to a tightly packed distribution of scores with Johnston, Burrillville and New Shoreham as clear below expectations performers. Those communities had the three highest per capita emission and New Shoreham and Burrillville also had the two highest per capita air emissions from the facilities listed in the TRI. As those two indicators alone account for seven of ten points and the mentioned communities exhibit significantly higher values, the remaining municipalities tend to receive rather high scores overall.

Lastly, the point distribution of waste related indicators is similar to those related to air. The $3,881.9 \frac{kg}{per\ capita}$ of solid waste generation in New Shoreham nearly dwarfs all other communities, as the average value for all is $555.7 \frac{kg}{per\ capita}$. Additionally, it also achieves considerably below average results regarding recycling rates and diversion from landfill, rendering it by far the most unfavorably rated municipality regarding waste. Furthermore, Providence has one of the lowest per capita waste generation but features the lowest overall values for all processing rates. In general, the same issues apply to Johnston but in a marginally more unfavorable magnitude, thus ranking it slightly below Providence.

Figure 3.5. Box plot for the six environmental ranking segments (Author's own figure)

Overall, the derived indicators are deemed to adequately represent the diverse sectors of environmental sustainability. However, actually recorded demand figures for water and energy may greatly enhance this assessment. The distribution of values is far less homogeneous than for the other two categories, which may stem from a higher variety of consulted data sources. The actual results of the environmental segments per community are displayed in figure 3.9 on page 115.

3.4.3 Economy

The economic indicators are distributed over only the four different segments of income, employment, value and mobility and connectivity. In comparison to the other overarching categories of social and environment, the economic category includes slightly fewer indicators overall and has noteworthy gaps of data. This is mainly due to the fact that no extensive database regarding significant economic aspects such as the GDP, which is seldom determined for individual municipalities, and number of businesses or workplaces was available. As a result, the economy of the individual municipalities may not always be portrayed absolutely accurately and certain refinements in future iteration may prove to be very beneficial. Therefore, the economic aspects have been apportioned with only 20% of the final score, while the other two areas were each accredited with 40% of the finalized results. However, the following indicators still provide a complementary overview over the respective economic situation while the chosen segments highlight different, important areas of interest. According to the previously reviewed categories, the economic indicators will first be discussed by segment in tables 3.17 to 3.20 with an overall comparison via a box plot visualization in figure 3.6, while the finalized scores per municipality will be listed in section 3.5.

To begin with, all income related indicators have been retrieved from ACS 2015 data and feature different references such as per capita, household or family. Additionally, the share of people with an income below the poverty level has also been included and allocated the most points within this segment as it differs substantially from the other featured categories. In an economic sense, higher income was interpreted to be more sustainable, as it allows more spending and thus a higher economic activity in general. [65]

Table 3.18 displays the indicators related to employment, which are arranged

Table 3.17. Indicators, economic category, income

Description	Unit	Min	Max	Score	Order	Year
Percentage of people with income below poverty level	%	2.20	33.20	4	low	2015 [65]
Mean per capita income	\$	14,026	55,429	2	high	2015 [65]
Mean household income	\$	39,147	145,033	2	high	2015 [65]
Mean family income	\$	41,216	181,942	2	high	2015 [65]

to reflect on both the current status of occupation via the unemployment rate and employment to population ratio, which have both been directly transferred from the ACS of 2015 and the potential availability of jobs and economic activity. This is done via a comparison of agricultural, commercial and industrial areas and overall issued building permits in 2014. [65] The area related categories have been derived from the LULC 2011 dataset as supplied by RIGIS, while the share on the total issued building permits has been derived from the 2015 Housing Fact Book. [64] [146] Frankly, the latter would benefit greatly from actually recorded employment opportunities or number of businesses per community, but unfortunately such measures were not available during the working process of this paper. Nonetheless, the featured categories may still capture the municipal economy adequately enough and thus contribute further to the subsequent detailed evaluations.

The indicators related to value, which are displayed in table 3.19, are designed to report on the per capita assets and the subsequent use thereof. The latter is most prominently displayed by the dependency ratio, which represents the ratio of working aged people to the entire populace and has been retrieved from ACS 2015 data. As high values indicate a high portion of inhabitants aged outside of the labor force, lower values have been deemed to be more sustainable in an economic sense. The next two indicators, both of which stem from the annual

Table 3.18. Indicators, economic category, employment

Description	Unit	Min	Max	Score	Order	Year
Unemployment rate	%	3.5	12.7	2.5	low	2015 [65]
Employment to population ratio	%	53.8	70.8	2.5	high	2015 [65]
Share of agricultural area to overall area	%	0.00	22.41	1	high	2011 [64]
Share of commercial and industrial area to overall area	%	0.25	29.40	2	high	2011 [64]
Share of total issued building permits for housing units	%	0.00	8.72	2	high	2014 [146]

reports of the Rhode Island Department of Revenue and specifically the Division of Municipal Finance, characterize value via annual tax intake and the estimated financial municipal assets broken down to a per capita basis. Both measures are reported in the categories of residential, commercial and industrial, tangible and motor vehicles and therefore cover a broad spectrum of applicable areas. [153] The remaining indicator has also been gathered from the ACS 2015 and in comparison to the municipal values focuses on privately owned houses, thus being rather directly allocated to the community's people instead of the overall assets. [65]

Table 3.19. Indicators, economic category, value

Description	Unit	Min	Max	Score	Order	Year
Dependency Ratio	%	38.80	77.20	4	low	2015 [65]
Tax levy per capita	$\frac{\$}{person}$	790	10,549	3	high	2015 [153]
Total municipal value per capita	$\frac{\$}{person}$	24,930	1,832,083	2	high	2015 [153]
Median housing value owner occupied units	\$	151,300	1,156,300	1	high	2015 [65]

Lastly, the indicators of table 3.20 characterize a communities ease of commencing in business both via the ability to communicate adequately per telephone service and Internet infrastructure and the accessibility and mobility. The former has been evaluated by determining the share of structures within areas with at least two Internet providers and within areas of existing fiber technology, for which the broadband availability dataset from 2012 and the E-911 sites from 2017 as supplied by RIGIS have been used. A comparison based on the sheer availability is not a reasonable approach as only a vanishingly small area is without service overall. [64] Additionally, the number of households lacking telephone service and workers without an available car have been retrieved from the ACS of 2015. The latter is a concise measure to evaluate personal mobility to get to work with lower values indicating increased flexibility and thus an easier commute. [65]

Table 3.20. Indicators, economic category, mobility and connectivity

Description	Unit	Min	Max	Score	Order	Year
Share of households without available telephone service	%	0.00	100.00	2	low	2015 [65]
Share of structures with at least two internet providers	%	0.00	100.00	1	high	2012 [64]
Share of structures within area of fiber availability	%	0.00	100.00	2	high	2012 [64]
Average distance to highway exit ramp	mi	0.782	18.431	1	low	2003 [64]
Average distance to commercial or industrial port	mi	1.065	18.558	1	low	2010 [64]
Average distance to an airport	mi	1.513	11.364	1	low	2013 [64]
Share of workers 16+ years without available vehicle	%	0.00	10.80	2	low	2015 [65]

In accordance to the other categories, the score distribution of the economic segments has also been visualized in a box plot, which is displayed in figure 3.6. Connectivity and mobility shows the highest average value with almost 7

points, while value has the lowest average score with slightly less than three points. Additionally, both employment and value have about the same compact distribution of scores, while income has the highest spread and the most outliers.

Negative outliers for income include the communities of Pawtucket, Woonsocket, Providence and Central Falls, with the latter persistently showing the lowest values thus receiving zero points for this segment. Barrington on the other hand exhibits the lowest share of people below the poverty level and features the highest income values but for families, resulting in the highest overall score close to ten points.

The segment of employment only features Cumberland as the sole positive outlier due to the lowest overall unemployment rate of 3.50% and well above average values for employment to population ratio and share of total issued building permits in 2014. The distribution of performances related to value is quite similar as there is only one outlying value with New Shoreham as it exhibits the highest values for three of the featured indicators. However, in comparison it strays further from the other values than Cumberland does, indicating an even stronger exceptional situation for the island community.

Lastly, connectivity and mobility features three unfavorably rated outliers. All three communities are located in rather remote places, resulting in low accessibility via highways, airports and harbors. Furthermore, all of them show a distinct lack of fiber service availability, indicating a comparably low communication capability. However, Newport is ranked most unfavorably as it displays the lowest share of workers without an available vehicle.

In conclusion, the featured indicators evaluate the communities based on income levels, current employment and potential availability of jobs, municipal value and the ease of commencing in business via telecommunication, proximity of relevant transportation infrastructure and personal mobility. However, a lack

Figure 3.6. Box plot for the four economic ranking segments (Author's own figure)

of data regarding the actual number of businesses and corresponding employment opportunities poses as a significant area for improvement, which should be addressed in future iterations. The total economic scores for each municipality can be found in figure 3.9 on page 115.

3.5 Results

In order to determine the most sustainable municipality the individual scores of the three segments were added up in order to achieve a single score on which to clearly rank the municipalities. While figure 3.7 shows the totally achieved score arranged from best to worst performing community, figures 3.8 to 3.10 display the composition of the social, environmental and economic scores by segment before the weighed sum and are also arranged from best to worst. In order to account for a lack of available data, the economic category was attributed with 20 points, while the other two areas each received 40 points. The scores per community were achieved by converting the score per category, for instance 60 points for social to 40 points in the overall rating, and adding them up afterwards. Additionally, the

rank regarding the overall rating or for the individual categories is also given in order to provide a concise overview for each community.

Figure 3.7. Aggregation of total score for all municipalities along with ranking position per category (Author's own figure)

As displayed in figure 3.7, Jamestown is the best performing community with in total 65.38 points while Central Falls receives the lowest overall score with 45.66 points, which results in a total range of 19.72 points. Furthermore, the gap to the total attainable score of 100 is 34.62 points, indicating that the percentage based comparison results in a diverse distribution of scores rather than cumulation for

specific communities. The visualization per category allows for identification weak spots as for instance New Shoreham achieves a significantly unfavorable performance regarding environmental aspects, while it amounts a rather high portion of points for economic considerations. Additionally, the listed ranks per category reveal that the best economically performing municipality East Greenwich, is at best average regarding the other two categories. On the other hand, Richmond, which is ranked second for economic, is placed third overall as it also performs well above average regarding social and environmental aspects. In general, social and environmental ranking position seem to correspond quite well with one another while the economic ranking often deviates for individual cases.

Next up, figure 3.8 displays the social scores per municipality divided into the six featured segments, which allows to identify weak spots regarding the composition of each individual score. For instance, Jamestown, which is also rated highest in the overall and environmental rating, receives 41.04 points in total and clearly performs best in the areas of education and voter participation and equal pay, while both work life balance and housing offer opportunities for improvement. On the other, Central Falls is rated worst with 24.94 points and exhibits clear defects regarding education. Other noteworthy communities are Johnston with work life balance as a major issue, Exeter and New Shoreham due to an evident lack of points for safety, and East Greenwich with voter participation and equal pay as a clear area for improvement.

Furthermore, the environmental rating results per community, as divided into six featured segments, can be seen in figure 3.9. Jamestown is also rated most favorably in this category and receives 40.37 points in total with energy being its by far worst performing segment. On the other hand, New Shoreham is clearly the most environmentally unsustainable community as it receives 8.82 points less than

Figure 3.8. Social score for each municipality divided into the six featured categories along with overall ranking position (Author's own figure)

the second worst performing municipality and just 18.04 points in total. In addition, it receives only few points for energy, water and waste, while the segment of land use is the biggest contributor to its overall score. Overall, energy seems to hold potential for improvement for numerous communities while Providence, Central Falls, North Kingstown and Coventry seemingly perform well above average in that regard. However, Providence, Pawtucket and Central Falls perform significantly below average regarding land use.

Figure 3.9. Environmental score for each municipality divided into the six featured categories along with overall ranking position (Author's own figure)

Lastly, figure 3.10 displays the economic rating results split into the four featured segments per community. In general, the ranking positions on the right hand side of the graph reveal that a lot of the high scoring economic communities do not perform well in the overall ranking, indicating a disparity between the three overarching categories. East Greenwich receives 24.11 points and thus sits on top of the economic ranking, while Central Falls is the worst performing community with only 11.14 points. Furthermore, Central Falls is also the worst performer for all four

Figure 3.10. Economic score for each municipality divided into the four featured categories along with overall ranking position (Author's own figure)

indicators related to income, resulting in zero points for that segment. Additionally, it also performs poorly regarding employment and value, while connectivity and mobility receives an average score. In general, there are only very few communities that perform significantly worse regarding income, such as Pawtucket, Providence and Woonsocket, or connectivity and mobility, which includes for instance New Shoreham and Newport.

This evaluation procedure is deemed to be well suited to compare all 39

communities to each other, while also providing an appropriate level of detail. However, the individual indicators need to be examined in detail in order to clearly identify areas for improvement. For that purpose, the rating score by category and segment can be found in the appendix beginning on page 195. However, the indicators per municipality are not listed in this thesis, but appendix B includes instructions on how to access them on-line.

3.6 Evaluation

This section incorporates an evaluation of the ranking results by analyzing the distribution of the attained scores with a box plot, segmental assessment of score composition per municipality, mapping to determine spatial trends and exploring possible correlations between the ranking and demographic parameters of the communities.

To begin with, figure 3.11 displays the range of values for all aforementioned categories in a box plot. As expected, the total score shows the highest variability as it incorporates the largest values overall. However, it is noteworthy that no extremely outlying values are present, thus all scores are captured within the interquartile range, indicating a decreased fluctuation in regards to the subcategories. Furthermore, the economic plot can not be directly compared to the social or environmental score, as it encompasses a lower amount of total points.

Additionally, figure 3.12 shows the ranking results of each municipality split into the three categories along with the actual values and the relation to the overall achieved score. This representation allows for the assessment of the composition for each score in order to determine if any communities perform significantly different regarding an individual category.

Overall, the distribution does not show any drastic developments, thus indicating a steady composition for the majority of communities. However, a few

Figure 3.11. Box plot for the social, environmental and economic categories and the overall score (Author's own figure)

municipalities definitely stand out, such as New Shoreham, which features by far the lowest environmental score and an about average social score, resulting in a significantly different score composition. Central Falls shows a similar situation, as it has both the lowest social and economic score, and as a result generates a majority of its points from the about average environmental performance.

In conclusion, there seems to be a fair amount of consistency within the ranking results, as the box plot in figure 3.11 only shows five outlying values overall and the composition of the ranking score is rather equally distributed regarding the three segments of social, environmental and economic. However, the cities of New Shoreham and Central Falls perform quite exceptionally in comparison to the other communities. The ongoing economic hardship of Central Falls seems to translate more directly into the social than the environmental sector, as it achieves the lowest scores overall for social and economic attributes. New Shoreham on the other hand is likely heavily influenced by the high number of visitors during the summertime, which may lead to inflated values when projecting measures to a

Figure 3.12. Share on total score by category for each municipality along with partial and total score (Author's own figure)

common population based denominator. Accordingly, its waste production and water or energy demand are by far the most unfavorable values on a per capita basis. Additionally, the potential influence of seasonal tourism is further emphasized by the fact that Little Compton, which is the second least populated town of Rhode Island, performs significantly better in both the environmental category and the total ranking, where it achieves the fourth best score overall.

3.6.1 Spatial Patterns

The ranking results were mapped in order to allow identification of spatial patterns. While figure 3.13 displays the overall results, figure 3.14 additionally shows the performance for the three categories. Both representations are scaled according to the best and worst performing communities of the respective category, allowing for an easily transferable overview.

Figure 3.13. Map of overall ranking score by municipality (Author's own figure)

At a first glance, the most unfavorably ranked communities seem to be clustered around Providence and the only the municipalities of Burrillville, Woonsocket and New Shoreham perform similarly but are located in other areas. On the other hand,

the best rated communities are mostly located in the southern part of Rhode Island including Jamestown, South Kingstown and Richmond.

Figure 3.14. Map of ranking score for each municipality divided into social, environmental, economic and total (Author's own figure)

This trend can also be observed when mapping the featured categories as displayed in figure 3.14. The urbanized area around Providence always features a majority of the rather poorly performing communities, while the municipalities

along the southern coast tend to perform steadily well overall. The social category seems to feature the most diverse spread of results with Jamestown and Central Falls being at opposite ends of the spectrum.

When comparing the municipalities regarding their environmental performance, New Shoreham is exceptionally unfavorably rated while a majority of the remaining areas performs above average. Additionally, as displayed in figure 3.11 North Providence is the only other town with an attributed negatively outlying value concerning environmental aspects. Lastly, mapping of the economic values reveals the below average performances of Providence, and nearby Pawtucket and Central Falls. Furthermore, Burrillville and Woonsocket are also rated unfavorably but are located outside of this cluster.

Overall, the communities located closely around Providence tend to perform below average in all featured categories, while the municipalities around the South Western part of Narragansett Bay and most of the associated rural background towards Kent county display favorable performance across all categories. While the mapping of the results allows for quick comparison and identification of overall rating of the individual communities, more detailed evaluations, which will be carried out in section 3.6.2, are necessary to clearly determine trends.

3.6.2 Relation to Municipal Parameters

As a next step, the results can be correlated to demographic attributes of the respective communities to determine if there are noteworthy correlations between the ranking performance and measures such as population density, median age or income. Overall, six different attributes, which are displayed in table 3.21, were examined with a linear regression approach. The demographic parameters were set as values for the x-axis, while the associated score of the overall ranking and the three segments were plotted as the y-axis values. Subsequently, linear trend lines

were added with the respective equation and Coefficient of Determination (COD) being used in follow up evaluations.

Table 3.21. Correlation between demographic parameters and ranking results

Parameter	Influence on Score				COD or R^2			
	All	Social	Env.	Ec.	All	Social	Env.	Ec.
Population $\frac{\text{score}}{10,000 \text{ people}}$	-0.7	-0.3	-0.2	-0.2	0.2071	0.0339	0.1543	0.1723
Area $\frac{\text{score}}{10 \text{ mi}^2}$	1	0.3	0.5	0.2	0.1424	0.0685	0.118	0.0589
Density $\frac{\text{score} \cdot \text{mi}^2}{1,000 \text{ people}}$	-1	-0.5	-0.2	-0.3	0.3866	0.4631	0.0442	0.5156
Urban $\frac{\text{score}}{1\% \text{ urbanized}}$	-0.3	-0.2	-0.1	-0.1	0.0536	0.1199	0.0001	0.0536
Median Age $\frac{\text{score}}{\text{year of age}}$	0.3	0.2	-0.1	0.2	0.119	0.2352	0.0063	0.3828
Income $\frac{\text{score}}{1,000 \$ \text{ per capita}}$	0.4	0.2	0.1	0.1	0.3992	0.3927	0.0618	0.5765

Table 3.21 summarizes the respective influence on the ranking results and the COD for all examined demographic parameters, of which per capita income and population density have the most pronounced impact with a COD of almost 0.4. Furthermore, while both area and population of the municipality exhibit a rather low correlation, their population density, which is the combined measure of both, reaches a far higher correlation to the ranking results. The two remaining demographic parameters of median age and people living in urban areas show a rather low correlation, indicating low suitability to conclude on sustainability performance. Regarding the individual segments, economic aspects are most strongly influenced by the per capita income of the communities, while the lowest correlation can be observed between environmental considerations and the share of people in urbanized areas.

Furthermore, with area, median age and income, about half of the comparative

measures have a negative influence on the ranking results while the remaining three show a positive correlation. Additionally, this is consistent within each measure regarding the individual segments save for median age, where social and economic aspects are positively linked to the rating while it has a negative influence on environmental aspects.

Figure 3.15. Linear correlation of population density to sustainability rating performance (Author's own figure)

Next, the connection between the two most significant measures of population density and income will be analyzed in more detail. Therefore, the respective development of all municipalities is visualized in figures 3.15 and 3.16. To begin with, figure 3.15 displays the ranking performance of all municipalities over the population density and shows a negative trend for all categories, which emphasizes that more densely settled communities tend to perform poorly in the ranking. Furthermore, the coefficient of performance varies with the categories and environmental aspects seem to be least closely connected to this parameter, while economic performance shows a rather high correlation to the ranking scores. In general, just about one

point of the overall score is deducted from the results with 1,000 additional people per square mile. However, as there is only a rather low correlation overall, the most densely populated community is not automatically the worst performing one.

Figure 3.16. Linear correlation of per capita income to sustainability rating performance (Author’s own figure)

Figure 3.16 shows the sustainability rating results over the respective per capita income of the communities. Overall, all segments have a positive influence, indicating that a more comfortable individual financial situation is beneficial to overall sustainability. As expected, this relationship is strongest regarding the economic aspects as it exhibits the highest COD for all featured parameters. However, social considerations are more significant in terms of total development due to the higher allocated score regarding the finalized ranking. Altogether, about 0.4 points are added with each additional 1,000 $\frac{\text{score}}{1,000 \text{ \$ per capita}}$. As a result, residents of more sustainable communities tend to have a higher income.

The featured correlation examinations have a rather simplified and brief

character, but point towards promising future research areas and help to characterize the communities of Rhode Island in more detail. However, the results of this section are hardly transferable to other areas as they are closely linked to the study area. Furthermore, they are inherently influenced by the derivation methods, which have noteworthy gaps as discussed in section 5.2. Nonetheless, population density and income have been identified to have the strongest influence on the sustainability rating.

3.7 Ranking Significant Findings

In conclusion, the worked out rankings hold a lot of promise for comparing the municipalities of Rhode Island against one another in regards to sustainability. However, it can not be stressed enough that this thesis largely concludes on the feasibility and potential benefits, as more detailed work with relevant state agencies is required to ensure adequate data quality and choice of indicators. At the very least, this chapter may be seen as a foundation regarding methodology, evaluation procedure and provisional results for the establishment of an official statewide rating system. Furthermore, a snapshot of the current situation is provided along with identification of areas for improvement for the individual municipalities. For instance, the box plots of figure 3.11 reveal both New Shoreham and North Providence as significantly below average performer regarding environmental aspects. This observation may then be further analyzed by consulting the results visualized per categories and segments in figures 3.8, 3.9 and 3.10, which identify energy and land use to be particular weak spots for both communities, while New Shoreham is also rated exceptionally unfavorably regarding waste.

CHAPTER 4

Urban Water-Energy-Nexus Evaluation

This chapter is devoted to evaluating potential approaches regarding UWE-Nexus thinking for Rhode Island. As discussed in sections 1.1.2 and 1.1.3 nexus applications aim to increase overall resource efficiency and enhance management by accounting for interactions between otherwise separately evaluated segments, which when applied to urban environments is referred to as the UWE-Nexus. For instance, energy demand for water conveyance may be reduced by limiting the ratio of unaccounted for water as pumping then works more efficiently. Furthermore, runoff from impervious surfaces, which are significantly more prominent in urban areas, conveys a higher amount of pollutants to water bodies, resulting in, amongst other things, a higher effort for necessary purification. These examples demonstrate how such considerations might create further incentives and benefits compared to only focusing on each resource separately. Accordingly, possible approaches will be assessed with the overall target to derive quantifiable measures.

First of all the applied methodologies will be explained followed by examinations of the water usage for energy generation and vice versa. Next, urban interactions will be assessed by evaluating implications from the UHI effect and point pollution sources. Lastly, section 4.6 will summarize the significant findings of this chapter.

4.1 General Approach

As mentioned previously, nexus approaches aim to account for all possible interactions between varying resources, which in turn may lead to a more efficient and comprehensive resource management. Furthermore, the specific relationships between individual resources may be highlighted and put into context to the influential parameters of the respective framework. When focusing on dependencies

between water and energy supply, there may be rather concealed aspects next to direct implications, for instance energy demand for conveyance of public water. Those somewhat allusive consequences vary with the respective surroundings and will be evaluated against the urban context of Rhode Island in this paper.

Overall, four different focus areas, which are displayed in figure 4.1, will be assessed regarding possible UWE-Nexus approaches. First of all, the amount of required energy to procure public water in Rhode Island will be analyzed in section 4.3, while the vice versa approach regarding the water demand for thermoelectric power generation will be discussed in section 4.4. Subsequently, section 4.5 features assessments of possible implications due to the respective urban landscape, which includes research for the magnitude of the UHI and pollution sources. While all attained results are closely tied to the state of Rhode Island, they will be put into a larger context to allow broad scoped comparisons.

Figure 4.1. Featured aspects of the UWE-Nexus evaluations (Author's own figure)

4.2 Methodology

The following section will concisely describe the used methodology for assessing the aspects of potential UWE-Nexus approaches in Rhode Island and are generally split into derivation of land surface temperature and the validation thereof, water for energy examinations and methods for assessing point pollution sources.

4.2.1 Derivation of Land Surface Temperature

This section will demonstrate the process which was applied to derive the Land Surface Temperature (LST) from remote sensing imagery in order estimate the extent of the associated UHI. As the effect is usually most strongly pronounced during summer days, a scene from 6th August 2013 recorded at 3:29 pm, which has a extremely low land cloud cover of 0.58 %, was selected for further evaluations from USGS Earth Explorer. [154]

The applied methodology has been derived for the most part from one study about mapping LST from Landsat 8 data with the majority of processing and evaluations being executed with ArcGIS. [155] The chosen procedure is generally referred to as retrieval with unknown emissivity, which is instead derived based of the Normalized Difference Vegetation Index (NDVI) for the scenery. This method assumes that the surface is largely composed of soil and vegetation, which is certainly applicable to the land area of the state, and that the emissivity is linearly dependent on the fraction of vegetation in each pixel of the imagery as displayed in equation 4.5. This method is easily feasible im comparison to other approaches but lacks accuracy as assumptions are made regarding NDVI thresholds and the associated emissivity values. Furthermore, this procedure is rather inaccurate for areas that are primarily composed of soil or contain a high amount of senescent vegetation and can not be applied to surfaces such as water, ice, snow or rocks. [156] Overall, the LST has a strong negative correlation with the amount of

present vegetation, which has traditionally been assessed with the NDVI. However, accounting for other contributing factors, such as solar illumination, atmospheric effects, land use or land cover pattern and topography, has great potential to enhance the accuracy regarding the influence of urban environments on the spatial distribution of temperatures. [157]

Subsequently, the work flow to obtain the LST will be described in detail. First of all, the downloaded image was imported into the program and the NDVI was determined for each pixel or raster grid cell with the integrated image analysis tools. Subsequently, the image was divided into four different categories according to the NDVI thresholds as listed in table 4.2 in order to enable the required processing steps. Accordingly, the scene is differentiated into the four different land cover types of water, soil, soil & vegetation and vegetation, of which only soil and vegetation required computation of an emissivity value for each cell, while the other three were assigned values as stated in the reference. Overall, the emissivity is a prerequisite for deriving the LST out of Landsat 8 imagery by converting the at-sensor temperature as recorded by the Thermal Infrared Sensor (TIRS) of the satellite.

First, the atmospheric spectral radiance according to equation 4.1 with Q_{cal} being the input of the thermal sensor, which may either be Band 10 or Band 11 for Landsat 8 imagery, has to be determined. Furthermore, A_L and M_L are rescaling factors, which were retrieved from the meta data and are listed in table 4.1 and O_i is a correction factor to account for calibration errors. [158] Additionally, more detailed instructions for working with Landsat data are supplied as official USGS resources on-line and as a data users handbook. [159] [160]

$$L\lambda = M_L Q_{cal} + A_L - O_i \quad (4.1)$$

Next, at-sensor temperature is to be obtained via equation 4.2 with the

previously determined spectral radiance as an input. Furthermore, the two thermal constants K_1 and K_2 are required. These values are also listed in the meta data and can be found in table 4.1. Additionally, the result is converted from Kelvin to degree Celsius by subtracting 273.15 K.

$$BT = \frac{K_2}{\ln(\frac{K_1}{L\lambda} + 1)} - 273.15K \quad (4.2)$$

All required constants, which includes rescaling factors, thermal constants and correction values, can be found in table 4.1. With the exception of the correction value, all figures were retrieved from the corresponding meta data of the chosen scenery.

Table 4.1. Constants for chosen Landsat 8 imagery and correction values (Data from Barsi et al. 2014 [158] Earth Explorer metadata 2017 [154])

Constant	Abbreviation	Band 10	Band 11
Multiplicative Rescaling Factor	M_L	0.0003342	0.0003342
Additive Rescaling Factor	A_L	0.1	0.1
Thermal Constant 1	K_1	774.8853	480.8883
Thermal Constant 2	K_2	1321.0789	1201.1442
Correction	O_i	0.29	0.51

The next step is to convert the at-sensor temperature to the LST by applying equation 4.6, which requires the emissivity as an input. The raster cells, that have been identified to be either water, soil or vegetation, were assigned emissivity values according to table 4.2. The remaining cells, which are constituted of a mix of soil and vegetation, require computation of the emissivity according to equations 4.4 and 4.5.

Additionally, equation 4.3 displays the procedure for determining the NDVI for the imagery. This step was executed with the image analysis software tools within ArcGIS instead of manual processing. Therefore, the band inputs had to be

specified, with band 4 holding the information for the visible red spectrum while band 5 incorporates the data regarding the near infrared spectrum. [136]

$$NDVI = \frac{band_5 - band_4}{band_5 + band_4} \quad (4.3)$$

For the raster cells consisting of a mix of both soil and vegetation, the proportion thereof has to be determined with applying equation 4.4. The NDVI values are compared against the chosen thresholds, which were predetermined by the reference methodology and can also be found in table 4.2. While $NDVI_S$ represents the threshold for soil at 0.2, $NDVI_V$ serves as the starting point for vegetation at 0.5.

$$P_v = \frac{NDVI - NDVI_S}{NDVI_V - NDVI_S} \quad (4.4)$$

Next, the proportion between soil and vegetation can be used via equation 4.5 to determine the emissivity for raster cells with both land cover types. Therefore the emissivity values for soil and vegetation, which were predetermined by the referenced methodology and can be found in table 4.2, are required. Furthermore, C_λ serves as an indicator for the surface roughness and has been set to 0.005 in accordance with the reference.

$$\varepsilon_\lambda = \varepsilon_{v\lambda}P_v + \varepsilon_{s\lambda}(1 - P_v) + C_\lambda \quad (4.5)$$

Finally, the LST can be obtained for each raster cell with equation 4.6, which requires the respective emissivity, the determined at-sensor temperature and the initially used thermal band are required as inputs. In order to achieve a coherent distribution of the LST, the priorly split up raster surface, which was necessary to assign or determine the emissivity values, was merged to a single raster dataset. At this point, ε represents the emissivity values of the merged raster, which is now constituted of all four different land cover types.

$$LST = T_S = \frac{BT}{(1 + [\frac{(Q_{cal}BT)}{\rho} \ln \varepsilon])} \quad (4.6)$$

In addition to equation 4.6, formula 4.7 displays the composite value of the required constants such as the Boltzmann constant σ , Planck's constant h and the velocity of light c . Overall, it's recommended to work with the composite value of all three constants instead of the individual ones.

$$\rho = h \frac{c}{\sigma} = 6.626 * 10^{-34} Js \frac{2.998 * 10^8 \frac{m}{s}}{1.38 * 10^{-23} \frac{J}{K}} = 1.438 * 10^{-2} mK \quad (4.7)$$

Table 4.2 displays the set-up of the NDVI thresholds and the respective emissivity values and has been referred to at the appropriate time. The set-up interprets cells with a NDVI value below 0 to be water, while cells higher or equal to 0 but below 0.2 are considered to be soil. Furthermore, if the cell has a NDVI value between or equal to 0.2 and 0.5, it is considered to be a mix of soil and vegetation. Lastly, values above 0.5 were interpreted to be largely constituted of vegetation.

Table 4.2. NDVI thresholds and assigned emissivity values (Data from Avdan & Jovanosvka [155])

Symbol	Land Cover	Range of NDVI Values	Emissivity
$\varepsilon_{w\lambda}$	Water	NDVI < 0	0.991
$\varepsilon_{s\lambda}$	Soil	$0 \leq \text{NDVI} < 0.2$	0.996
ε_{λ}	Mix	$0.2 \leq \text{NDVI} \leq 0.5$	equations 4.4 & 4.5
$\varepsilon_{v\lambda}$	Vegetation	$0.5 < \text{NDVI}$	0.973

The priorly described work flow results in a raster surface with the LST values of the chosen Landsat scene. Figure 4.2 displays the three main processing steps beginning with the original imagery on the very left hand side. The middle part shows the distribution of the NDVI values and watered areas are clearly discernible

with the Scituate reservoir being a prominent inland water body. Additionally, the area around Providence, which is located at the northern end of Narragansett Bay, primarily shows NDVI values of lesser vegetated areas. Accordingly, this area also features the most predominantly elevated LST as displayed in the spatial distribution thereof in the very right hand side of the figure.

Next, the LST values will be validated against records from weather stations and further processing applications will be evaluated, which is described in detail in section 4.2. Furthermore, subsequent evaluations regarding UHI implications for the state of Rhode Island will be carried in out in section 4.5.1.

4.2.2 Validation of obtained LST values

The obtained LST values will be validated against actually recorded readings from weather stations in Rhode Island with the same date of origin than the evaluated Landsat imagery. First of all, there are going to be discrepancies between the two values as LST and air temperature describe different phenomena. Overall, validation is deemed to be an important step to enhance the reliability of results from remote sensing evaluations, thus significantly increasing the applicability thereof. [156]

The determined values will be compared against recorded temperature readings in Rhode Island to put their magnitude into perspective, which goes in accordance to the validation procedure of the used reference methodology. [155] Therefore, data has been extracted from the five NOAA weather stations with available records during the 6th August 2013 when the Landsat scene was taken. Overall, the recording time from the weather stations and the time of record for the remote imagery matches well and does not exceed 30 minutes of difference. Therefore, it was assumed that temporal disparities may be neglected in this case. Additionally, the highest recorded temperature is 24.4 °C from the Providence station. [67]

Figure 4.2. Landsat 8 imagery August 2013, NDVI and land surface temperature (Author's own figure)

Figure 4.3 shows the locations of the weather stations and compares the spatial distribution of derived LST to interpolation from the five stations. In comparison, the derived LST shows a spatial distribution that is well matched to the urban boundaries and developed areas shown in figures 2.1 and 2.23, while the interpolated values display a clearly deviating pattern. However, basic splining was used for interpolation and thus more sophisticated methods may achieve better results. On the other hand, this comparison shows the potential benefits of deriving the LST in comparison to using only weather stations or interpolation thereof for spatial considerations.

Table 4.3. Readings from Rhode Island weather stations for 6th August 2013 (Data from NOAA 2017 [67])

ID	Station	Latitude	Longitude	Time	Temperature in °C
1	Newport State Airport	41.53	-71.28	15:53	22.22
2	North Central State Airport	41.92	-71.49	15:35	22.78
3	Providence	41.72	-71.43	15:51	24.44
4	Kingston 1 NW	41.49	-71.54	15:30	23.33
5	Westerly State Airport	41.35	-71.80	15:53	22.78

Lastly, table 4.4 compares the differently derived results to the recorded measurements. As both band 10 and 11 show records from thermal scanners, either can be used to compute the LST, but band 10 was used due in accordance to the referenced methodology. However, as table 4.4 shows band 11 results are actually much closer to the measurements from the weather stations, but as literature suggests band 11 to have significantly higher calibration error it was not used directly in this thesis. [158] But instead of just using band 10 results, the average for each pixel from both methods was calculated in order to better match the obtained results to the recorded data. Additionally, the averaged raster surface was further edited with a one cell circular mean by applying focal statistics on it in

order to embed each raster cell in its surrounding parameters. This step was taken in order to account for influences e.g. wind and air movements without generalizing the values too drastically.

Figure 4.3. Validation of derived LST via comparison to weather stations and interpolation result (Author's own figure)

For the most part, the calculated LST values are considerably above the recorded data with the highest difference coming from station 3 with 5.68 K. This matches well to the validation procedure of the referenced source, where eleven meteorological stations were used for one study area and the highest difference was 5.8 K. Furthermore, the reference source also experienced exceedingly low temperatures, which were interpreted to be clouds or otherwise exceptional events. Accordingly, the minimum temperature of -2.4 °C, as determined in this thesis, will be considered to be negligible. [155]

Table 4.4. Comparison measurements and LST values in °C at weather stations

Station ID	Measurements	Band 10	Band 11	Both averaged	Focal Mean	Difference in K
1	22.22	26.95	21.58	24.26	24.19	+ 1.97
2	22.78	30.13	24.95	27.54	27.29	+ 4.51
3	24.44	33.58	26.97	30.28	30.30	+ 5.86
4	23.33	24.57	19.31	21.94	22.04	- 1.29
5	22.78	31.37	25.24	28.30	28.13	+ 5.35

In conclusion, the derived LST performs adequately in comparison to the weather stations and matches the deviation as indicated from the referenced methodology. Therefore, the magnitude of potential impacts arising from this spatially distributed temperature will be analyzed in detail in section 4.5.1.

4.2.3 Water Withdrawals for Thermoelectric Power Plants

The USGS water use reports from 2010 and the form EIA-923 have proven to be the most significant resources for assessing the water for energy requirements of the state. However, those two sources are not sufficient for adequately determining measures of withdrawn or consumed water per generated amount of energy. While the latter only includes detailed data for three of the six biggest power plants in Rhode Island, the USGS data shows significant inconsistencies when comparing reports with different years of origin. Therefore, this renders future data collection even more important. However, the achieved results are still sufficient for estimating the situation in Rhode Island.

In general, the United States Geological Survey has been founded as a state agency in 1879 and is tasked with providing high qualitative data for an abundance of fields related to the natural world and the monitoring or mapping thereof. [161] Accordingly, an extensive amount of information is available regarding water and comprehensive reports on water use have been worked out every five years beginning

in 1950. [162] The sources for each iteration include national dataset, state agencies, local authorities and individual surveys, resulting in a certain lack of consistency and varying levels of accuracy. However, the reports still hold invaluable information as there is hardly no other elaboration on a national scale [104]

Overall, data from 1990 to 2010 has been retrieved for the evaluations of section 4.4 with reference to individual states. While the water use composition of nine states was compared for 2010, only Rhode Island was featured in trend analysis beginning in 1990. The USGS reports include both water withdrawal for thermoelectric power plants and the amount of generated electricity, thus allowing for calculation efficiency thereof. While water withdrawals are reported on a daily basis, the electricity generation is referenced over the entire year or equally 365 days. [104] Accordingly, equation 4.8 displays the necessary steps to derive the efficiency of water withdrawal per amount of generated electricity in $\frac{l}{kWh}$. This measure can be used to compare generation technologies to one another and varies primarily with the employed cooling method. Therefore, it will be used in section 4.4 to assess the situation in Rhode Island in detail.

$$\frac{l}{kWh} = \frac{\text{water withdrawals in MGD} * 365 \text{ days} * 3.79 \frac{l}{gal}}{\text{generated electricity in GWh}} \quad (4.8)$$

Additionally, the measure of water withdrawal per amount of generated was also determined by scrutinizing the major power plants of the states. The necessary data is available on-line and is collected by annual surveys that are conducted by the EIA, which is tasked with providing statistical information associated with the entire energy sector of the USA. [163] Overall, there are two forms which have been especially useful for the elaborations of section 4.4. While form EIA-860 has been used to obtain information about the cooling technology for each plant, form EIA-923 contains annual and monthly data regarding associated water withdrawal.

[164] [165] However, both fail to include all power plants of Rhode Island, thus limiting the possible analyses. Furthermore, the reported data monthly of form EIA-923 shows apparent inconsistencies and gaps before 2013. Therefore, the trend analysis of water requirements of the individual power plants had to be limited to the period of 2013 to 2015.

4.2.4 Spatial Analysis of Pollution Sources

The assessments regarding point pollution sources of section 4.5.2 largely feature spatial analysis with ArcGIS. Overall, the three different elements of major roads, impervious surfaces and the location of TRI facilities were evaluated against the extent of sole source aquifers, wellhead protection and surface water protection areas. All of the aforementioned features were retrieved from RIGIS with the exception of TRI data. [64] [124]

While RIGIS supplied data is optimized for usage within the state of Rhode Island, the TRI facilities require a higher amount of preparatory work. First of all, sums per depository categories of air, water, underground and others were computed, of which only air and water were retained as they account for virtually all toxic releases in 2015. Furthermore, only the respective locations with recorded pollutants were mapped according to the listed coordinates, resulting in a reduction from 88 official facilities of the state to 62.

Major roads were retrieved with the road classification of two from the RIDOT roads dataset, as published in RIGIS in February 2016. The distribution of impervious surfaces was also obtained from RIGIS and dates back to 2013. All of the priorly mentioned featured were allocated to the spatial extent of the areas of interest, of which the surface water protection areas are the oldest with an origin date from 2002. Additionally, the average distance to TRI air or surface water release locations was determined as an euclidean distance raster and then

evaluated with zonal statistics for the respective areas. Lastly, statewide figures were computed to provide a basis of comparison and all values were normalized to the respective area.

4.3 Energy for Water

This section will examine the current state of energy requirements for water procurement in the state of Rhode Island. As mentioned in section 2.8.2, there are almost 500 individual companies involved in the provision of public water. These range significantly regarding the amount of annually provided water and customers. As a result, any assessments concerning this matter are extremely complex and extensive due to the required effort for appropriate data gathering. Unfortunately, no comprehensive data reports regarding energy demand for water procurement in Rhode Island existed during the research phase for this paper. However, some key aspects will be explored by the means of literature and suggestions for further research objectives will be worked out.

To begin with, figure 4.4 depicts water supply system, end use and wastewater system as the three main components of urban water systems and also displays the associated connections with energy. Literally each component requires an energy input and only the wastewater system may also generate electricity, for instance, via power generation with methane. Next to centralized water supply systems, which require energy for transfer of raw water and treatment and distribution thereof, there may also be other local sources, such as decentralized rain water harvesting, with differing energy requirements. Large scale operations as managed by public utilities may have different energy intensities depending on climate, topography, use patterns and operational efficiency. [33] Next, the water end use, which includes residential, commercial or industrial, also has an influence on energy intensity. For instance, efficiency of heating appliances and personal habits like

choice of shower temperature and duration affect the amount of required energy considerably. [166] Lastly, wastewater systems require energy for collection, transfer and treatment, with the efficiency depending on level of purification, pumping and terrain amongst other factors. Additionally, energy performance may be enhanced by including anaerobic digestion to operate biogas generators for electricity. [167] In addition, the category of externalities covers resources and effort for construction and maintenance of facilities and associated infrastructure. Overall, energy for water assessments have so far been hindered by a large number of dependencies, lack of quantifiable data and missing frameworks and analytical tools, which highlights the importance of potential future research areas. [168]

Adapted from (Kenway & Lam 2015)

Figure 4.4. Overview of urban water components and resource flows (Adapted from Kenway & Lam 2015 [168])

Aspects and parameters regarding energy efficiency of water supply and wastewater systems will be discussed in more detail, as these areas are best suited to describe entire cities or even broader applications as a whole. Overall, the local conditions and frameworks may differ greatly for each city, requiring in depth

analysis with extensive full life cycle considerations for the respective situation to achieve the best possible results. [32] This observation is further emphasized by the vast differences between individual communities, as for instance, water procurement in Melbourne requires only $10 \frac{kWh}{person \ a}$ while this value increases to $372 \frac{kWh}{person \ a}$ in San Diego. This difference is largely caused by the employed technologies as Melbourne is able to utilize gravity for conveyance while San Diego has to use inter-basin water transfer systems with a high energy demand. [33] However, even though there is a high range between these extreme cases, general trends and developments can be worked out.

Accordingly, figure 4.5 displays the qualitative influence of several parameters on the energy intensity of urban water systems as observed in a study featuring the cities of Nantes, Turin, Oslo and Toronto. [32] Given the relatively small sample size of the study, the reported result will be compared against a study with 30 featured communities, which unfortunately does not explore the connections between energy and water in depth. [33]

Figure 4.5. Impact of ten parameters on energy intensity of water systems (Author's own figure, data from Venkatesh et al. 2014 [32])

Overall, the four different categories of geography, technology, socioeconomics and climate have been determined to influence energy requirements for water procurement in the four previously mentioned cities. While technology has been attributed with the most factors, climate has only received one, rendering it the least complex influential aspect. Climate is deemed to have a significant influence on water availability, which induces increased energy demand if the overall supply is scarce and more distant or alternative sources have to be used. The same context applies to the geographic attribute of distance, as longer conveyance processes require more energy. Additionally, a diversely shaped topography with steep contours leads to laborious traversal, resulting in a higher energy demand. This is especially true when water or waste water has to be pumped uphill, thus preventing the usage of gravity-fed conveyance. In addition, energy demand for pumping also increases if groundwater is the predominantly used water source. Socio-economic aspects, such as water quality, network size and use or consumption, also influence energy intensity. A higher water quality of the respective source, which is heavily influenced by the activity around the intake locations, enables the utilization of less intricate treatment procedures. This reduces the associated amount of energy. The same approach applies to water usage with industrial consumption generally requiring more effort regarding waste water treatment and consequently more energy. Additionally, a larger size of the associated network entails a higher energy demand as the conveyance distance can be assumed to increase with it. Technology features four individual parameters that are largely related to treatment processes or age of appliances. While anaerobic digestion releases methane, which may be used as a fuel for electricity generation, the process features energy intensive aeration and thus is less favorable than trickling filters. Furthermore, sanitation of drinking water with chlorine is less energy intensive than the rather modern method of ozonation

with UV-lighting technologies. Accordingly, both older treatment and systems conditions have been found to lead to a lessened energy demand. [32] However, increasing operational efficiency, which generally involves the deployment of novel and new appliances or approaches, has been determined as a prime opportunity for reducing the overall energy demand of water supply systems. [33] Thus, a more up-to-date condition of the overall infrastructure should still result in a more efficient operation and a reduced energy intensity.

Accordingly, the prior discussed aspects will be transferred to Rhode Island in order to work out a qualitative analysis regarding the energy efficiency of public water supply and waste water treatment. Therefore, table 4.5 lists the categories, for which an adequate amount of data and information was available, and the influence on energy intensity along with a brief description. First of all, Rhode Island's topography ranges from sea level to 247 m above and lacks difficult to traverse topography, resulting in a potentially low energy demand for water conveyance. [62] Additionally, about 85% of the overall public demand is sourced from surface water bodies, which requires less energy than groundwater procurement. [103] Both the conveyance distance and network size are utterly limited, due to the small land area and maximum extent of 48 miles from North to South, indicating a comparably low energy demand for these aspects. [62] In addition, both the high water availability and quality thereof, which significantly reduces the required treatment of raw water, point towards a low energy intensity. [103] While residential demand accounts for about 30% of water usage, industrial consumption is almost negligible with only 2% overall. This in turn, reduces the required effort for the corresponding waste water treatment, thus further denoting a low energy intensity. [104] Furthermore, municipal treatment facilities amount to 130 MGD, of which the majority of roughly 77% utilizes chlorination instead of the more energy intensive ozonation. [105] On

the other hand, the urbanized areas of Rhode Island feature some of the oldest water supply infrastructure assets in comparison to the entire USA. Even though suburban systems have been installed rather recently beginning around 1950, this aspect still strongly points towards an unfavorable energy efficiency. [103]

Table 4.5. Evaluation of energy efficiency for water supply in RI

Category	Description	Influence
Topography	sea level to 247 meters above	positive [62]
Water source	85% of drinking water from surface	positive [103]
Distance	Compact state, small land area	positive [62]
Water availability	Sufficient supply	positive [103]
Treatment process	Majority treated with chlorination	positive [105]
Water quality	High quality drinking water supplies	positive [103]
Network size	Limited extent	positive [62]
Use & consumption	High share of residential use	positive [104]
System condition	One of the oldest systems nationwide	negative [103]

Overall, as eight of nine aspects indicate a favorable situation, the procurement of public water and the treatment of waste water potentially entail a below average energy demand. Accordingly, the respective facilities and services should exhibit a relatively low energy intensity in comparison to other cities or regions with more unfavorable conditions.

4.4 Water for Energy

Contrary to the preceding section, where energy demand for water procurement has been discussed, there are promising data resources available for researching the water demand regarding the generation of electricity in Rhode Island. However, even though the three sectors of electricity, thermal and transportation are virtually equal for the overall energy demand in Rhode Island, generation of electricity and the according water requirements will be the focus of subsequent evaluations.

Additionally, the applied methodology and data issues are discussed in section 4.2.3.

First of all, in order to provide an adequate frame of reference, water usage in Rhode Island and its development since 1990 will be discussed in detail by using data from the 5-year estimations as carried out by the USGS. Their reports are available statewide beginning in 1950, with county level data being published since 1985. They are intended to provide a comprehensive accumulation of information to enable research on national and regional trends of water withdrawal and usage. Accordingly, figure 4.6 displays the total water usage and the respective shares by use category along with water withdrawals for energy generation for all states in New England, the USA, California and Florida with using 2010 data. [104]

Figure 4.6. Total water use in MGD 2010, share by eight water usage categories and withdrawals for energy generation for selected states (Author's own figure, data from USGS 2014 [104])

There are clearly discernible regional differences, as for instance all New England states, with the exception of Maine where industrial usage accounts for the highest share, water for thermoelectric power generation is the most significant

category with public supply ranking second. This results in a clearly different distribution in New England in comparison to the entire USA, where water for energy generation remains the biggest sector but irrigation, which is heavily tied to agricultural activity, accounts for a much higher share overall. In conclusion, water usage may differ substantially by state or region and thus knowledge about the individual situation is crucial for determining advisable future steps and measures regarding water supply. For instance, researching and implementing more efficient irrigation technologies or procedures is likely to yield more benefits in California or Florida than in any of the states of New England. [104]

Furthermore, Rhode Island exhibits the lowest generation efficiency regarding water withdrawals with $283 \frac{l}{kWh}$. However, this measure can be considered to be unreliable, as literature suggests much lower values in general and about $52.6 \frac{l}{kWh}$ of total withdrawal as a worst case scenario for natural gas power plants. As will be described in more detail later on, all major power plants of Rhode Island utilize natural gas with a combined cycle technology, which performs favorably regarding water requirements per generated electricity in comparison to other technologies. Accordingly, table 4.6 lists the requirements for chosen generation methods differentiated into closed-loop cooling, which generally deploys cooling towers, and open-loop cooling. In comparison, rather conventional fuels, such as nuclear or coal, have a considerably higher water demand than natural gas, which is only inferior to the renewable technologies of solar and wind in that regard. Additionally, the deployed cooling technology is highly influential. This is emphasized by the fact that natural gas power plants with recirculation or closed-loop cooling can be estimated to require only $1.6 \frac{l}{kWh}$ in total, while open-loop or once through procedures may amount up to $52.6 \frac{l}{kWh}$. Furthermore, consumptive usage, which includes water being temporally lost due to evaporation, is highest

when deploying closed-loop cooling. [23] [99] In general, consumptive water use of the power sector in the USA amounts to 3,310 MGD or about 2.5% of total withdrawals, indicating consumption to be the less influential category besides the sheer amount of withdrawals. [169]

Table 4.6. Water withdrawal and consumption for chosen generation technologies (Data from UN 2012 [23])

Technology figures in $\frac{l}{kWh}$	Closed-Loop		Open-Loop	
	With- drawal	Consum- ption	With- drawal	Consum- ption
Nuclear	3.8	2.6	160.9	1.5
Coal	1.9	1.9	132.5	1.1
Solar photovoltaic	negligible	negligible	negligible	negligible
Wind	negligible	negligible	negligible	negligible
Natural gas combined cycle	0.9	0.7	52.2	0.4
Natural gas combustion turbine	negligible	negligible	negligible	negligible

The suitability of USGS data for evaluating water for energy demands has to be further questioned as the energy intensity ranges considerably for different observation years as displayed in figure 4.7. For instance, the water withdrawals for thermoelectric plants range from almost $1,400 \frac{l}{kWh}$ in 1995 to negligible figures in 2000 and 2005. Furthermore, none of the determined values are considerably close to the worst case withdrawal of $52.6 \frac{l}{kWh}$, as suggested by literature. However, evaluating water requirements for thermoelectric power generation is highly important in Rhode Island, as it has consistently been the major demand sector since 1990 and has never accounted for less than 62% of the total withdrawal. In conclusion, other resources besides USGS data need to be consulted for adequately assessing water demand for energy generation. [104] [23]

So, as the USGS figures are not well suited to assess water withdrawals per

Figure 4.7. Total water use in MGD from 1990 to 2010, share by eight categories for RI and energy intensity (Author's own figure, data from USGS 2017 [162])

energy generations, detailed examinations of the state's major power plants, the associated power output and water withdrawals will be carried out. Therefore, EIA resources, namely the two forms EIA-860 and EIA-923, will be scrutinized, for which the approach and methods are stated in section 4.2.3. Additionally, a detailed overview of Rhode Island's energy sector and generation capacity has been discussed in section 2.8.1, of which the six biggest natural gas power plants will now be examined in detail. While table 4.7 lists all of those six facilities, table 4.8 contains detailed data regarding cooling technology for the power plants listed in form EIA-860. The state's largest power plant is the Rhode Island State Energy Center in Johnston with a generation capacity of 539 MW, followed by the Manchester Street facility in Providence with 475.5 MW. The Pawtucket Power Associates plant is the smallest of the featured plants with a capacity of only 60 MW. Additionally, all but the Tiverton Power Plant are located in the county of Providence, indicating a noteworthy concentration of infrastructure in this area.

Table 4.7. Six biggest power plants in Rhode Island (Data from EIA 2017 [99])

Plant Code	Plant Name	City	County	Total MW
55107	Rhode Island State Energy Center	Johnston	Providence	539
3236	Manchester Street	Providence	Providence	475.5
55048	Tiverton Power Plant	Tiverton	Newport	268
51030	Ocean State Power	Harrisville	Providence	218.6
54324	Ocean State Power II	Harrisville	Providence	218.6
54056	Pawtucket Power Associates	Pawtucket	Providence	60

Those six power plants amount to a total generation capacity of 1,779.2 MW, which accounts for 90.5% of both the capacity from power plants and from distributed generation. As a result, evaluating the six chosen facilities delivers results for almost the entire state’s electricity generation capability. This is further emphasized by the monthly generation time-line, which is displayed in figure 4.8 for the year 2015. As the difference between the sum of the chosen power plants and the statewide generation is nearly negligible, besides for the month of November, results from evaluating those six facilities can be considered to reliably serve as a statewide characterization. Additionally, the generation time-line shows a distinct peak during the months of May to August, while there is considerably less demand during the winter months. As a result, the highest water withdrawals for cooling are expected to occur in the summertime, as it is the period of overall peak electricity generation. [96] [98]

As mentioned previously, all of the six biggest power plants of Rhode Island are fueled with natural gas and utilize a combined cycle technology. This refers to the continuing process of burning fuel to provide electricity, while exhaust heat is used to generate steam for utilization in turbines to increase efficiency and the

Figure 4.8. Monthly generation for the six biggest power plants in Rhode Island plus statewide generation for 2015 (Author's own figure, data from EIA 2016 [98])

subsequent cooling of the steam to retrieve and reuse the inherent water. [170] Overall, natural gas power plants promise a more beneficial operation regarding emissions of greenhouse gases, in comparison to conventional fuels such as coal. [171] Additionally, they generally require the least amount of water for cooling next to renewable technologies, which often do not have an operational water demand. However, the deployed cooling technology has been determined to be the decisive factor for adequately assessing the overall water demand of power plants over the fuel type alone. [172] Accordingly, the deployed technology of the facilities in Rhode Island has to be taken into account. Unfortunately, only three of the six mentioned power plants are featured in form EIA-860 and no other viable source was found at this point of time. As a result, only half of the power plants, which are displayed in table 4.8 along with key information, could be considered for further evaluations.

The three power plants each have different cooling technologies, resulting in vastly varying associated water demands. Naturally, the Tiverton power plant has a virtually negligible demand, as it uses dry air technology. The Rhode Island State Energy Center (RISEC) facility also performs favorably with a maximum intake

Table 4.8. Cooling system information for the three biggest power plants in RI (Data from EIA 2016 [164])

Plant Name	Rhode Island State Energy Center	Tiverton Power Plant	Manchester Street Power Plant
Acronym	RISEC	TPP	MS
Inservice year	2002	2000	1995
Capacity	539 MW	475.5 MW	268 MW
Cooling type	Recirculating with natural draft cooling towers	Dry air	Once through without cooling ponds
Cooling water source	Cranston Water Pollution Control Facility	-	Providence River
Discharge	Plant cooling system	-	Providence River
Water source	Plant discharge water	-	Surface water
Water type	Reclaimed water	-	Brackish water
Intake rate at 100%	3,007 $\frac{\text{gallons}}{\text{minute}}$	-	181,777 $\frac{\text{gallons}}{\text{minute}}$
Water for energy	1,25 $\frac{\text{l}}{\text{kWh}}$	-	154,04 $\frac{\text{l}}{\text{kWh}}$

rate of 3,007 $\frac{\text{gallons}}{\text{minute}}$. The recirculation along with natural draft cooling towers lead to a significantly reduced maximum intake in comparison to the Manchester Street power plant. This facility lacks recirculation of cooling water and uses cooling ponds, resulting in a maximum intake rate of 181,777 $\frac{\text{gallons}}{\text{minute}}$. The significant difference between the two technologies becomes even more apparent when the associated energy production is taken into account. Peak generation and thus maximum cooling water intake over a whole hour leads to a water requirement of 1,25 $\frac{\text{l}}{\text{kWh}}$ for the RISEC facility and 154,04 $\frac{\text{l}}{\text{kWh}}$ for the Manchester Street plant. This dramatically higher water demand per amount of generated electricity indicates that the latter facility is more likely influence local water systems more severely.

Furthermore, assessing these two facilities in more detail should lead to a better understanding of the water demand characteristics. Accordingly, more

detailed examinations regarding seasonal development have been carried out with the monthly specifications for electricity generation and water withdrawal from form EIA-923. As there are occasional recording gaps, the data was averaged over three years beginning in 2013 to achieve more consistent results and to reduce the influence of outliers.

Table 4.9. Header abbreviations and units for table 4.10

Short	Detail	Unit
Power	Generated power for entire power plant	MWh
Water	Withdrawn water for cooling	million gallons
Temp	Increase in average temperature	Kelvin
WFE	Water withdrawal for energy generation	$\frac{l}{kWh}$

Table 4.10, for which the abbreviations and units are listed in table 4.9, shows the three year averaged values for generated power, cooling water withdrawal, difference between mean water intake and discharge temperature and the withdrawal per generated electricity. Additionally, the monthly minimum and maximum values are also displayed to provide further reference points.

Table 4.10. Three year averages for RISEC and Manchester Street facilities (Data from EIA 2016 [165])

Power Plant	RISEC			Manchester Street		
Category	Minimum	Maximum	Average	Minimum	Maximum	Average
Power	39,563	203,027	105,908	42,862	169,396	110,010
Water	16.2	71.3	39.3	4,762.9	7,577.7	6,829.2
Temp	18.0	35.0	23.6	4.3	17.4	7.5
WFE	0.97	2.41	1.50	161.56	589.06	301.32

Accordingly, figure 4.9 displays the monthly trends for both power plants by plotting the monthly values in relation to the maximum values of each variable. This approach allows to determine coherent or diverging development between the

featured datasets and allows for comparison of seasonal variability. Overall, there are clearly discernible seasonal differences, as for instance the power generation and the cooling water withdrawal both tend to peak during the summer months. However, the two remaining measures show different behavior and are at rather average levels during the summer. Furthermore, while the mean difference between intake and discharge temperature of the cooling water peaks only in the spring, the efficiency of water withdrawal for energy generation is at low levels both during the spring and autumn. This indicates an especially unfavorable usage pattern outside of summer months as more water is required per generated electricity. Additionally it recedes to average values during the winter months. The later is largely due to a bigger relative decrease of generated energy in comparison to withdrawn water, resulting in a higher cooling water demand if normalized to $\frac{l}{kWh}$.

Figure 4.9. Relative, monthly distribution of three year averages for Rhode Island's two biggest power plants (Author's own figure, data from EIA 2016 [165])

In general both facilities exhibit a similar development regarding the previously discussed features. However, the main difference between the two plants is the rather steady level of cooling water withdrawal, which is higher than 80% relative to the maximum value for most of the year but in February, at Manchester Street. As a

result, the development of power output and water withdrawal diverges significantly at the Manchester Street plant over the course of the year, leading to a greatly enhanced cooling efficiency during the summer. This observation does not apply to the RISEC facility, where electricity generation and water withdrawal develop almost entirely coherently, resulting in less diverging trends in general.

Overall, researching water requirements for energy generation may yield great benefits in Rhode Island, as this sector has regularly been the the highest water usage category of the state. However, a lack of coherent data makes said evaluations somewhat unreliable at the moment. While, USGS data shows drastic inconsistencies for the different reporting years, EIA supplied figures do not lead to realistic values in $\frac{l}{kWh}$ in comparison to literature references. Accordingly, the quality of data has been determined as a major area for improvement to enable comprehensive assessments, which has been deemed to be especially applicable to natural gas fired power plants with combined cycle technologies. [172]

However, the evaluation of this section are sufficient to indicate promising areas for future research. For instance, evaluations of the six biggest power plants may serve as statewide characterizations, leading to a less excessive data gathering process. Additionally, both the electricity generation and the associated water withdrawals are at high levels during the summer time, thus further intensifying stress on the respective water sources and the aquatic, natural environment.

4.5 Urban Interactions

This section will assess potential implications on energy and water provision due to pressures posed by urbanized areas in Rhode Island. This will involve examining the extent of the UHI effect via evaluation of the derived LST values and scrutiny of point pollution sources. Both aspects will be spatially related to public supply infrastructure to assess the magnitude of possible impacts.

4.5.1 Urban Heat Island Implications

As discussed in section 1.1.3 urban environments simultaneously put pressure on the associated environment and alter ambient conditions within their respective confinements. As a result, they form an intricate network of interactions and conditions such as elevated surface and air temperatures via the UHI effect. Assessing its extent and consequences for the state of Rhode Island is the main objective for this chapter. Therefore, the UHI and its spatial distribution has to be determined first. While section 4.2.1 discusses the applied methodology, the mapped results, which can be seen in figure 4.2 on page 135, and the validation procedure, the following examinations focus on characterizing the effect and the associated implications.

First of all, the magnitude of the UHI is most concisely described by comparing the average temperatures of corresponding urban and rural areas to one another. This has been done by averaging the computed LST for the urban areas declared by the USCB and the remaining rural territory, which results in a 4.3 K higher temperature for urban areas. Given that the featured scene, from which the LST was recorded, is dated to mid August, thermal complacency is already challenged by generally high temperatures, which is even more relevant to cities and towns due to the UHI. Furthermore, elevated temperatures entail an abundance of other detrimental influences, which will be discussed in more detail in the closing remarks of this section. However, as the featured LST determination procedure is rather basic and lacks the sophistication of advanced and increasingly complex methods, there are some dissonant data points. For instance, the overall minimum temperature is -1.62° , which is far too low for ambient summertime conditions. The results have been used regardless, as the large scale average values are acceptably close to actually recorded readings of NOAA weather stations and to the expected accuracy of the reference methodology, as discussed in more detail in section 4.2.2.

Table 4.11. Minimum, maximum, mean and standard deviation for statewide, urban & rural LST derived from Landsat imagery

	Land Surface Temperature in °C			
Region	Min	Max	Mean	STD
Statewide	-1.62	42.50	19.01	3.41
Urban	-1.62	42.50	21.65	3.69
Rural	12.61	35.07	17.35	1.80

Next to categorizing the UHI solely into urban and rural measures, more detailed analysis allow for better understanding and characterization of the phenomena in application to Rhode Island. Accordingly, table 4.12 shows the minimum, maximum, mean and standard deviation for the LST of the individual Land Use Land Cover classes. As expected, 100 coded areas, which are generally associated with developed space, have both the highest maximum and mean temperature, indicating a particularly locally pronounced UHI influence. Furthermore, categories associated with open or natural environments such as brushland, forest, water and wetland show significantly decreased temperature values, indicating those categories to be associated with lessened LST values in general and thus a potential for mitigating high temperatures. Those findings go along with current literature on UHI mitigation, which state the enlargement of vegetated areas and open water bodies to be among the most effective measures for abatement of high temperatures in cities. Naturally, the high number of variables and required resources makes excessive amounts of effort necessary to conclude the most favorable course of action in each specific case.

As a result, localized UHI research efforts may not be initiated easily due the required amount of effort and somewhat elusively projected or difficultly quantified benefits. Accordingly, being able to associate the LST distribution with more directly applicable measures may yield further incentives for research and mitigation

Table 4.12. Minimum, maximum, mean and standard deviation for by LULC category derived from Landsat imagery

Land Use Land Cover		Land Surface Temperature in °C			
Code	Type	Min	Max	Mean	STD
100	Developed	-1.62	42.50	22.46	3.57
200	Agriculture	15.02	31.88	20.43	2.35
300	Brushland	14.08	32.36	18.81	2.04
400	Forest	13.61	32.84	17.16	1.58
500	Water	12.61	31.74	17.95	1.39
600	Wetland	14.23	27.50	18.29	1.63
700	Other	13.57	31.89	21.41	2.91

efforts. For instance, determining the share of residents affected by those high temperatures allows for estimating further consequences such as water demand next to direct implications e.g. heat stress. Therefore, the magnitude of people living under certain temperature thresholds in Rhode Island has been determined in order to provide a concise measure of the potentially affected population. Furthermore, the distribution has been allocated to the individual communities and a statewide average has been computed. The share of each municipality's affected population in 5 K intervals beginning at 20 °C is displayed in figure 4.10, sorted in relation to the statewide maximum population density.

Figure 4.10 clearly shows an opposing trend between the share of residents living in areas with 25 °C and above and the population density, indicating that the most densely populated communities tend to more severely affected by high temperatures. This observation is even more emphasized by the fact that the municipalities with the four highest population density values also show the highest mean LST values. However, there are some exceptions from this trend. For instance, Woonsocket and West Warwick are the 5th and 6th most densely populated communities but show a significant decrease in affected population and average temperatures. The

Figure 4.10. Municipal evaluation of people living in areas with 5 K LST thresholds along with ratios of urbanized population, population density and mean LST (Author's own figure)

connection between settlement density and LST seems to weaken eventually, as the communities with less than 10% of the maximum value, which is equivalent to roughly $1,500 \frac{\text{people}}{\text{mi}^2}$, show a variable development in both the respective share of affected people and the mean LST values. However, beginning with the town of Burrillville, the ratio of urbanized inhabitants and the associated temperature thresholds decrease significantly. Furthermore, this area almost without exception incorporates all LST values between 16 and 18 °C, indicating drastically cooler ambient conditions in the communities with a rather rural character.

In conclusion, there seems to be a strong connection between population density and LST, with urban versus rural community set-up being a less significant driver overall. Altogether, elevated temperatures due to the UHI effect may potentially affect the majority of Rhode Island's population, as the state's average LST has

been determined to be about 19 °C while over 80% of the inhabitants live in areas with 20 °C or more and about 48% in areas with 25 °C or more. This discrepancy indicates potentially high benefits of future UHI related research for the state of Rhode Island.

As displayed in table 4.12 land cover may have a significant influence on the corresponding ambient temperature with developed areas generally showing the highest values. Therefore, the connection between the share of developed land to total area and LST is shown in figure 4.11, which is organized in accordance to figure 4.10. In general, the ratio of the developed area decreases according to the population density, as the most densely populated communities naturally also exhibit a high share of development. However, Foster and New Shoreham are two of the most spread out communities but feature a high share of developed land. At the same time, these two towns exhibit a significantly higher mean LST than the communities with similar population densities, which indicates land use to be a relevant driver of ambient temperatures.

In general, figure 4.11 displays an obvious correlation between land use and LST, as the highest temperature values occur in cities with a high share of development. On the other hand, the lowest overall LST values can be found in communities with a high share of forested areas or other LULC categories. Furthermore, the three municipalities of Central Falls, Providence and Pawtucket have both the highest values regarding developed land and are overall the only three communities with mean LST values above 26 °C. Foster is located at the other end of the spectrum with the highest share of forested land and also has the lowest mean LST overall.

The observed correlation between the share of developed or forested area may to a certain degree stem from the derivation method, which evaluates the spatial distribution of a NDVI raster dataset and thus utilizes differences in distribution

Figure 4.11. Municipal evaluation of land cover type and corresponding LST derived from Landsat imagery (Author's own figure)

of vegetation. On the other hand, state of the art mitigation approaches include raising the amount of urban green and implementing vegetated roofs, amongst other techniques, to lessen the magnitude of the associated UHI. This further emphasizes the correlation between the increase of forested or the decrease of developed areas and the observable diminishing LST values. [173] Overall, the priorly discussed findings may benefit greatly from evaluating additional cases while taking differing seasonality into account.

Additionally, there are plenty of incentives to evaluate the potential degree of the UHI effect in Rhode Island even further, as elevated temperatures may entail an abundance of detrimental consequences. Next to rather obvious connections, such as increased energy demand for cooling of indoor spaces or rising heat-stress induced mortality, there are even more far reaching implications like increased smog formation and a subsequently deteriorating air quality. [29] [174] Potentially all

areas of public life may be affected and the impacts on water resources have been determined to be highly diverse. The impacts range, for example, from an increased residential demand to impaired quality of water bodies and easier transmission of waterborne pathogens, such as salmonella or cholera. [175] [176] [177]

Accordingly, in order to further highlight the potential gains of UHI mitigation, the associated decrease on summertime average water demand will be evaluated. Therefore, significant findings for the city of Phoenix, for which the associated UHI and its implications have been thoroughly researched, will be transferred to Rhode Island. For instance, it has been determined that each additional increase of 1 °F causes an overall raised water demand by 0.8%, or 1.44% per 1 °C, for the entire city of Phoenix in June. [178] Assuming that this correlation can be transferred to Rhode Island and applied to the statewide daily summertime water demand of 210.47 MGD, an overall decrease of 1 °C may result in lower demand of only 207.44 MGD. However, the influence of UHI mitigation can be more precisely assessed when taking the displayed conditions of figure 4.10 and table 4.11 into account.

Accordingly, a best case scenario has been worked out under the assumption that all municipal average temperatures mirror the rural average value of 17.35 °C, thus completely mitigating the UHI effect. Therefore, the difference of average LST per community to the rural mean value and the corresponding decrease in summer water demand were computed. The results of this approach are visualized in figure 4.12. Overall, the statewide summer demand can be reduced from 210.47 MGD to 193.70 MGD, which equals an reduction by about 8% in total.

These reductions are of a high significance, as management of increasing summer peak water demand has been identified as a major challenge for the water supply of Rhode Island. Additionally, water scarcity and stress on natural water

Figure 4.12. Potential water demand reduction by UHI mitigation per community (Author's own figure)

bodies is already a significant influence factor during the summer, rendering further reduction efforts highly important. Furthermore, the PWSB supplies a majority of municipalities around Providence, which may benefit even more from UHI mitigation as they tend to exhibit extremely high temperatures, and rely heavily on the Scituate Reservoir. In fact, the four municipalities that are directly associated with the PWSB, namely Johnston, Cranston, North Providence and Providence account for 90.59 MGD of the summertime demand, which can be reduced to just 80.89 MGD. As a result, the stress on the Scituate Reservoir may be significantly reduced and the associated withdrawal may even fall below the estimated safe yield of 83 MGD. [103]

4.5.2 Point Pollution Sources

Lastly, in this section impacts of point pollution sources in the context of an Urban-Water-Energy-Nexus approach, such as increased effort or energy demand

for water treatment due to heightened levels of pollutants and emissions, will be evaluated. For the most part, this will include spatial evaluation of TRI facilities in relation to significant areas of the public water supply infrastructure. Additionally, land use features, e.g. impervious surface and major roads, will be allocated to the aforementioned areas.

As of 2015, the TRI lists 88 facilities for Rhode Island, of which 62 reported emissions in that year. Overall, they combine for a total 293,932 lb of potentially toxic releases. This amount is further distributed to depository categories such as underground, other, air and surface water with the latter two accounting for virtually all of the recorded releases. Furthermore, toxic air emitters make up 99.75% of all pollutants, rendering the most significant category overall.

Figure 4.13 displays the location of the aforementioned 62 TRI facilities, which are differentiated into air and water releases and marked in relation to the most emitting case. In addition, significant protection areas such as sole source aquifers, wellhead protection and surface water protection areas are shown as well. While the latter are largely related to public water supply, the first two are relevant for self supply, which largely relies on wells for communities or individual households.

Overall, the TRI facilities are predominantly clustered in close vicinity around Providence and a few can also be found in the rather remote rural areas. However, the relatively highest emitters are located outside of the aforementioned cluster. Regarding air releases, the most significant pollution source, which is responsible for 43.81% of all pollutants and belongs to Ocean State Power, is located in the north western area close to the Massachusetts state border. In addition, a facility belonging to Newport Biodiesel is the second highest emitter with 20.86% of all air releases and can be found in the south western Aquidneck Island region. Regarding toxic water releases, which are significantly lower in comparison with only 732 lb

in total, the most significant pollution source is a lumber processing plant located south of Providence and accounts for 68.94% of all respective releases. Additionally, a company called Toray Plastics is the second highest emitter with 22.98% regarding surface water pollutants and is located in the same area as the priorly discussed facility. Even though the amount of toxic compounds released in water bodies is relatively low in comparison, the two most significant facilities are located in close proximity to one another, rendering more detailed investigations advisable. Overall, the spread of toxic air releases is significantly influenced by wind direction, which may vary greatly on a daily basis in Rhode Island. Due to this lack of predominant wind direction, trends regarding the dispersion of these pollutants can not be formulated with a high level of certainty. However, as most applicable facilities are clustered around of Providence, a high share of inhabitants may be affected by the released substances, highlighting the importance of ongoing monitoring and research. [124] [70]

In addition, figure 4.13 also displays the distribution of major roads, for instance US routes and connectors, and impervious surfaces, which have been identified to cause an abundance of detrimental consequences especially in relation to water quality. In general, about 12.94 % of the state's land area is composed of impervious surface with a distinct agglomeration thereof at the northern end of Narragansett Bay around Providence. However, the concentration of this specific land cover type tends to diminish further inland, where most of the relevant protection areas are located. The same trend can be observed for major traffic ways, which tend to be further dispersed with increasing distance from the coast and specifically the city of Providence. Overall, this should result in decreasing stress or detrimental consequences on the protection areas due to urbanized areas with increasing remoteness. This is further emphasized by the fact, that runoff

Figure 4.13. Map of pollution sources and protection areas related to public water supply (Author's own figure, data from RIGIS 2017 [64] TRI 2017 [124])

from impervious surfaces and transportation features has been determined to be a significant threat regarding the health of Rhode Island's water resources. [103] On a first glance, the south western area of the state features the least amount of impervious surfaces, major roads and TRI facilities, potentially resulting in a lessened amount of negative environmental consequences.

Next to visual observations, table 4.13 provides evaluations for all three relevant areas and a statewide comparison based on the urban development factors displayed

Table 4.13. Statewide evaluation of pollution sources and protection areas related to public water supply

Category	Statewide	Sole source aquifer	Wellhead protection area	Surface water protection area
Area in mi^2	1,033.8	301.4	157.3	146.5
Ratio of impervious surface in %	12.94%	6.32%	29.39%	6.35%
Major streets per area in $\frac{mi}{mi^2}$	0.701	0.439	1.005	0.592
TRI air releases per area in $\frac{lb}{mi^2}$	283.6	41.8	908.8	0.0
Mean distance to TRI air facility in mi	4.510	4.110	4.850	14.510
Mean distance to TRI water facility in mi	10.550	12.870	12.500	11.320

in figure 4.13. In general, all figures were normalized to the respective area to allow for a concise comparison between the different features. Overall, the wellhead protection areas are potentially most affected according to the status of developed land as they feature a significantly increased share of impervious surface, the most released toxic air pollutants and the highest mileage in relation to major roads. This development may largely be due to wells being primarily used by communities or private households, which automatically entails a close proximity to built-up areas. Additionally, as these wells are not overseen by a central body, the management and maintenance lies largely in the responsibility of private citizen, who generally do not possess the same capability regarding assurance of drinking water quality as rather large public suppliers. On the other hand, surface water protection areas, which are used to supply over 85% of the state's drinking water, show significantly less potential to be influenced by development, as they do not encompass any TRI facilities, have a significantly lessened road mileage and impervious surface

ratio. The same observations apply to sole source aquifers, which are generally less impacted due to their underground position.

In conclusion, the wellhead protection areas show by far the highest potential to experience detrimental consequences due to development in their respective vicinity. While the carried out assessments only shape potential impacts on water procurement due to pollution, further efforts for deriving quantifiable measures of the consequences may greatly help to create further incentive and a more sophisticated risk assessment. Regarding UWE-Nexus approaches, a diminishing water quality may lead to a higher energy demand of the treatment process in order to achieve sufficient quality for consumption, as discussed in section 4.3. [32]

4.6 Urban-Water-Energy-Nexus Significant Findings

In this chapter potential effects of urban areas on the associated energy and water supply systems in Rhode Island were assessed in detail in order to quantify UWE-Nexus approaches. Most of the featured sections may still benefit significantly from further work and research, but each of the featured topics offers strong potential for individual elaborations. Accordingly, the majority of this chapter is best seen as a foundation for future work, but some areas have been able to characterize the situation in Rhode Island quite appropriately. Overall, the findings are deemed to advance the understanding of linkages between water and energy in the state in an elaborate and meaningful way.

While it was possible to assess both water for energy measures and UHI influences in detail, energy for water figures and implications of point pollution sources could not be examined in detail. The latter demands much more work overall as there are many more aspects and interactions to consider. However, of the three assessed areas of interest, wellhead protection areas have been determined to be most under threat from urban development. Furthermore, most parameters

fundamentally promise to have an advantageous effect on energy demand for public water procurement, indicating a potentially low requirement thereof. Backing this suggestion up with actually recorded demand figures from water suppliers is going to a challenging but ultimately worthwhile undertaking.

While both water for energy and UHI related assessments may also be improved upon with adequate data availability, it was possible to derive rather reliable conclusions for these two areas. As over 90% of Rhode Island's annual electricity generation stems from natural gas power plants, which generally exhibit the lowest water intensity of the conventional technologies, the water demand for energy generation promises to be relatively low in comparison to other states. However, improvements in this area may yield considerable benefits, because thermoelectric power plants regularly account for a vast majority of the state's water usage. Additionally, peak generation during the summer months leads to accordingly increasing withdrawals, culminating with seasonality that already experiences stress of adequate water supply. Additionally, this strain on water resources is further intensified by an increased demand due to more severe heat. Overall, Rhode Island's urbanized areas, which house 90.7% of the state's citizens as of 2010, may exhibit about 4 K higher temperatures than the remaining rural areas. Furthermore, about 48% of the population lives in areas above 25 °C, resulting in great potential gains via mitigation of the associated UHI. For instance, the best case reduction regarding municipal water demand has been determined to yield a 8% statewide decrease, which may be sufficient to comply with safe withdrawal figures for the Scituate Reservoir.

CHAPTER 5

Evaluation

As stated earlier, this paper aims to examine sustainability in the state of Rhode Island while focusing on two major objectives, which are as follows:

- Compilation of a comprehensive municipality ranking
- Examination of potentials regarding UWE-Nexus approaches

Accordingly, the study region of Rhode Island has been described in great detail as a prerequisite for the aforementioned assessments with special effort spent on utility infrastructure and other relevant sectors for research objectives. The following three sections will state a summary of the study findings, a discussion regarding areas for improvement or advisable future steps and the finalized conclusion.

5.1 Summary

The worked out rating features 75 indicators, which are allocated to sixteen thematic segments and the three categories of social, environmental and economic. Accordingly, it is closely matched to the initially discussed definition of sustainability. While Jamestown has been identified to be the most sustainable municipality, Central Falls is rated most unfavorably overall. Furthermore, the latter takes up a particular spot amongst all communities as it attains by far the lowest economic rating. The same observation applies to New Shoreham, which ranks last regarding environmental aspects and shows an even bigger margin to the second worst rated town of North Providence. Next, the rating is well suited to reveal specific areas of concern for individual communities, for instance, waste for Johnston, New Shoreham and Providence and education for Central Falls and Pawtucket. Additionally, unfavorably rated municipalities seem to be clustered around Providence, while

the southern shore of Rhode Island tends to house above average performing municipalities for all examined categories. Lastly, of the evaluated demographic parameters, population density and income have the most influence on the ranking. While rating results tend to diminish with increasing population density, they tend to increase with per capita income of the municipalities.

Regarding the UWE-Nexus aspects, a high potential for beneficial research has been determined for water requirements due to electricity generation. This usage category has by far the highest water demand and has accounted at least for 62% of total water usage since 1990. Additionally, the six biggest power plants of the state, which are all fueled by natural gas, have significantly different cooling technologies ranging from maximum intake of 3,007 $\frac{\text{gallons}}{\text{minute}}$ for the RISEC facility to 181,777 $\frac{\text{gallons}}{\text{minute}}$ for the Manchester Street power plant. Furthermore, as energy generation peaks during the summer months, the corresponding cooling water withdrawals rise accordingly, putting additional pressure on the local environment where water is already scarce during the summer time. Unfortunately, no appropriate data records were available to research the energy requirements for water procurement, which may require extensive effort for data gathering as there are nearly 500 individual water supply companies in the state. However, qualitative assessments of parameters related to water supply and waste water treatment indicate a favorable situation regarding energy efficiency for the these two sectors.

Furthermore, potentials impacts of the urban landscape have been evaluated largely by determining the magnitude of the UHI, which amounts to roughly 4 °C during the examined afternoon in August, and by assessing the spatial distribution of pollution sources. Due to the elevated land surface temperatures over 40% of the state's citizens are potentially affected by temperatures above 25 °C, which amounts to more than 80% for areas over 20 °C, even though the statewide mean

temperature has been determined to be around 19 °C. This indicates a high level of potential impacts ranging from heat stress, higher energy and water demand and an easier transmission of pathogens. Furthermore, complete mitigation of the UHI promises a water demand reduction to 193.70 MGD in the summer, which may be sufficient to meet the safe yield requirements of the Scituate reservoir. As a result, research of appropriate mitigation approaches is deemed to be very beneficial for Rhode Island. Additionally, allocation of facilities with toxic release, major traffic-ways and impervious surfaces to protection areas related to public water supply has revealed wellhead protection areas to be under the biggest threat by urban development. These areas exhibit a exceedingly high share impervious surfaces, road mileages and toxic releases per area.

5.2 Discussion

This section will assess areas for improvement and state requirements or advice for further work on the examined subject matters. Both the ranking and nexus assessments will be discussed separately, while the overall conclusion in section 5.4 will highlight the most significant findings and consequences thereof.

While the worked out sustainability ranking was constructed to cover all relevant aspects and includes 75 individual indicators, it is best seen as a starting point from which the state offices or interested personnel may draw conclusions and experiences for implementation of a more refined ranking. Furthermore, periodic reassessments with tangible goals and measures may greatly help to improve this snapshot of the current situation. In turn, this approach has a high potential for promoting sustainable development in Rhode Island and for laying out a road map from which the conditions, that may affect all areas of everyday life, can be incrementally improved upon. Accordingly, the worked out ranking already excels at depicting individual areas of concern and providing the respective reasoning by

detailed evaluations of the associated indicators.

Chapter 2 aims to give a comprehensive overview for the entire state while focusing on key areas for interest in section 2.8. Environmental aspects and utility infrastructure have been most prominently discussed, while other important areas regarding economic and social aspects are only briefly analyzed. As a result, future reports shall aim to include all relevant sectors equally and may benefit greatly from the in-depth introduction to the state and the environmental discussions.

Unfortunately, even though extensive effort has been spent on compiling the current version of the ranking, some areas still require further refinement. This is especially true for a lack of data regarding energy and water demand and economic measures such as number of businesses and employment opportunity. Additionally, this study would further benefit from an analysis of the political aspects, which could be carried out by reviewing the comprehensive plans per community. Next, the score per indicator is distributed based on the respective best and worst performing communities, resulting in attributing zero points per measure to some communities. While this approach works well for comparing the municipalities to one another, it might result in occasionally too unfavorably rated indicators. Overall, future iterations should aim to fill in the gaps of available data, include political aspects as a fourth category and establish independent reference thresholds instead of referring to the minimum and maximum values per indicator.

Additionally, as stated in section 1.1.1, evaluations of sustainable development should aim to be repeated in periodic intervals in order to measure change and evaluate goals or adapt them accordingly. About half of the used indicators stem from USCB resources, which are published on an annual basis as part of the ACS. Furthermore, a few other figures, such as municipal waste and housing reports, are also revisited each year, indicating a proficient basis to repeat the rating over several

years. However, some indicators are likely not changing very much on an annual basis, which applies for instance to public transportation infrastructure, number of LEED projects and renewable energy assets. Accordingly, it is recommended to revisit the rating about every five years, which would also leave enough time for the municipalities to evaluate the results and hopefully implement beneficial measures.

UWE-Nexus approaches require an extensive amount of information, which was lacking at times during the research process for this thesis, in order to properly assess the connections between energy and water in the chosen study area. This is applicable to the energy for water measures, which have largely been examined by applying already existing literature findings on which to assess the current situation in Rhode Island. In turn, verification of the worked out findings with actual recordings is a strongly advised future step. On the other hand, there is plenty of data available regarding water for energy measures, such as USGS water use figures and water withdrawal information for the individual power plants from the EIA. As a result, water for energy relationships could be examined in more detail, but lack consistency to literature reference. Accordingly, a close cooperation with power plant operators is advised for future research in this area. Assessments related to the UHI may be improved upon by implementing more sophisticated derivation procedures, thus increasing the accuracy and broadening the applicability of the carried out evaluations. This may be done by increasing temporal resolution and evaluating days with differing seasonality. The latter is especially emphasized as findings from the city of Phoenix, which is exposed to vastly different ambient conditions, have been used. Lastly, determining actual consequences related to the pollution sources may help to create further incentives for the mitigation thereof.

5.3 Limitations of this study

This section discusses the appropriate scope of the study and the inherent concerns regarding applicability or otherwise noteworthy issues. Accordingly, controversial aspects and potential future research objectives will be highlighted.

To begin with, rising income levels have been interpreted to be more sustainable regarding economic aspects as higher affluence allows more spending, thus increasing economic activity and attractiveness of the respective area. On the other hand, this may also lead to a higher degree of consumption, which in turn leads to increased stress on the associated supply framework and a more unsustainable situation overall. Accordingly, future research in this area should explore this relationship and correlations between sustainability and demographic parameters in more detail. Overall, this is thought to be highly beneficial for deriving appropriate indicators and refining the rating approach carried out in this thesis.

As discussed in the introductory segment of this paper, urban areas are centers for cultural activity, as they offer access to many vital services and institutions, and resource consumption. Accordingly, appropriately accounting for both of these aspects within sustainability rating schemes will likely result in a more holistic assessment. In this thesis, the rural areas of Rhode Island have been rated more favorably than the urban centers of the state. At the moment, it is up for debate if this observation stems from the applied procedures or if it accurately depicts differences between rural and urban areas. This also raises the question of how to design assessments that equally account for both the associated benefits as well as the inherent disadvantages of consumption patterns. These may often be allocated to diverging locations, such as commuters that cause emissions at their respective place of employment instead of their community of residency. Resolving this issue may potentially lead towards a more appropriate score allocation by highlighting

the contribution of urban areas to the overall assets and activity within the state. Future iterations should explore other opportunities for reaching appropriate results besides normalization of the indicators.

Additionally, the sustainability rating results are closely tied to Rhode Island. However, the scoping is deemed to be transferable to other areas within the USA, as the goals and points of emphasis should be quite similar. On the other hand, the focus and featured areas should be adapted when evaluating communities in other countries. Overall, availability and quality of data is the key concern for this kind of assessment. When focusing on the USA, detailed demographic parameters are published by the USCB on an annual basis, providing an outstanding foundation to evaluate most social and some economic aspects. However, the environmental assessments of this thesis are based primarily on publications from state agencies with a few federal resources being used as well. Accordingly, successful transferal to other states is dependent on the level of detail and availability of publications. Overall, a majority of the states should already have appropriate data records available, as environmental regulations are generally applicable nationwide. Additionally, federal agencies usually publish their work on a county level. Accordingly, rating approaches in other parts of the USA may benefit from referring to counties instead of municipalities, which would also drastically lower the required effort for evaluations in the bigger and more populous states.

Lastly, the sustainability rating may be improved by including more directly applicable scores and indicators, which would help to inform municipalities on how to improve their respective situation. This can be done by reducing the number of indicators, thus decreasing the amount of effort to derive tangible measures for each community, or by compiling separate overviews for each municipality. The latter would provide a central accumulation of data on which to comprehensively

assess and evaluate each individual situation.

Overall, the worked out ranking is one of few iterations primarily focused on rather small communities while also accounting for the entirety of a whole state. Accordingly, there are unresolved or unproven issues and areas for improvement, which have been thoroughly discussed in order to provide a strong basis for improvements regarding future research in this field.

5.4 Conclusion

In conclusion, the proposed sustainability ranking is deemed to be a beneficial tool to evaluate all communities regarding their social, environmental and economic sustainability, and the respective individual areas of concern in a comprehensive manner. Furthermore, periodically recurring revisions may greatly promote sustainable development and thus improve the sustainability of the state as a whole while focusing on the municipalities. Furthermore, they are deemed to be the best suitable frame of reference in Rhode Island to provide a close link to local government and the affected residents. Overall, this approach can be seen as a foundation to improve upon and attain a higher quality of life for the state's citizens.

As Rhode Island features a highly urbanized composition and densely populated settlement structure, interactions within the urban landscape may have far reaching implications. Elevated temperatures due to the UHI effect have been identified to potentially affect a majority of the state's citizens, indicating high benefits via implementation of appropriate mitigation measures. Additionally, allocation of pollution sources and the development of counteractions may play a major role in increasing the resiliency of public water infrastructure. Furthermore, proper quantifications of water demand for energy generation and energy requirements for water provision are deemed to reveal the interactions between these sectors, thus highlighting the true cost of supplying for the state's population.

LIST OF REFERENCES

- [1] M. P. Weinstein and R. E. Turner, *Sustainability science: The emerging paradigm and the urban environment*. New York, NY: Springer New York, 2012.
- [2] Martin Jänicke, “Conditions for environmental policy success: An international comparison,” *Environmentalist*, vol. 12, no. 1, pp. 47–58, 1992. [Online]. Available: <https://link.springer.com/article/10.1007/BF01267594>
- [3] Roger Anders, “The Federal Energy Administration,” 12.04.2017. [Online]. Available: <https://www.energy.gov/sites/prod/files/FEA%20History.pdf>
- [4] World Commission on Environment and Development, *Report of the World Commission on Environment and Development: Our Common Future*. Nairobi: United Nations, 1987. [Online]. Available: <http://www.un-documents.net/our-common-future.pdf>
- [5] K. E. Portney, *Sustainability*, ser. MIT Press essential knowledge series. Cambridge, Massachusetts: MIT Press, 2015.
- [6] R. W. Kates, T. M. Parris, and A. A. Leiserowitz, “What Is Sustainable Development? Goals, Indicators, Values, and Practice,” *Environment Science and Policy for Sustainable Development*, vol. 47, no. 3, pp. 8–21, 2005.
- [7] T. Theis and J. Tomkin, Eds., *Sustainability: A Comprehensive Foundation*. Houston Texas: Rice University, 2012. [Online]. Available: <http://cnx.org/content/col11325/1.38/>
- [8] P. P. Kalbar, M. Birkved, S. Karmakar, S. E. Nygaard, and M. Hauschild, “Can carbon footprint serve as proxy of the environmental burden from urban consumption patterns?” *Ecological Indicators*, vol. 74, pp. 109–118, 2017.
- [9] Virginia W. Maclaren, “Urban Sustainability Reporting,” *Journal of the American Planning Association*, vol. 62, no. 2, pp. 184–202, 1996. [Online]. Available: <http://dx.doi.org/10.1080/01944369608975684>
- [10] D. S. Graber and K. A. Birmingham, Eds., *Urban planning in the 21st century: Planning and Sustainability*. Hauppauge, N.Y: Nova Science Publishers, 2009.
- [11] T. L. Daniels and K. Daniels, *The environmental planning handbook for sustainable communities and regions*. Chicago: Planners Press, American Planning Association, 2003.

- [12] S. N. Pollalis, A. Georgoulas, S. J. Ramos, and D. Schodek, Eds., *Infrastructure Sustainability and Design*. Hoboken: Taylor & Francis, 2012.
- [13] Melanie Dawn, “Introduction to LEED V4,” 01.06.2017. [Online]. Available: <http://miami-urban-green.com/introduction-to-leed-v4/>
- [14] N. A. Szibbo, “Assessing Neighborhood Livability: Evidence from LEED for Neighborhood Development and New Urbanist Communities,” *Articulo Journal of Urban Research*, no. 14, 2015.
- [15] United States Green Building Council, “LEED For Cities Pilot: Performance Score to LEED Certification,” 02.06.2017. [Online]. Available: <http://www.usgbc.org/cityperformance>
- [16] D. N. Peach and A. L. Petach, “Development and Quality of Life in Cities,” *Economic Development Quarterly*, vol. 30, no. 1, pp. 32–45, 2016.
- [17] Don Chen et. al., *US and Canada Green City Index: Assessing the environmental performance of 27 major US and Canadian cities*. New York: Economist Intelligence Unit, 2011.
- [18] Arcadis, *Sustainable Cities Index 2016: Putting people at the heart of city sustainability*. Amsterdam: Arcadis, 2016.
- [19] International Organisation for Standardisation, “ISO 37120:2014: Sustainable development of communities - Indicators for city services and quality of life,” 01.05.2017. [Online]. Available: <https://www.iso.org/obp/ui/#iso:std:iso:37120:ed-1:v1:en>
- [20] T. D. Cohen, W. G. Hatchard, and G. S. Wilson, *Population Trends in Incorporated Places: 2000 to 2013: Current Population Reports*. Washington D.C.: U.S. Government Printing Office, 2015.
- [21] H. Hoff, *Understanding the Nexus: Background paper for the Bonn 2011 Nexus Conference: The Water, Energy and Food Security Nexus*. Stockholm: Stockholm Environment Institute, 2011.
- [22] A. Endo, I. Tsurita, K. Burnett, and P. M. Orenco, “A review of the current state of research on the water, energy, and food nexus,” *Journal of Hydrology: Regional Studies*, 2015.
- [23] M. E. Webber, *The United Nations World Water Development Report 4: The global nexus of energy and water*, ser. United Nations world water development report. Paris: UNESCO, 2012, vol. 4,3.
- [24] J.-F. Hake, H. Schlör, K. Schürmann, and S. Venghaus, “Ethics, Sustainability and the Water, Energy, Food Nexus Approach – A New Integrated Assessment of Urban Systems,” *Energy Procedia*, vol. 88, pp. 236–242, 2016.

- [25] C. Vogt, M. Zimmerman, and K. Brekke, *Operationalizing the Urban Nexus: Towards resource-efficient and integrated cities and metropolitan regions*. Eschborn: Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH, 2014.
- [26] J. Pittock, K. Hussey, and S. R. Dovers, Eds., *Climate, energy and water: Managing trade-offs, seizing opportunities*. Cambridge: Cambridge Univ. Press, 2015.
- [27] United States Environmental Protection Agency, “Water and Energy Efficiency at Utilities and in the Home,” 07.03.2017. [Online]. Available: <https://www.epa.gov/sustainable-water-infrastructure/water-and-energy-efficiency-utilities-and-home>
- [28] R. C. Brears, *Urban water security*, ser. Challenges in water management series. Chichester, UK and Hoboken, NJ: John Wiley & Sons, 2016.
- [29] H. Akbari, “Energy Saving Potentials and Air Quality Benefits of Urban Heat Island Mitigation,” *Heat Island Group*, vol. 56, pp. 5–6, 2001.
- [30] H. Silva and B. S. Fillpot, “Modeling nexus of urban heat island mitigation strategies with electricity/power usage and consumer costs: A case study for Phoenix, Arizona, USA,” *Theoretical and Applied Climatology*, 2016.
- [31] P. Gober, A. Brazel, R. Quay, and S. Myint, “Using Watered Landscapes to Manipulate Urban Heat Island Effects: How Much Water Will It Take to cool Phoenix,” *Journal of the American Planning Association*, vol. 76, pp. 109–121, 2010.
- [32] G. Venkatesh, A. Chan, and H. Brattebø, “Understanding the water-energy-carbon nexus in urban water utilities: Comparison of four city case studies and the relevant influencing factors,” *Energy*, vol. 75, pp. 153–166, 2014.
- [33] K. L. Lam, S. J. Kenway, and P. A. Lant, “Energy use for water provision in cities,” *Journal of Cleaner Production*, vol. 143, pp. 699–709, 2017.
- [34] Elizabeth Minne et al., Ed., *Water, energy, land use, transportation and socioeconomic nexus: A blue print for more sustainable urban systems*, Chicago, USA, 2011.
- [35] A. Wolman, “The Metabolism of Cities,” *Scientific American Inc.*, 1965.
- [36] C. Kennedy, J. Cuddihy, and J. Engel-Yan, “The Changing Metabolism of Cities,” *Journal of Industrial Ecology*, vol. 0, no. 0, p. 070322093406001, 2007.
- [37] V. R. Walker and M. B. Beck, “Understanding the metabolism of urban-rural ecosystems,” *Urban Ecosystems*, vol. 15, pp. 809–848, 2012.

- [38] S. Lee, A. Quinn, and C. Rogers, “Advancing City Sustainability via Its Systems of Flows: The Urban Metabolism of Birmingham and Its Hinterland,” *Sustainability*, vol. 8, no. 3, p. 220, 2016.
- [39] J. M. Levy, *Contemporary Urban Planning*, 10th ed. Hoboken: Taylor and Francis, 2015.
- [40] UN Habitat, *Prosperity of cities*, ser. The state of the world’s cities. New York: Routledge, 2013, vol. 2012/2013.
- [41] J. Kotkin, W. Cox, A. Modarres, and A. M. Renn, *The Problem With Megacities*. Orange: Chapman University Press, 2014.
- [42] E. Moreno, P. McCarney, and Arimah, *World Cities Report 2016: Urbanization and Development: Emerging Futures*. Nairobi: United Nations Human Settlements Program, 2016.
- [43] The World Bank, “Overview,” 02.02.2017. [Online]. Available: <http://www.worldbank.org/en/topic/urbandevelopment/overview#1>
- [44] B. Cohen, “Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability,” *Technology in Society*, vol. 28, no. 1-2, pp. 63–80, 2006.
- [45] G. Bugliarello, “Urban sustainability: Dilemmas, challenges and paradigms,” *Technology in Society*, vol. 28, no. 1-2, pp. 19–26, 2006.
- [46] United Nations, Department of Economic and Social Affairs, Population Division, Ed., *World Urbanization Prospects: The 2014 Revision, Highlights*. (ST/ESA/SER.A/352), 2014.
- [47] United States Census Bureau, *United States Summary: 2010: Population and Housing Units Counts*. Washington D.C.: U.S. Government Printing Office, 2012.
- [48] A. Dewan and R. Corner, Eds., *Dhaka Megacity: Geospatial Perspectives on Urbanisation, Environment and Health*, ser. Springer Geography. Dordrecht and s.l.: Springer Netherlands, 2014.
- [49] United Nations, *World Urbanization Prospects: The 2011 Revision*. New York: United Nations, 2012.
- [50] A. S. Akanda and F. Hossain, “The Climate-Water-Health-Nexus in Emerging Megacities,” *American Geophysical Union*, vol. 93, no. 37, pp. 353–360, 2012.
- [51] National Oceanic and Atmospheric Administration, “What is Climate Change,” 10.05.2017. [Online]. Available: <http://www.nws.noaa.gov/om/brochures/climate/Climatechange.pdf>

- [52] Thomas J. Crowley, “Causes of Climate Change Over the Past 1000 Years,” *Science*, vol. 289, 2000.
- [53] C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, and M. D. Mastrandrea, *Climate Change 2014 Impacts, Adaptation, and Vulnerability*. New York: Cambridge University Press, 2014.
- [54] UN Habitat, *Global Report on Human Settlements 2011: Cities and Climate Change*, ser. Global report on human settlements. London: Earthscan, 2011, vol. 2011.
- [55] M. A. McGeehin and M. Mirabelli, “The Potential Impacts of Climate Variability and Change on Temperature-Related Morbidity and Mortality in the United States,” *Environmental Health Perspectives*, vol. 109, p. 185, 2001.
- [56] SUNY Levin Institute, “What Is Globalization,” 14.06.2018. [Online]. Available: <http://www.globalization101.org/what-is-globalization/>
- [57] J. M. Sirgy, D.-J. Lee, C. Miller, and J. E. Littlefield, “The Impact of Globalization on a Country’s Quality of Life: Toward an Integrated Model,” *Social Indicators Research*, vol. 68, pp. 251–298, 2004.
- [58] Adil Najam, David Runnalls, and Mark Halle, *Environment and Globalization: Five Propositions*. Winnipeg, Canada: International Institute for Sustainable Development, 2007.
- [59] United Nations, *World economic and social survey 2013: Sustainable development challenges*, ser. Economic & social affairs. New York: United Nations, 2013, vol. 2013.
- [60] United States Census Bureau, “Guide to State and Local Census Geography,” 11.05.2017. [Online]. Available: <https://www.census.gov/geo/reference/geoguide.html>
- [61] RI Government, “Historical Information,” 13.05.2017. [Online]. Available: <http://www.ri.gov/facts/history.php>
- [62] Encyclopedia Britannica, “Rhode Island,” 13.05.2017. [Online]. Available: <https://www.britannica.com/place/Rhode-Island-state>
- [63] C. Jones, *The history and future of Narragansett Bay*. Boca Raton, Fla.: Universal Publishers, 2006.
- [64] Environmental Data Center, “Rhode Island Geographic Information System (RIGIS) Data Distribution System,” Kingston, 20.03.2017. [Online]. Available: <http://www.rigis.org/>

- [65] United States Census Bureau, “American FactFinder,” 12.05.2017. [Online]. Available: <https://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml>
- [66] Encyclopedia Britannica, “Humid continental climate,” 13.05.2017. [Online]. Available: <https://www.britannica.com/science/humid-continental-climate>
- [67] National Oceanic and Atmospheric Administration, “National Centers for Environmental Information: Climate Data Online Search,” 11.05.2017. [Online]. Available: <https://www.ncdc.noaa.gov/cdo-web/search>
- [68] National Oceanic and Atmospheric Administration, “Land-Based Datasets and Products,” 13.05.2017. [Online]. Available: <https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets>
- [69] Anthony Arguez et al., “NOAA’s 1981–2010 U.S. Climate Normals: An Overview,” *Bulletin of the American Meteorological Society*, vol. 93, no. 11, pp. 1687–1697, 2012.
- [70] Rhode Island Department of Environmental Management, “Overview of Climate in Rhode Island,” 22.06.2017. [Online]. Available: <http://www.dem.ri.gov/climate/climate-overview-ri.php>
- [71] Y. Petri and K. Caldeira, “Impacts of global warming on residential heating and cooling degree-days in the United States,” *Scientific reports*, vol. 5, p. 12427, 2015.
- [72] United States Environmental Protection Agency, *Heating and Cooling Degree Days: Climate Change Indicators in the United States*. Cincinnati: National Service Center for Environmental Publications, 2016.
- [73] NOAA National Centers for Environmental Information, “State Climate Summaries: Rhode Island,” 11.05.2017. [Online]. Available: <https://statesummaries.ncics.org/ri>
- [74] National Oceanic and Atmospheric Administration, “Shoreline Mileage of The United States,” 12.05.2017. [Online]. Available: <https://coast.noaa.gov/data/docs/states/shorelines.pdf>
- [75] Rhode Island Climate Change Commission, *Adapting to Climate Change in the Ocean State: A Starting Point: 2012 Progress Report*. Rhode Island: Rhode Island Climate Change Commission, November 2012.
- [76] Rhode Island Sea Grant, “Climate Change to Home Septic Systems,” 10.05.2017. [Online]. Available: <http://seagrant.gso.uri.edu/climate-change-threat-home-septic-systems/>

- [77] L. Heffner, R. Williams, V. Lee, P. Rubinoff, and C. Lord, Eds., *Climate Change and Rhode Island's Coasts: Past, Present and Future*. South Kingstown: Rhode Island Sea Grant, 2012.
- [78] Rhode Island Executive Climate Change Council, "A Resilient Rhode Island: Being Practical About Climate Change," 28.05.2017. [Online]. Available: <http://www.planning.ri.gov/documents/climate/EC3ReportJune2014final.pdf>
- [79] RI Government, "Rhode Island Cities and Towns," 10.05.2017. [Online]. Available: <https://www.ri.gov/towns/>
- [80] Rabin and Jack, Eds., *Encyclopedia Of Public Administration and Public Policy: County Government*. New York, NY: Marcel Dekker, Inc., 2003.
- [81] T. P. Haas, "Constitutional Home Rule in Rhode Island," *Roger Williams University Law Review*, vol. 11, no. 3, pp. 1–45, 2006.
- [82] J. C. Caruso, J. E. Coduri, and S. D. Moss, *Municipal Charters in Rhode Island: Home Rule in Rhode Island: 50 Years Later*. Providence: Rhode Island Department of Revenue, 2013.
- [83] Carl Vinson Institute of Government, *A Brief Summary of Municipal Incorporation Procedures by State*. Athens: The University of Georgia, 2015.
- [84] United States Census Bureau, "Geographic Areas Reference Manual," 11.05.201. [Online]. Available: <https://www.census.gov/geo/reference/garm.html>
- [85] State of Rhode Island Board of Elections, "Department of Administration: Division of Planning," 07.02.2017. [Online]. Available: <http://www.planning.ri.gov/>
- [86] Rhode Island Statewide Planning Programm, "Comprehensive Plans and State Approval Status," 15.06.2017. [Online]. Available: <http://www.planning.ri.gov/planning-areas/local-comprehensive-planning/plans-currently-under-review.php>
- [87] Farhad Atash, *CPL 410 Introduction to Community Planning: Lecture Notes*. South Kingstown: University of Rhode Island, 2014.
- [88] National Geographic, "urban area," 11.05.2017. [Online]. Available: <https://www.nationalgeographic.org/encyclopedia/urban-area/>
- [89] M. Ratcliffe, C. Burd, K. Holder, and A. Fields, *Defining Rural at the U.S. Census Bureau: American Community Survey and Geography Brief*. Washington D.C.: U.S. Government Printing Office, 2016.

- [90] United States Census Bureau, “2010 Census Urban and Rural Classification and Urban Area Criteria,” 11.05.2107. [Online]. Available: <https://www.census.gov/geo/reference/ua/urban-rural-2010.html>
- [91] United States Census Bureau, “2010 Census Data,” 11.05.2017. [Online]. Available: <https://www.census.gov/2010census/data/>
- [92] Brendan Murphy, Andrew Owen, and David Levinson, *Access Across America: Transit 2015: Final Report*. University of Minnesota: Accessibility Observatory, 2015.
- [93] Statewide Planning Program, *Energy 2035: Rhode Island State Energy Plan*. Providence: Rhode Island Department of Administration, 2015.
- [94] Rhode Island Public Utilities Commission, “Division of Public Utilities and Carriers,” 11.06.2017. [Online]. Available: <http://www.ripuc.org/>
- [95] Energy Information Administration, “Electricity: State Electricity Profiles,” 18.05.2017. [Online]. Available: <https://www.eia.gov/electricity/state/RhodeIsland/>
- [96] Energy Information Administration, “U.S. States: State Profiles and Energy Estimates, Rankings,” 20.05.2017. [Online]. Available: <https://www.eia.gov/state/rankings/#/series/12>
- [97] Energy Information Administration, “2015 Average Monthly Bill Residential,” 19.05.2017. [Online]. Available: https://www.eia.gov/electricity/sales_revenue_price/pdf/table5_a.pdf
- [98] Energy Information Administration, “Electricity: Detailed State Data,” 06.06.2017. [Online]. Available: <https://www.eia.gov/electricity/data/state/>
- [99] Energy Information Administration, “Maps: Layer Information for Interactive State Maps,” 11.06.2017. [Online]. Available: https://www.eia.gov/maps/layer_info-m.php
- [100] Cassius Shuman, “Island operating on wind farm power,” 14.05.2017. [Online]. Available: <http://www.blockislandtimes.com/article/island-operating-wind-farm-power/49352>
- [101] Danny Musher, Office of Energy Resources, “e-mail correspondence: data for thesis,” 04.04.2017.
- [102] J. K. Burke, K. Crawley, and R. Mendes, *2012 Strategic Plan*. Providence: Rhode Island Water Resource Board, 2012.
- [103] Statewide Planning Program, *Rhode Island Water 2030: State Guide Plan Element 721, Report 115*. Providence: Rhode Island Department of Administration, 2012.

- [104] Molly A. Maupin et al., *Estimated use of water in the United States in 2010*, ser. US Geological Survey circular. Reston, Va.: US Geological Survey, 2014, vol. 1405.
- [105] Rhode Island Department of Environmental Management, “Waste Water Treatment Facilities,” 12.06.2017. [Online]. Available: <http://www.dem.ri.gov/programs/water/wwtf/>
- [106] Rhode Island Department of Environmental Management, *Summary of Rhode Island Municipal Onsite Wastewater Programs*. Providence: DEM, 2014.
- [107] American Society of Civil Engineers, “Infrastructure in Rhode Island: 2017 Infrastructure Report Card,” 11.06.2017. [Online]. Available: <https://www.infrastructurereportcard.org/state-item/rhode-island/>
- [108] Statewide Planning Program, *Solid Waste 2038: Rhode Island Comprehensive Solid Waste Management Plan*. Providence: Rhode Island Department of Administration, 2015.
- [109] Rhode Island Resource Recovery Corporation, “About us,” 18.05.2017. [Online]. Available: <http://www.rirrc.org/about>
- [110] Rhode Island Resource Recovery Corporation, “Annual Metrics: Municipal Summary,” 14.05.2017. [Online]. Available: <http://www.rirrc.org/municipal-officials-haulers/municipal-officials/annual-metrics>
- [111] Statewide Planning Program, *Transportation 2035: Long Range Transportation Plan*. Providence: Rhode Island Department of Administration, 2012.
- [112] U.S. Department of Transportation, “Geopsatial at the Bureau of Transportation Statistics,” 20.03.2017. [Online]. Available: <http://osav-usdot.opendata.arcgis.com/>
- [113] Rhode Island Public Transportation Authority, “Flex Service,” 14.06.2017. [Online]. Available: <http://www.ripta.com/flex-service>
- [114] National Transit Database Program, *Rhode Island Public Transit Authority: 2014 Agency Profile*. Washington D.C.: Federal Transit Authority, 2014.
- [115] J. Neff and M. Dickens, *Public Transportation Fact Book*, 67th ed. Washington D.C.: American Public Transportation Association, 2016.
- [116] American Association of State Highway and Transportation Officials, *Transportation and Sustainability: Best Practices Background*. Washington D.C.: Center for Environmental Excellence, 2009.
- [117] Rhode Island Department of Transportation, “Rhode Works,” 13.06.2017. [Online]. Available: <http://www.dot.ri.gov/rhodeworks/>

- [118] B. Brunekreef and S. T. Holgate, “Air pollution and health,” *Lancet*, vol. 360, no. 42, pp. 1233–1243, 2002.
- [119] United States Environmental Protection Agency, “Overview of the Clean Air Act and Air Pollution,” 11.06.2017. [Online]. Available: <https://www.epa.gov/clean-air-act-overview>
- [120] United States Environmental Protection Agency, *The Plain English Guide to the Clean Air Act*. Cincinnati: National Service Center for Environmental Publications, 2007.
- [121] Rhode Island Department of Environmental Management, “Air Resources,” 05.06.2017. [Online]. Available: <http://www.dem.ri.gov/programs/air/>
- [122] Rhode Island Department of Environmental Management, *Air Quality Summary: State of Rhode Island*. Providence: DEM, 2011.
- [123] Rhode Island Department of Environmental Management, *Office of Air Resources: Rhode Island 2016 Annual Monitoring Network Plan*. DEM: Providence, 2016.
- [124] United States Environmental Protection Agency, “TRI Explorer: 2015 Factsheet: State of Rhode Island.” [Online]. Available: https://iaspub.epa.gov/triexplorer/tri_factsheet.factsheet_forstate?&pstate=RI&pyear=2015&pParent=TRI&pDataSet=TRIQ1
- [125] Rhode Island Department of Environmental Management, “Emissions Inventory,” 20.05.2017. [Online]. Available: <http://www.dem.ri.gov/programs/air/emissions.php>
- [126] S. V. Chitra, M. N. Harindranathan, A. Amarnath, and N. Anjana, “Impacts of Impervious Surfaces on the Environment,” *International Journal of Engineering Science Invention*, vol. 4, no. 5, pp. 27–31, 2015.
- [127] Christopher D. Elvidge et al., “Global Distribution and Density of Constructed Impervious Surfaces,” *Sensors*, vol. 7, no. 9, pp. 1962–1979, 2007.
- [128] Rhode Island Department of Environmental Management, *Land Conservation and Acquisition Program: Annual Report Fiscal Year 2011*. Providence: DEM, 2011.
- [129] Statewide Planning Program, *Land Use 2025: Rhode Island State Land Use Policies and Plan*. Providence: Department of Administration, 2006.
- [130] Statewide Planning Programm, *Rhode Island Rising: A Plan For People, Places and Prosperity*. Providence: Rhode Island Department of Administration, December 2014.

- [131] Bureau of Economic Analysis, “Regional Data: Gross Domestic Product by State,” 13.06.2017. [Online]. Available: https://www.bea.gov/iTable/index_regional.cfm
- [132] INTRASOFT International, Ed., *Indicators for sustainable cities*, ser. Science for Environment Policy In-depth report. Luxembourg: Publications Office of the European Union, 2015, vol. issue 12 (November 2015). [Online]. Available: <http://dx.doi.org/10.2779/61700>
- [133] United Nations, “SDG Indicators: Revised list of global Sustainable Development Goal indicators,” 17.05.2017. [Online]. Available: <https://unstats.un.org/sdgs/indicators/indicators-list/>
- [134] Excel Team, “Visualize Statistics with Histogram, Pareto and Box and Whisker charts,” 12.06.2017. [Online]. Available: <https://blogs.office.com/2015/08/18/visualize-statistics-with-histogram-pareto-and-box-and-whisker-charts/>
- [135] K. Potter, *Methods for Presenting Statistical Information: The Box Plot*. Salt Lake City: University of Utah, 2006.
- [136] B. A. Shellito, *Discovering GIS and ArcGIS*. New York, NY: W. H. Freeman, 2015.
- [137] M. Law and A. Collins, *Getting to know ArcGIS*, 4th ed. Redlands, Calif.: Esri Press, 2015.
- [138] United States Census Bureau, “American Community Survey: Concepts and Definitions,” 11.04.2017. [Online]. Available: <https://www.census.gov/programs-surveys/acs/geography-acs/concepts-definitions.html>
- [139] ProximityOne, “Neighborhood Analysis: Using census block & block group demographics,” 11.05.2017. [Online]. Available: <http://proximityone.com/chelsea.htm>
- [140] Energy Information Administration, “Residential Energy Consumption Survey,” 12.05.2017. [Online]. Available: <https://www.eia.gov/consumption/residential/data/2009/>
- [141] P. Thakuriah, N. Tilahun, and M. Zellner, Eds., *Seeing Cities Through Big Data: Research, Methods and Applications in Urban Informatics*, ser. Springer Geography. Cham and s.l.: Springer International Publishing, 2017.
- [142] United States Census Bureau, “About the Bureau,” 03.04.2017. [Online]. Available: <https://www.census.gov/about.html>
- [143] United States Census Bureau, “American Community Survey: Information Guide,” 11.04.2017. [Online]. Available: www.census.gov/acs

- [144] National Highway Safety Administration, “State Traffic Safety Information: Rhode Island,” 15.05.2017. [Online]. Available: <https://cdan.nhtsa.gov/stsi.htm#>
- [145] United States Green Building Council, “LEED Projects,” 13.05.2017. [Online]. Available: <http://www.usgbc.org/projects>
- [146] HousingWorksRI, *2015 Housing Fact Book*. Providence: Roger Williams University, 2015.
- [147] Federal Bureau of Investigations, “2015 Crime in the United States,” 19.05.2017. [Online]. Available: <https://ucr.fbi.gov/crime-in-the-u.s>
- [148] A. C. Fontana, L. Trejo, and A. Reyes, *Vital Statistics Annual Report 2005*. Providence: Rhode Island Department of Health, 2014.
- [149] RI Datahub, “Data Catalogue,” 11.05.2017. [Online]. Available: <http://ridatahub.org/dictionary/indicator-search/>
- [150] State of Rhode Island Board of Elections, “Previous Election Results: Statewide Primary,” 13.05.2017. [Online]. Available: <http://www.elections.state.ri.us/elections/preresults/>
- [151] Tomas Smieszek United States Geological Survey, “e-mail correspondence: water usage data Rhode Island,” 30.03.2017.
- [152] Environmental Protection Agency, “Indoor Air Quality: Wood Smoke,” 11.06.2017. [Online]. Available: <https://www.epa.gov/indoor-air-quality-iaq/wood-smoke>
- [153] State of Rhode Island Department of Revenue, “Assessed Values & Levies,” 16.05.2017. [Online]. Available: <http://www.municipalfinance.ri.gov/data/tax-levies/>
- [154] United States Geological Survey, “Earth Explorer,” 20.03.2017. [Online]. Available: <https://earthexplorer.usgs.gov/>
- [155] U. Avdan and G. Jovanovska, “Algorithm for Automated Mapping of Land Surface Temperature Using LANDSAT 8 Satellite Data,” *Journal of Sensors*, vol. 2016, no. 2, pp. 1–8, 2016.
- [156] Zhao-Liang Li et al., “Satellite-derived land surface temperature: Current status and perspectives,” *Remote Sensing of Environment*, vol. 131, pp. 14–37, 2013.
- [157] Q. Weng, D. Lu, and J. Schubring, “Estimation of land surface temperature–vegetation abundance relationship for urban heat island studies,” *Remote Sensing of Environment*, vol. 89, no. 4, pp. 467–483, 2004.

- [158] Julia A. Barsi et al., “Landsat-8 Thermal Infrared Sensor (TIRS) Vicarious Radiometric Calibration,” *Remote Sensing*, vol. 6, no. 11, pp. 11 607–11 626, 2014.
- [159] United States Geological Survey, *LANDSAT 8 Data Users Handbook: Version 2.0*. Sioux Falls, South Dakota: USGS, 2016.
- [160] United States Geological Survey, “Using the USGS Landsat 8 Product,” 04.05.2017. [Online]. Available: <https://landsat.usgs.gov/using-usgs-landsat-8-product>
- [161] United States Geological Survey, “About: Who We Are,” 25.06.2017. [Online]. Available: <https://www.usgs.gov/about/about-us/who-we-are>
- [162] United States Geological Survey, “Water Use Data available from USGS,” 05.06.2017. [Online]. Available: <https://water.usgs.gov/watuse/data/index.html>
- [163] Energy Information Administration, “About EIA,” 25.06.2017. [Online]. Available: <https://www.eia.gov/about/>
- [164] Energy Information Administration, “Electricity: Form EIA-860 detailed data,” 07.06.2017. [Online]. Available: <https://www.eia.gov/electricity/data/eia860/>
- [165] Energy Information Administration, “Electricity: Form EIA-923 detailed data,” 06.06.2017. [Online]. Available: <https://www.eia.gov/electricity/data/eia923/>
- [166] A. N. Binks, S. J. Kenway, P. A. Lant, and B. W. Head, “Understanding Australian household water-related energy use and identifying physical and human characteristics of major end uses,” *Journal of Cleaner Production*, vol. 135, pp. 892–906, 2016.
- [167] d. D. Haas and M. Dancey, “Wastewater Treatment Energy Efficiency: A review of current Australian perspectives,” *Australian Water Association*, pp. 53–58, 2015.
- [168] S. J. Kenway and K. L. Lam, “Quantifying and managing urban water-related energy use systemically: Case study lessons from Australia,” *International Journal of Water Resources Development*, vol. 32, no. 3, pp. 379–397, 2015.
- [169] P. Torcellini, N. Long, and R. Judkoff, *Consumptive Water Use for U.S. Power Production*. Golden: National Renewable Energy Laboratory, 2003.
- [170] P. L. Spath and M. K. Mann, *Life Cycle Assessment of a Natural Gas Combined Cycle Power Generation System*. Golden: National Renewable Energy Laboratory, 2000.

- [171] J. A. de Gouw, D. D. Parrish, G. J. Frost, and M. Trainer, “Reduced Emissions of CO₂, NO_x and SO₂ from U.S. Power Plants Due to the Switch from Coal to Natural Gas with Combined Cycle Technology,” *Earth’s Future*, pp. n/a–n/a, 2014.
- [172] J. Macknick, R. Newmark, G. Heath, and K. C. Hallett, *Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies*. Golden: National Renewable Energy Laboratory, 2011.
- [173] Hashem Akbari et al., “Local climate change and urban heat island mitigation techniques: The state of the art,” *Journal of Civil Engineering and Management*, vol. 22, no. 1, pp. 1–16, 2015.
- [174] O. Buchin, M.-T. Hoelscher, F. Meier, T. Nehls, and F. Ziegler, “Evaluation of the health-risk reduction potential of countermeasures to urban heat islands,” *Energy and Buildings*, vol. 114, pp. 27–37, 2016.
- [175] Rimjhim M. Aggarwal et al., “How do variations in Urban Heat Islands in space and time influence household water use? The case of Phoenix, Arizona,” *Water Resource Research*, vol. 48, 2012.
- [176] Jean O’Dwyer, Aideen Dowling, and Catherine Adley, “The impact of climate change on the incidence of infectious waterborne disease,” *ResearchGate*, 2016.
- [177] P. S. Murdoch, J. S. Baron, and T. L. Miller, “Potential Effects Of Climate Change on Surface-Water Quality in North America,” *Journal of the American Water Resources Association*, vol. 36, no. 2, pp. 1–20, 2000.
- [178] S. Guhathakurta and P. Gober, “The impact of the Phoenix Urban Heat Island on Residential Water Use,” *Journal of the American Planning Association*, vol. 73, no. 3, pp. 317–329, 2007.

APPENDIX A

National Ambient Air Quality Standards

The following tables hold information about the NAAQS in order to provide further context for section 2.8.5. In Rhode Island the respective Department for Environmental Management monitors air quality regarding the threshold values displayed in figure A.1, which are worked out by the EPA. Furthermore, table A.1 displays the explanations for the superscripted notations of figure A.1.

POLLUTANT	AVERAGING TIME	PRIMARY STANDARD	SECONDARY STANDARD
Sulfur Dioxide (SO ₂)	3-Hour ^A	None	0.5 ppm (1300 µg/m ³)
	1-Hour ^B	75 ppb (196 µg/m ³)	None
	Annual Arithmetic Mean ^B	0.03 ppm (80 µg/m ³)	None
	24-Hour ^{AB}	0.14 ppm (365 µg/m ³)	None
Carbon Monoxide (CO)	8-Hour ^A	9 ppm (10 mg/m ³)	None
	1-Hour ^A	35 ppm (40 mg/m ³)	None
Ozone (O ₃)	8-Hour ^C	0.075 ppm (157 µg/m ³)	Same as Primary Standard
Nitrogen Dioxide (NO ₂)	Annual Arithmetic Mean	0.053 ppm (100 µg/m ³)	Same as Primary Standard
	1-Hour ^D	100 ppb (188 µg/m ³)	None
Particulate Matter ≤ 10 micrometers (PM ₁₀)	24-Hour ^E	150 µg/m ³	Same as Primary Standard
Particulate Matter ≤ 2.5 micrometers (PM _{2.5})	Annual Arithmetic Mean ^F	15.0 µg/m ³	Same as Primary Standard
	24-Hour ^G	35 µg/m ³	Same as Primary Standard
Lead (Pb)	Rolling 3-Month Average ^H	0.15 µg/m ^{3F}	Same as Primary Standard

Figure A.1. National ambient air quality standards as monitored by RIDEM [122]

Table A.1. Code descriptions for NAAQS from figure A.1 [122]

Code	Description
A	Not be exceeded more than once a year.
B	A rule promulgating a 1-hour SO ₂ NAAQS was signed on June 2, 2010. The rule revokes the annual and 24-hour SO ₂ NAAQS one year after designations for the 1-hour NAAQS are final. To attain the 1-hour NAAQS, the 3-year average of the 99th percentile of the daily maximum 1-hour average SO ₂ level at each monitor must not exceed 75 ppb.
C	The ozone NAAQS is violated when the average of the 4th highest daily eight-hour concentration measured in 3 consecutive years exceeds 0.075 ppm (the 0.075 ppm NAAQS became effective in May 2008)
D	To attain the 1-hour NO ₂ NAAQS, effective January 22, 2010, the 3-year average of the 98th percentile of the daily maximum 1-hour average NO ₂ concentration at each monitor must not exceed 100 ppb.
E	To attain the PM ₁₀ standard, the 24-hour concentration at each site must not exceed 150 g/m more than once per year, on average over 3 years.
F	To attain the PM _{2.5} annual standard, the 3-year average of the weighted annual means of 24-hour concentrations must not exceed 15 g/m ³ .
G	To attain the PM _{2.5} 24-hour standard, the 3-year average of the 98th percentile of 24-hour concentrations at each population-based monitor must not exceed 35 g/m ³ .

APPENDIX B

Ranking Scores per Category and Segment

The following tables hold all ranking values for the overall score, the three categories and the twelve segments. Table B.1 displays the coding, which was used to make tables B.2 to B.11 more compact and easier to read. The listed values are sufficient to work out all visualizations of chapter 3, rendering them of a high significance regarding long-term documentation. The individual indicators are not listed here, but can be accessed via:

<https://drive.google.com/file/d/0BxcDHeV9Td3mTmRQ0DR6UWxQSjA/view?usp=sharing>

This file link holds all values and points for the categories, segments and indicators.

Table B.1. Coding of ranking categories and segments for summary tables

Code	Segment or category	Code	Segment or category
A	Overall	K	Energy
B	Social	L	Transportation
C	Environmental	M	Water
D	Economic	N	Land Use
E	Education	O	Air
F	Safety	P	Waste
G	Health	Q	Income
H	Work Life Balance	R	Employment
I	Housing	S	Value
J	Voter Participation and Equal Pay	T	Connectivity and Mobility

Table B.2. Overall ranking score and total social score

Overall ranking score and total social score					
Municipality	A	B	Municipality	A	B
Barrington	60.08	22.96	New Shoreham	46.08	22.87
Bristol	57.5	24.58	Newport	55.31	22.93
Burrillville	48.58	20.77	North Kingstown	59.27	22.96
Central Falls	45.66	16.63	North Providence	48.8	21.1
Charlestown	58.64	23.96	North Smithfield	56.42	21.14
Coventry	57.69	21.86	Pawtucket	46.91	17.98
Cranston	50.38	20.57	Portsmouth	57.22	22.94
Cumberland	58.31	22.48	Providence	47.86	18.97
East Greenwich	56.64	20.98	Richmond	61.15	25.05
East Providence	52.77	21.34	Scituate	59.74	23.48
Exeter	56.92	22.02	Smithfield	58.61	23.82
Foster	54.64	21.97	South Kingstown	63.04	26.39
Glocester	56.76	22.51	Tiverton	55.97	22.56
Hopkinton	56.98	23.09	Warren	52.2	21.63
Jamestown	65.38	27.36	Warwick	54.2	21.29
Johnston	47.3	19.05	West Greenwich	59.63	23.57
Lincoln	56.5	22.55	West Warwick	52.69	21.22
Little Compton	59.82	24.88	Westerly	54.52	21.37
Middletown	55.14	21.27	Woonsocket	47.55	19.56
Narragansett	59.34	25.15	Average	55.18	22.23

Table B.3. Total environmental and total economic score

Total environmental and total economic score					
Municipality	C	D	Municipality	C	D
Barrington	25.77	11.34	New Shoreham	12.03	11.19
Bristol	24.11	8.81	Newport	22.99	9.39
Burrillville	20.15	7.67	North Kingstown	25.46	10.84
Central Falls	23.47	5.57	North Providence	17.91	9.79
Charlestown	25.75	8.93	North Smithfield	24.83	10.44
Coventry	25.87	9.96	Pawtucket	21.49	7.43
Cranston	20.43	9.38	Portsmouth	24.65	9.63
Cumberland	24.6	11.24	Providence	21.91	6.98
East Greenwich	23.61	12.06	Richmond	24.46	11.64
East Providence	22.78	8.65	Scituate	25.08	11.18
Exeter	24.47	10.43	Smithfield	24.51	10.28
Foster	22.77	9.9	South Kingstown	26.84	9.81
Glocester	24.76	9.48	Tiverton	24.11	9.31
Hopkinton	22.9	11	Warren	22.29	8.27
Jamestown	26.91	11.1	Warwick	22.04	10.87
Johnston	18.27	9.98	West Greenwich	26.12	9.94
Lincoln	22.85	11.11	West Warwick	21.12	10.35
Little Compton	25.01	9.92	Westerly	22.73	10.42
Middletown	24.49	9.38	Woonsocket	21.25	6.73
Narragansett	23.86	10.33	Average	23.2	9.76

Table B.4. Social category, education and safety score

Education and safety score					
Municipality	E	F	Municipality	E	F
Barrington	7.43	7.14	New Shoreham	8.88	2.64
Bristol	6.58	6.90	Newport	5.28	5.40
Burrillville	3.71	6.00	North Kingstown	6.18	6.29
Central Falls	0.97	6.05	North Providence	5.02	7.35
Charlestown	5.50	6.35	North Smithfield	5.83	6.03
Coventry	5.54	5.51	Pawtucket	2.46	5.16
Cranston	4.74	6.09	Portsmouth	5.93	6.24
Cumberland	5.51	6.19	Providence	3.85	4.73
East Greenwich	8.10	6.24	Richmond	6.23	6.22
East Providence	3.50	6.95	Scituate	5.86	6.50
Exeter	7.02	1.54	Smithfield	7.54	6.83
Foster	5.74	6.22	South Kingstown	8.51	6.38
Glocester	4.99	7.10	Tiverton	4.97	6.00
Hopkinton	6.41	5.98	Warren	5.37	6.11
Jamestown	8.72	6.64	Warwick	5.50	6.26
Johnston	4.46	6.81	West Greenwich	6.51	5.90
Lincoln	6.04	6.24	West Warwick	4.00	6.75
Little Compton	7.87	6.83	Westerly	5.74	5.86
Middletown	5.56	6.31	Woonsocket	3.79	5.77
Narragansett	7.57	6.87	Average	5.73	6.06

Table B.5. Social category, health and work life balance score

Health and work life balance score					
Municipality	G	H	Municipality	G	H
Barrington	6.42	3.93	New Shoreham	7.07	4.04
Bristol	6.20	6.23	Newport	5.58	4.41
Burrillville	6.63	3.50	North Kingstown	6.96	2.91
Central Falls	3.55	5.38	North Providence	5.83	3.21
Charlestown	7.19	4.53	North Smithfield	5.46	2.94
Coventry	6.51	3.72	Pawtucket	4.76	3.70
Cranston	5.31	3.60	Portsmouth	6.97	4.35
Cumberland	6.84	3.38	Providence	4.09	5.98
East Greenwich	6.44	2.50	Richmond	7.44	4.53
East Providence	5.49	4.08	Scituate	7.48	4.20
Exeter	7.76	5.71	Smithfield	6.09	5.01
Foster	6.05	4.17	South Kingstown	7.08	5.72
Glocester	6.20	4.64	Tiverton	6.32	4.24
Hopkinton	6.51	3.72	Warren	5.59	4.27
Jamestown	7.43	4.83	Warwick	4.92	3.43
Johnston	6.05	0.41	West Greenwich	6.72	5.24
Lincoln	5.97	3.63	West Warwick	5.96	3.86
Little Compton	6.12	5.00	Westerly	5.97	4.52
Middletown	6.61	2.63	Woonsocket	5.09	3.76
Narragansett	6.65	5.77	Average	6.19	4.15

Table B.6. Social category, housing and participation & equal pay score

Housing and voter participation & equal pay score					
Municipality	I	J	Municipality	I	J
Barrington	4.30	5.22	New Shoreham	5.45	6.22
Bristol	5.01	5.96	Newport	7.36	6.36
Burrillville	5.97	5.35	North Kingstown	6.60	5.50
Central Falls	4.21	4.77	North Providence	5.45	4.80
Charlestown	5.03	7.35	North Smithfield	6.42	5.05
Coventry	5.74	5.77	Pawtucket	5.28	5.60
Cranston	5.28	5.82	Portsmouth	4.96	5.95
Cumberland	5.91	5.88	Providence	5.31	4.50
East Greenwich	5.66	2.53	Richmond	7.19	5.96
East Providence	6.26	5.73	Scituate	5.73	5.44
Exeter	4.73	6.27	Smithfield	5.90	4.36
Foster	5.17	5.61	South Kingstown	5.55	6.35
Glocester	5.46	5.38	Tiverton	5.75	6.56
Hopkinton	5.46	6.55	Warren	4.91	6.21
Jamestown	5.80	7.62	Warwick	5.62	6.22
Johnston	5.77	5.08	West Greenwich	4.95	6.03
Lincoln	6.71	5.23	West Warwick	5.74	5.53
Little Compton	4.10	7.41	Westerly	5.30	4.66
Middletown	5.21	5.58	Woonsocket	6.58	4.35
Narragansett	4.84	6.02	Average	5.56	5.66

Table B.7. Environmental category, energy and transportation score

Energy and transportation score					
Municipality	K	L	Municipality	K	L
Barrington	3.03	4.95	New Shoreham	1.55	4.42
Bristol	2.32	5.88	Newport	1.39	8.05
Burrillville	2.97	3.59	North Kingstown	5.52	3.93
Central Falls	4.52	8.41	North Providence	0.98	4.95
Charlestown	2.09	3.24	North Smithfield	3.22	3.80
Coventry	5.87	3.96	Pawtucket	2.83	6.32
Cranston	2.50	5.31	Portsmouth	2.64	4.47
Cumberland	3.31	4.30	Providence	6.39	8.66
East Greenwich	2.69	4.54	Richmond	2.69	2.56
East Providence	2.59	5.62	Scituate	3.45	2.53
Exeter	2.72	3.48	Smithfield	2.43	4.78
Foster	2.49	1.35	South Kingstown	3.03	5.12
Glocester	2.45	2.75	Tiverton	1.87	3.65
Hopkinton	1.36	2.46	Warren	1.39	5.17
Jamestown	1.93	5.66	Warwick	1.61	4.92
Johnston	3.00	3.73	West Greenwich	3.11	3.28
Lincoln	2.80	3.82	West Warwick	1.87	5.51
Little Compton	2.17	4.45	Westerly	1.65	4.06
Middletown	2.52	5.55	Woonsocket	2.57	5.24
Narragansett	1.78	5.06	Average	2.70	4.60

Table B.8. Environmental category, water and land use score

Water and land use score					
Municipality	M	N	Municipality	M	N
Barrington	7.95	4.96	New Shoreham	1.49	7.19
Bristol	7.94	4.68	Newport	6.16	3.03
Burrillville	2.85	8.20	North Kingstown	5.43	6.69
Central Falls	7.21	0.26	North Providence	4.13	1.94
Charlestown	7.30	8.36	North Smithfield	7.18	6.96
Coventry	6.11	7.57	Pawtucket	6.97	0.66
Cranston	3.25	3.71	Portsmouth	6.96	6.41
Cumberland	6.49	6.81	Providence	4.72	0.34
East Greenwich	5.98	6.13	Richmond	6.15	8.30
East Providence	7.06	3.03	Scituate	7.09	8.78
Exeter	6.30	8.75	Smithfield	6.55	6.57
Foster	7.14	8.36	South Kingstown	6.13	7.56
Glocester	7.40	8.31	Tiverton	7.27	7.23
Hopkinton	6.64	8.22	Warren	7.83	5.00
Jamestown	8.21	6.84	Warwick	6.52	3.37
Johnston	3.87	5.52	West Greenwich	6.74	9.43
Lincoln	7.30	5.93	West Warwick	6.55	3.27
Little Compton	7.68	7.55	Westerly	5.85	6.71
Middletown	5.74	4.71	Woonsocket	5.63	2.98
Narragansett	6.87	5.79	Average	6.27	5.80

Table B.9. Environmental category, air and waste score

Air and waste score					
Municipality	O	P	Municipality	O	P
Barrington	9.47	8.29	New Shoreham	2.61	0.78
Bristol	7.90	7.46	Newport	7.77	8.08
Burrillville	4.98	7.62	North Kingstown	8.18	8.43
Central Falls	7.90	6.90	North Providence	8.12	6.74
Charlestown	8.73	8.91	North Smithfield	8.30	7.80
Coventry	8.51	6.78	Pawtucket	7.87	7.57
Cranston	8.18	7.70	Portsmouth	9.11	7.38
Cumberland	8.76	7.21	Providence	8.03	4.73
East Greenwich	8.64	7.43	Richmond	8.25	8.74
East Providence	7.92	7.95	Scituate	8.97	6.80
Exeter	8.79	6.67	Smithfield	8.50	7.94
Foster	8.52	6.29	South Kingstown	8.98	9.43
Glocester	8.78	7.46	Tiverton	8.67	7.48
Hopkinton	8.58	7.09	Warren	8.20	5.85
Jamestown	9.78	7.95	Warwick	8.53	8.11
Johnston	6.74	4.54	West Greenwich	9.14	7.48
Lincoln	8.11	6.30	West Warwick	7.97	6.52
Little Compton	9.47	6.20	Westerly	8.73	7.09
Middletown	8.71	9.50	Woonsocket	8.43	7.04
Narragansett	8.56	7.73	Average	8.24	7.18

Table B.10. Economic category, income and employment score

Income and employment score					
Municipality	K	L	Municipality	K	L
Barrington	9.84	4.29	New Shoreham	6.56	3.60
Bristol	5.34	3.03	Newport	5.48	5.17
Burrillville	5.50	2.94	North Kingstown	6.75	4.33
Central Falls	0.00	2.57	North Providence	5.03	4.04
Charlestown	5.68	2.97	North Smithfield	7.14	4.03
Coventry	5.82	3.78	Pawtucket	2.57	2.52
Cranston	4.94	2.84	Portsmouth	6.97	3.40
Cumberland	6.57	6.33	Providence	1.73	2.15
East Greenwich	9.37	3.78	Richmond	7.12	5.95
East Providence	4.31	2.81	Scituate	7.32	4.94
Exeter	6.00	3.63	Smithfield	6.48	2.90
Foster	7.00	3.08	South Kingstown	5.89	3.14
Glocester	6.37	4.26	Tiverton	6.43	3.63
Hopkinton	6.06	5.19	Warren	5.10	3.88
Jamestown	8.29	4.30	Warwick	5.97	4.57
Johnston	5.59	4.06	West Greenwich	7.11	3.71
Lincoln	6.23	5.39	West Warwick	3.76	3.77
Little Compton	7.05	4.12	Westerly	5.68	4.37
Middletown	5.71	4.02	Woonsocket	1.92	2.59
Narragansett	5.80	4.29	Average	5.81	3.86

Table B.11. Economic category, value and mobility and connectivity score

Value and mobility & connectivity score					
Municipality	M	N	Municipality	M	N
Barrington	1.28	7.28	New Shoreham	7.78	4.44
Bristol	3.16	6.08	Newport	4.61	3.53
Burrillville	2.81	4.08	North Kingstown	2.29	8.32
Central Falls	1.99	6.58	North Providence	2.57	7.93
Charlestown	2.49	6.72	North Smithfield	1.77	7.94
Coventry	3.04	7.30	Pawtucket	2.59	7.19
Cranston	3.04	7.94	Portsmouth	1.53	7.36
Cumberland	1.97	7.61	Providence	3.61	6.47
East Greenwich	2.33	8.64	Richmond	3.28	6.93
East Providence	2.14	8.05	Scituate	2.92	7.17
Exeter	4.68	6.55	Smithfield	3.30	7.90
Foster	3.57	6.14	South Kingstown	3.77	6.82
Glocester	3.62	4.71	Tiverton	1.90	6.66
Hopkinton	3.53	7.22	Warren	2.38	5.18
Jamestown	3.74	5.87	Warwick	2.68	8.51
Johnston	2.29	8.02	West Greenwich	2.29	6.76
Lincoln	2.16	8.43	West Warwick	5.25	7.92
Little Compton	2.03	6.65	Westerly	2.14	8.64
Middletown	2.14	6.88	Woonsocket	2.34	6.63
Narragansett	3.84	6.74	Average	2.94	6.92

APPENDIX C

Data for Derivation of Municipal Water Demand

The following figures display the data which was used to derive the water demand per municipality as described in detail in section 3.2.2. Next to the values from figure C.2 public supply data for New Shoreham and the Richmond Water Supply System were retrieved from the strategic plan worked out by RIWRB, which has otherwise only been consulted for self supply estimates. [103]

- New Shoreham public supply **0.1 MGD**
- Richmond Water Supply System public supply **0.06 MGD** [102]

Furthermore, the strategic plan reports public and self supply for four study regions, which are displayed in figure C.1. The featured public supply figures of this report were not used as they are from 2005 and therefore more likely to be outdated than the values from 2010 as reported by Rhode Island Water 2030. Furthermore, tables C.1 to C.4 show all self supply values for the municipalities from 2005 as listed in the strategic plan of RIWRB. The sum of the apportioned public supply and self supply has been used to determine the per capita demand on which the communities were subsequently compared to one another. [102]

Figure C.1. Study regions from RIWRB strategic plan (Adapted from RIWRB 2012 [102])

Table C.1. Self supply for municipalities in Islands Region (Data from RIWRB 2012 [102])

Municipality	2005 Average Demand in MGD	2025 Average Demand in MGD	Buildout Average Demand in MGD
Jamestown Self	0.2	0.2	0.2
New Shoreham Self	0.2	0.2	0.2
Total Islands Region	0.8	0.9	1.1

Table C.2. Self supply for municipalities in Northern Region (Data from RIWRB 2012 [102])

Municipality	2005 Average Demand in MGD	2025 Average Demand in MGD	Buildout Average Demand in MGD
Barrington	0.1	0.1	0.1
Bristol	0.2	0.2	0.2
Burriville	3.2	4	4.9
Central Falls	0	0	0
Coventry	0.6	-	-
Cranston	0.1	0.1	0.1
Cumberland	0.2	0.2	0.2
East Greenwich	0.3	0.3	0.3
East Providence	0.1	0.1	0.1
Foster	0.3	0.3	1.7
Glocester	0.4	0.8	1.1
Harrisville and Pascoag	0.6	0.7	1.5
Johnston	0.3	0.3	0.3
Lincoln	0.1	0.1	0.1
North Smithfield	0.1	0.1	0.1
North Providence	0	0	0
Pawtucket	0.1	0.1	0.1
Providence	0	0	0
Scituate	0.6	0.8	1.4
Smithfield	0.3	0.3	0.3
Warren	0.1	0.1	0.1
Warwick	0.1	0.1	0.1
West Warwick	0	0	0
Woonsocket	2	2	2
Total Self Supply Northern Region	10	10.8	14.8
Allowable Depletion (SDM)	16.9	16.9	16.9
Surplus	6.9	6.1	2.1

Table C.3. Self supply for municipalities in Southern Region (Data from RIWRB 2012 [102])

Municipality	2005 Average Demand in MGD	2025 Average Demand in MGD	Buildout Average Demand in MGD
Charlestown	0.5	0.7	1.7
Exeter	0.7	0.7	1.7
Hopkinton	0.8	0.8	1.7
Narragansett	0.1	0.1	0.1
North Kingstown	0.4	0.4	0.4
Richmond	1	1.6	3
South Kingstown	0.9	1.8	2.4
West Greenwich	0.4	0.5	1.3
Westerly	0.4	0.5	0.5
Southern Region Total	5.3	7.1	12.8
Increase Over Current	-	1.8	7.5

Table C.4. Self supply for municipalities in Aquidneck Region (Data from RIWRB 2012 [102])

Municipality	2005 Average Demand in MGD	2025 Average Demand in MGD	Buildout Average Demand in MGD
Little Compton	0.3	0.3	0.6
Middletown	0.3	0.3	0.3
Newport	0.1	0.1	0.1
Portsmouth	0.3	0.3	0.3
Tiverton	0.4	0.8	0.9
Total Aquidneck Region Self Supply	1.4	1.8	2.2
Increase over Current	-	0.4	0.8

Water Supplier	Recent ADD	Maximum DD	5 Year Anticipated ADD	20 Year Anticipated ADD	Available Water
Bristol County	3.75	5.01	4.80	5.00	10.9
Cumberland	2.86	5.57	3.36	3.80	8.94
East Providence	5.25	8.81	5.33	5.59	7.34
East Smithfield	0.71	2.22	0.83	1.16	0.91
Greenville	0.97	Not available	1.26	1.36	1.21
Harrisville	0.55	1.09	0.60	0.65	1.45
Jamestown	0.19	0.39	0.21	0.23	0.58
Johnston	0.81	1.23	4.70	4.70	4.7
Kent County	11	21.1	11.60	13.40	31.79
Kingston	0.42	0.68	0.33	0.33	2.4
Lincoln	2.25	Not available	2.40	2.71	3.32
Narragansett	0.76	1.82	0.79	0.81	2.57
Newport	7.8	12.48	8.34	9.30	12.2
North Kingstown	3	5.7	2.86	3.75	7.8
North Tiverton	0.52	Not available	0.86	1.12	0.7
Pascoag	0.65	1.23	0.90	0.85	4.7
Pawtucket	10.42	20.23	11.02	11.32	19.6
Portsmouth	1.31	2.56	1.37	1.45	1.53
Providence (Retail Service Area)	31.45	Not available	32.18	33.63	83
Quonset	0.63	1.2	0.81	1.37	4.95
Smithfield	0.95	1.7	1.10	1.70	1.97
South Kingstown	0.47	1.11	0.58	0.78	1.38
Stone Bridge	0.65	Not available	0.81	1.12	1.9
United Water	3	5.91	3.72	Not available	6.74
URI	0.42	Not available	0.44	0.50	0.49
Warwick	8.81	19.84	9.54	9.60	11.35
Westerly	3.43	6.49	3.52	3.95	6.93
Woonsocket	5.3	6.9	5.80	6.80	8
Total ADD	108.33		120.06	126.98	
Providence (Retail Service Area)	31.45	Not available	32.18	33.63	83
Providence (Wholesale)	32.32	Not available	32.32	34.44	83
Providence (Total)	68.14	113.5	71.7^	75.6^	83

Figure C.2. Public water supply figures as reported by Rhode Island Water 2030 (Adapted from RISPP 2012 [103])

APPENDIX D

Criteria for Derivation of Residential Energy Demand

The following tables display the criteria from which the residential energy demand per capita has been derived as described in detail in section 3.2.2. The values have been retrieved from the RECS 2009 as worked out by the EIA for end-use expenditures in relation to Northeast homes. Furthermore, the next iteration of this survey will be published in 2018. [140]

Table D.1. Residential household energy demand for year the structure was built (Data from EIA 2017 [140])

Year of construction	Per household in million Btu	Per household in kWh
Before 1940	109.20	32,003.4
1940 to 1949	108.30	31,739.6
1950 to 1959	116.10	34,025.6
1960 to 1969	104.20	30,538.0
1970 to 1979	94.50	27,695.2
1980 to 1989	100.30	29,395.0
1990 to 1999	107.60	31,534.5
2000 to 2009	119.90	35,139.2

Table D.2. Residential household energy demand for annual income (Data from EIA 2017 [140])

Annual household income	Per household in million Btu	Per household in kWh
Less than \$20,000	83.3	24,412.8
\$20,000 to \$39,999	98.2	28,779.6
\$40,000 to \$59,000	98.9	28,984.7
\$60,000 to \$79,999	99.9	29,277.8
\$80,000 to \$99,999	119.2	34,934.1
\$100,000 to \$119,999	131.1	38,421.6
\$120,000 or More	154.8	45,367.4

Table D.3. Residential household energy demand for tenure (Data from EIA 2017 [140])

Tenure	Per household in million Btu	Per household in kWh
Owned	124.5	36,487.4
Rented	79.5	23,299.2

Table D.4. Residential household energy demand for household size (Data from EIA 2017 [140])

Number of Household Members	Per household in million Btu	Per household in kWh
1 Person	81.1	23,768.1
2 Persons	106.7	31,270.7
3 Persons	118	34,582.4
4 Persons	123.6	36,223.6
5 Persons	144.2	42,260.9
6 or more Persons	150.5	44,107.20

Table D.5. Residential household energy demand for unit type (Data from EIA 2017 [140])

Housing Unit Type	Per household in million Btu	Per household in kWh
Single-Family	126.9	37,190.7
Multi-Family	77.4	22,683.7

BIBLIOGRAPHY

- Adil Najam, David Runnalls, and Mark Halle, *Environment and Globalization: Five Propositions*. Winnipeg, Canada: International Institute for Sustainable Development, 2007.
- Akanda, A. S. and Hossain, F., “The Climate-Water-Health-Nexus in Emerging Megacities,” *American Geophysical Union*, vol. 93, no. 37, pp. 353–360, 2012.
- Akbari, H., “Energy Saving Potentials and Air Quality Benefits of Urban Heat Island Mitigation,” *Heat Island Group*, vol. 56, pp. 5–6, 2001.
- American Association of State Highway and Transportation Officials, *Transportation and Sustainability: Best Practices Background*. Washington D.C.: Center for Environmental Excellence, 2009.
- American Society of Civil Engineers, “Infrastructure in Rhode Island: 2017 Infrastructure Report Card,” 11.06.2017. [Online]. Available: <https://www.infrastructurereportcard.org/state-item/rhode-island/>
- Anthony Arguez et al., “NOAA’s 1981–2010 U.S. Climate Normals: An Overview,” *Bulletin of the American Meteorological Society*, vol. 93, no. 11, pp. 1687–1697, 2012.
- Arcadis, *Sustainable Cities Index 2016: Putting people at the heart of city sustainability*. Amsterdam: Arcadis, 2016.
- Avdan, U. and Jovanovska, G., “Algorithm for Automated Mapping of Land Surface Temperature Using LANDSAT 8 Satellite Data,” *Journal of Sensors*, vol. 2016, no. 2, pp. 1–8, 2016.
- Binks, A. N., Kenway, S. J., Lant, P. A., and Head, B. W., “Understanding Australian household water-related energy use and identifying physical and human characteristics of major end uses,” *Journal of Cleaner Production*, vol. 135, pp. 892–906, 2016.
- Brears, R. C., *Urban water security*, ser. Challenges in water management series. Chichester, UK and Hoboken, NJ: John Wiley & Sons, 2016.
- Brendan Murphy, Andrew Owen, and David Levinson, *Access Across America: Transit 2015: Final Report*. University of Minnesota: Accessibility Observatory, 2015.
- Brunekreef, B. and Holgate, S. T., “Air pollution and health,” *Lancet*, vol. 360, no. 42, pp. 1233–1243, 2002.

- Buchin, O., Hoelscher, M.-T., Meier, F., Nehls, T., and Ziegler, F., "Evaluation of the health-risk reduction potential of countermeasures to urban heat islands," *Energy and Buildings*, vol. 114, pp. 27–37, 2016.
- Bugliarello, G., "Urban sustainability: Dilemmas, challenges and paradigms," *Technology in Society*, vol. 28, no. 1-2, pp. 19–26, 2006.
- Bureau of Economic Analysis, "Regional Data: Gross Domestic Product by State," 13.06.2017. [Online]. Available: https://www.bea.gov/iTable/index_regional.cfm
- Burke, J. K., Crawley, K., and Mendes, R., *2012 Strategic Plan*. Providence: Rhode Island Water Resource Board, 2012.
- Carl Vinson Institute of Government, *A Brief Summary of Municipal Incorporation Procedures by State*. Athens: The University of Georgia, 2015.
- Caruso, J. C., Coduri, J. E., and Moss, S. D., *Municipal Charters in Rhode Island: Home Rule in Rhode Island: 50 Years Later*. Providence: Rhode Island Department of Revenue, 2013.
- Cassius Shuman, "Island operating on wind farm power," 14.05.2017. [Online]. Available: <http://www.blockislandtimes.com/article/island-operating-wind-farm-power/49352>
- Chitra, S. V., Harindranathan, M. N., Amarnath, A., and Anjana, N., "Impacts of Impervious Surfaces on the Environment," *International Journal of Engineering Science Invention*, vol. 4, no. 5, pp. 27–31, 2015.
- Christopher D. Elvidge et al., "Global Distribution and Density of Constructed Impervious Surfaces," *Sensors*, vol. 7, no. 9, pp. 1962–1979, 2007.
- Cohen, B., "Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability," *Technology in Society*, vol. 28, no. 1-2, pp. 63–80, 2006.
- Cohen, T. D., Hatchard, W. G., and Wilson, G. S., *Population Trends in Incorporated Places: 2000 to 2013: Current Population Reports*. Washington D.C.: U.S. Government Printing Office, 2015.
- Daniels, T. L. and Daniels, K., *The environmental planning handbook for sustainable communities and regions*. Chicago: Planners Press, American Planning Association, 2003.
- Danny Musher, Office of Energy Resources, "e-mail correspondence: data for thesis," 04.04.2017.

- de Gouw, J. A., Parrish, D. D., Frost, G. J., and Trainer, M., “Reduced Emissions of CO₂, NO_x and SO₂ from U.S. Power Plants Due to the Switch from Coal to Natural Gas with Combined Cycle Technology,” *Earth’s Future*, pp. n/a–n/a, 2014.
- Dewan, A. and Corner, R., Eds., *Dhaka Megacity: Geospatial Perspectives on Urbanisation, Environment and Health*, ser. Springer Geography. Dordrecht and s.l.: Springer Netherlands, 2014.
- Don Chen et. al., *US and Canada Green City Index: Assessing the environmental performance of 27 major US and Canadian cities*. New York: Economist Intelligence Unit, 2011.
- Elizabeth Minne et al., Ed., *Water, energy, land use, transportation and socioeconomic nexus: A blue print for more sustainable urban systems*, Chicago, USA, 2011.
- Encyclopedia Britannica, “Humid continental climate,” 13.05.2017. [Online]. Available: <https://www.britannica.com/science/humid-continental-climate>
- Encyclopedia Britannica, “Rhode Island,” 13.05.2017. [Online]. Available: <https://www.britannica.com/place/Rhode-Island-state>
- Endo, A., Tsurita, I., Burnett, K., and Orencio, P. M., “A review of the current state of research on the water, energy, and food nexus,” *Journal of Hydrology: Regional Studies*, 2015.
- Energy Information Administration, “Electricity: Detailed State Data,” 06.06.2017. [Online]. Available: <https://www.eia.gov/electricity/data/state/>
- Energy Information Administration, “Electricity: Form EIA-923 detailed data,” 06.06.2017. [Online]. Available: <https://www.eia.gov/electricity/data/eia923/>
- Energy Information Administration, “Electricity: Form EIA-860 detailed data,” 07.06.2017. [Online]. Available: <https://www.eia.gov/electricity/data/eia860/>
- Energy Information Administration, “Maps: Layer Information for Interactive State Maps,” 11.06.2017. [Online]. Available: https://www.eia.gov/maps/layer_info-m.php
- Energy Information Administration, “Residential Energy Consumption Survey,” 12.05.2017. [Online]. Available: <https://www.eia.gov/consumption/residential/data/2009/>
- Energy Information Administration, “Electricity: State Electricity Profiles,” 18.05.2017. [Online]. Available: <https://www.eia.gov/electricity/state/RhodeIsland/>

- Energy Information Administration, “2015 Average Monthly Bill Residential,” 19.05.2017. [Online]. Available: https://www.eia.gov/electricity/sales_revenue_price/pdf/table5_a.pdf
- Energy Information Administration, “U.S. States: State Profiles and Energy Estimates, Rankings,” 20.05.2017. [Online]. Available: <https://www.eia.gov/state/rankings/#!/series/12>
- Energy Information Administration, “About EIA,” 25.06.2017. [Online]. Available: <https://www.eia.gov/about/>
- Environmental Data Center, “Rhode Island Geographic Information System (RIGIS) Data Distribution System,” Kingston, 20.03.2017. [Online]. Available: <http://www.rigis.org/>
- Environmental Protection Agency, “Indoor Air Quality: Wood Smoke,” 11.06.2017. [Online]. Available: <https://www.epa.gov/indoor-air-quality-iaq/wood-smoke>
- Excel Team, “Visualize Statistics with Histogram, Pareto and Box and Whisker charts,” 12.06.2017. [Online]. Available: <https://blogs.office.com/2015/08/18/visualize-statistics-with-histogram-pareto-and-box-and-whisker-charts/>
- Farhad Atash, *CPL 410 Introduction to Community Planning: Lecture Notes*. South Kingstown: University of Rhode Island, 2014.
- Federal Bureau of Investigations, “2015 Crime in the United States,” 19.05.2017. [Online]. Available: <https://ucr.fbi.gov/crime-in-the-u.s>
- Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., and Mastrandrea, M. D., *Climate Change 2014 Impacts, Adaptation, and Vulnerability*. New York: Cambridge University Press, 2014.
- Fontana, A. C., Trejo, L., and Reyes, A., *Vital Statistics Annual Report 2005*. Providence: Rhode Island Department of Health, 2014.
- Gober, P., Brazel, A., Quay, R., and Myint, S., “Using Watered Landscapes to Manipulate Urban Heat Island Effects: How Much Water Will It Take to cool Phoenix,” *Journal of the American Planning Association*, vol. 76, pp. 109–121, 2010.
- Graber, D. S. and Birmingham, K. A., Eds., *Urban planning in the 21st century: Planning and Sustainability*. Hauppauge, N.Y: Nova Science Publishers, 2009.
- Guhathakurta, S. and Gober, P., “The impact of the Phoenix Urban Heat Island on Residential Water Use,” *Journal of the American Planning Association*, vol. 73, no. 3, pp. 317–329, 2007.

- H. Hoff, *Understanding the Nexus: Background paper for the Bonn 2011 Nexus Conference: The Water, Energy and Food Security Nexus*. Stockholm: Stockholm Environment Institute, 2011.
- Haas, d. D. and Dancey, M., “Wastewater Treatment Energy Efficiency: A review of current Australian perspectives,” *Australian Water Association*, pp. 53–58, 2015.
- Haas, T. P., “Constitutional Home Rule in Rhode Island,” *Roger Williams University Law Review*, vol. 11, no. 3, pp. 1–45, 2006.
- Hake, J.-F., Schlör, H., Schürmann, K., and Venghaus, S., “Ethics, Sustainability and the Water, Energy, Food Nexus Approach – A New Integrated Assessment of Urban Systems,” *Energy Procedia*, vol. 88, pp. 236–242, 2016.
- Hashem Akbari et al., “Local climate change and urban heat island mitigation techniques: The state of the art,” *Journal of Civil Engineering and Management*, vol. 22, no. 1, pp. 1–16, 2015.
- Heffner, L., Williams, R., Lee, V., Rubinoff, P., and Lord, C., Eds., *Climate Change and Rhode Island’s Coasts: Past, Present and Future*. South Kingstown: Rhode Island Sea Grant, 2012.
- HousingWorksRI, *2015 Housing Fact Book*. Providence: Roger Williams University, 2015.
- International Organisation for Standardisation, “ISO 37120:2014: Sustainable development of communities - Indicators for city services and quality of life,” 01.05.2017. [Online]. Available: <https://www.iso.org/obp/ui/#iso:std:iso:37120:ed-1:v1:en>
- INTRASOFT International, Ed., *Indicators for sustainable cities*, ser. Science for Environment Policy In-depth report. Luxembourg: Publications Office of the European Union, 2015, vol. issue 12 (November 2015). [Online]. Available: <http://dx.doi.org/10.2779/61700>
- Jean O’Dwyer, Aideen Dowling, and Catherine Adley, “The impact of climate change on the incidence of infectious waterborne disease,” *ResearchGate*, 2016.
- Jones, C., *The history and future of Narragansett Bay*. Boca Raton, Fla.: Universal Publishers, 2006.
- Julia A. Barsi et al., “Landsat-8 Thermal Infrared Sensor (TIRS) Vicarious Radiometric Calibration,” *Remote Sensing*, vol. 6, no. 11, pp. 11 607–11 626, 2014.

- Kalbar, P. P., Birkved, M., Karmakar, S., Nygaard, S. E., and Hauschild, M., "Can carbon footprint serve as proxy of the environmental burden from urban consumption patterns?" *Ecological Indicators*, vol. 74, pp. 109–118, 2017.
- Kates, R. W., Parris, T. M., and Leiserowitz, A. A., "What Is Sustainable Development? Goals, Indicators, Values, and Practice," *Environment Science and Policy for Sustainable Development*, vol. 47, no. 3, pp. 8–21, 2005.
- Kennedy, C., Cuddihy, J., and Engel-Yan, J., "The Changing Metabolism of Cities," *Journal of Industrial Ecology*, vol. 0, no. 0, p. 070322093406001, 2007.
- Kenway, S. J. and Lam, K. L., "Quantifying and managing urban water-related energy use systemically: Case study lessons from Australia," *International Journal of Water Resources Development*, vol. 32, no. 3, pp. 379–397, 2015.
- Kotkin, J., Cox, W., Modarres, A., and Renn, A. M., *The Problem With Megacities*. Orange: Chapman University Press, 2014.
- Lam, K. L., Kenway, S. J., and Lant, P. A., "Energy use for water provision in cities," *Journal of Cleaner Production*, vol. 143, pp. 699–709, 2017.
- Law, M. and Collins, A., *Getting to know ArcGIS*, 4th ed. Redlands, Calif.: Esri Press, 2015.
- Lee, S., Quinn, A., and Rogers, C., "Advancing City Sustainability via Its Systems of Flows: The Urban Metabolism of Birmingham and Its Hinterland," *Sustainability*, vol. 8, no. 3, p. 220, 2016.
- Levy, J. M., *Contemporary Urban Planning*, 10th ed. Hoboken: Taylor and Francis, 2015.
- Macknick, J., Newmark, R., Heath, G., and Hallett, K. C., *Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies*. Golden: National Renewable Energy Laboratory, 2011.
- Martin Jänicke, "Conditions for environmental policy success: An international comparison," *Environmentalist*, vol. 12, no. 1, pp. 47–58, 1992. [Online]. Available: <https://link.springer.com/article/10.1007/BF01267594>
- McGeehin, M. A. and Mirabelli, M., "The Potential Impacts of Climate Variability and Change on Temperature-Related Morbidity and Mortality in the United States," *Environmental Health Perspectives*, vol. 109, p. 185, 2001.
- Melanie Dawn, "Introduction to LEED V4," 01.06.2017. [Online]. Available: <http://miami-urban-green.com/introduction-to-leed-v4/>
- Molly A. Maupin et al., *Estimated use of water in the United States in 2010*, ser. US Geological Survey circular. Reston, Va.: US Geological Survey, 2014, vol. 1405.

- Moreno, E., McCarney, P., and Arimah, *World Cities Report 2016: Urbanization and Development: Emerging Futures*. Nairobi: United Nations Human Settlements Program, 2016.
- Murdoch, P. S., Baron, J. S., and Miller, T. L., “Potential Effects Of Climate Change on Surface-Water Quality in North America,” *Journal of the American Water Resources Association*, vol. 36, no. 2, pp. 1–20, 2000.
- National Geographic, “urban area,” 11.05.2017. [Online]. Available: <https://www.nationalgeographic.org/encyclopedia/urban-area/>
- National Highway Safety Administration, “State Traffic Safety Information: Rhode Island,” 15.05.2017. [Online]. Available: <https://cdan.nhtsa.gov/stsi.htm#>
- National Oceanic and Atmospheric Administration, “What is Climate Change,” 10.05.2017. [Online]. Available: <http://www.nws.noaa.gov/om/brochures/climate/Climatechange.pdf>
- National Oceanic and Atmospheric Administration, “National Centers for Environmental Information: Climate Data Online Search,” 11.05.2017. [Online]. Available: <https://www.ncdc.noaa.gov/cdo-web/search>
- National Oceanic and Atmospheric Administration, “Shoreline Mileage of The United States,” 12.05.2017. [Online]. Available: <https://coast.noaa.gov/data/docs/states/shorelines.pdf>
- National Oceanic and Atmospheric Administration, “Land-Based Datasets and Products,” 13.05.2017. [Online]. Available: <https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets>
- National Transit Database Program, *Rhode Island Public Transit Authority: 2014 Agency Profile*. Washington D.C.: Federal Transit Authority, 2014.
- Neff, J. and Dickens, M., *Public Transportation Fact Book*, 67th ed. Washington D.C.: American Public Transportation Association, 2016.
- NOAA National Centers for Environmental Information, “State Climate Summaries: Rhode Island,” 11.05.2017. [Online]. Available: <https://statesummaries.ncics.org/ri>
- Peach, D. N. and Petach, A. L., “Development and Quality of Life in Cities,” *Economic Development Quarterly*, vol. 30, no. 1, pp. 32–45, 2016.
- Petri, Y. and Caldeira, K., “Impacts of global warming on residential heating and cooling degree-days in the United States,” *Scientific reports*, vol. 5, p. 12427, 2015.

- Pittock, J., Hussey, K., and Dovers, S. R., Eds., *Climate, energy and water: Managing trade-offs, seizing opportunities*. Cambridge: Cambridge Univ. Press, 2015.
- Pollalis, S. N., Georgoulas, A., Ramos, S. J., and Schodek, D., Eds., *Infrastructure Sustainability and Design*. Hoboken: Taylor & Francis, 2012.
- Portney, K. E., *Sustainability*, ser. MIT Press essential knowledge series. Cambridge, Massachusetts: MIT Press, 2015.
- Potter, K., *Methods for Presenting Statistical Information: The Box Plot*. Salt Lake City: University of Utah, 2006.
- ProximityOne, "Neighborhood Analysis: Using census block & block group demographics," 11.05.2017. [Online]. Available: <http://proximityone.com/chelsea.htm>
- Rabin and Jack, Eds., *Encyclopedia Of Public Administration and Public Policy: County Government*. New York, NY: Marcel Dekker, Inc., 2003.
- Ratcliffe, M., Burd, C., Holder, K., and Fields, A., *Defining Rural at the U.S. Census Bureau: American Community Survey and Geography Brief*. Washington D.C.: U.S. Government Printing Office, 2016.
- Rhode Island Climate Change Commission, *Adapting to Climate Change in the Ocean State: A Starting Point: 2012 Progress Report*. Rhode Island: Rhode Island Climate Change Commission, November 2012.
- Rhode Island Department of Environmental Management, "Air Resources," 05.06.2017. [Online]. Available: <http://www.dem.ri.gov/programs/air/>
- Rhode Island Department of Environmental Management, "Waste Water Treatment Facilities," 12.06.2017. [Online]. Available: <http://www.dem.ri.gov/programs/water/wwtf/>
- Rhode Island Department of Environmental Management, "Emissions Inventory," 20.05.2017. [Online]. Available: <http://www.dem.ri.gov/programs/air/emissions.php>
- Rhode Island Department of Environmental Management, *Air Quality Summary: State of Rhode Island*. Providence: DEM, 2011.
- Rhode Island Department of Environmental Management, *Land Conservation and Acquisition Program: Annual Report Fiscal Year 2011*. Providence: DEM, 2011.
- Rhode Island Department of Environmental Management, *Summary of Rhode Island Municipal Onsite Wastewater Programs*. Providence: DEM, 2014.

- Rhode Island Department of Environmental Management, *Office of Air Resources: Rhode Island 2016 Annual Monitoring Network Plan*. DEM: Providence, 2016.
- Rhode Island Department of Environmental Management, “Overview of Climate in Rhode Island,” 22.06.2017. [Online]. Available: <http://www.dem.ri.gov/climate/climate-overview-ri.php>
- Rhode Island Department of Transportation, “Rhode Works,” 13.06.2017. [Online]. Available: <http://www.dot.ri.gov/rhodeworks/>
- Rhode Island Executive Climate Change Council, “A Resilient Rhode Island: Being Practical About Climate Change,” 28.05.2017. [Online]. Available: <http://www.planning.ri.gov/documents/climate/EC3ReportJune2014final.pdf>
- Rhode Island Public Transportation Authority, “Flex Service,” 14.06.2017. [Online]. Available: <http://www.ripta.com/flex-service>
- Rhode Island Public Utilities Commission, “Division of Public Utilities and Carriers,” 11.06.2017. [Online]. Available: <http://www.ripuc.org/>
- Rhode Island Resource Recovery Corporation, “Annual Metrics: Municipal Summary,” 14.05.2017. [Online]. Available: <http://www.rirrc.org/municipal-officials-haulers/municipal-officials/annual-metrics>
- Rhode Island Resource Recovery Corporation, “About us,” 18.05.2017. [Online]. Available: <http://www.rirrc.org/about>
- Rhode Island Sea Grant, “Climate Change to Home Septic Systems,” 10.05.2017. [Online]. Available: <http://seagrants.gso.uri.edu/climate-change-threat-home-septic-systems/>
- Rhode Island Statewide Planning Program, “Comprehensive Plans and State Approval Status,” 15.06.2017. [Online]. Available: <http://www.planning.ri.gov/planning-areas/local-comprehensive-planning/plans-currently-under-review.php>
- RI Datahub, “Data Catalogue,” 11.05.2017. [Online]. Available: <http://ridatahub.org/dictionary/indicator-search/>
- RI Government, “Rhode Island Cities and Towns,” 10.05.2017. [Online]. Available: <https://www.ri.gov/towns/>
- RI Government, “Historical Information,” 13.05.2017. [Online]. Available: <http://www.ri.gov/facts/history.php>
- Rimjhim M. Aggarwal et al., “How do variations in Urban Heat Islands in space and time influence household water use? The case of Phoenix, Arizona,” *Water Resource Research*, vol. 48, 2012.

- Roger Anders, “The Federal Energy Administration,” 12.04.2017. [Online]. Available: <https://www.energy.gov/sites/prod/files/FEA%20History.pdf>
- Shellito, B. A., *Discovering GIS and ArcGIS*. New York, NY: W. H. Freeman, 2015.
- Silva, H. and Fillpot, B. S., “Modeling nexus of urban heat island mitigation strategies with electricity/power usage and consumer costs: A case study for Phoenix, Arizona, USA,” *Theoretical and Applied Climatology*, 2016.
- Sirgy, J. M., Lee, D.-J., Miller, C., and Littlefield, J. E., “The Impact of Globalization on a Country’s Quality of Life: Toward an Integrated Model,” *Social Indicators Research*, vol. 68, pp. 251–298, 2004.
- Spath, P. L. and Mann, M. K., *Life Cycle Assessment of a Natural Gas Combined Cycle Power Generation System*. Golden: National Renewable Energy Laboratory, 2000.
- State of Rhode Island Board of Elections, “Department of Administration: Division of Planning,” 07.02.2017. [Online]. Available: <http://www.planning.ri.gov/>
- State of Rhode Island Board of Elections, “Previous Election Results: Statewide Primary,” 13.05.2017. [Online]. Available: <http://www.elections.state.ri.us/elections/preresults/>
- State of Rhode Island Department of Revenue, “Assessed Values & Levies,” 16.05.2017. [Online]. Available: <http://www.municipalfinance.ri.gov/data/tax-levies/>
- Statewide Planning Program, *Land Use 2025: Rhode Island State Land Use Policies and Plan*. Providence: Department of Administration, 2006.
- Statewide Planning Program, *Rhode Island Water 2030: State Guide Plan Element 721, Report 115*. Providence: Rhode Island Department of Administration, 2012.
- Statewide Planning Program, *Transportation 2035: Long Range Transportation Plan*. Providence: Rhode Island Department of Administration, 2012.
- Statewide Planning Program, *Energy 2035: Rhode Island State Energy Plan*. Providence: Rhode Island Department of Administration, 2015.
- Statewide Planning Program, *Solid Waste 2038: Rhode Island Comprehensive Solid Waste Management Plan*. Providence: Rhode Island Department of Administration, 2015.
- Statewide Planning Programm, *Rhode Island Rising: A Plan For People, Places and Prosperity*. Providence: Rhode Island Department of Administration, December 2014.

- SUNY Levin Institute, “What Is Globalization,” 14.06.2018. [Online]. Available: <http://www.globalization101.org/what-is-globalization/>
- Szibbo, N. A., “Assessing Neighborhood Livability: Evidence from LEED for Neighborhood Development and New Urbanist Communities,” *Articulo Journal of Urban Research*, no. 14, 2015.
- Thakuriah, P., Tilahun, N., and Zellner, M., Eds., *Seeing Cities Through Big Data: Research, Methods and Applications in Urban Informatics*, ser. Springer Geography. Cham and s.l.: Springer International Publishing, 2017.
- The World Bank, “Overview,” 02.02.2017. [Online]. Available: <http://www.worldbank.org/en/topic/urbandevelopment/overview#1>
- Theis, T. and Tomkin, J., Eds., *Sustainability: A Comprehensive Foundation*. Houston Texas: Rice University, 2012. [Online]. Available: <http://cnx.org/content/col11325/1.38/>
- Thomas J. Crowley, “Causes of Climate Change Over the Past 1000 Years,” *Science*, vol. 289, 2000.
- Tomas Smieszek United States Geological Survey, “e-mail correspondence: water usage data Rhode Island,” 30.03.2017.
- Torcellini, P., Long, N., and Judkoff, R., *Consumptive Water Use for U.S. Power Production*. Golden: National Renewable Energy Laboratory, 2003.
- UN Habitat, *Global Report on Human Settlements 2011: Cities and Climate Change*, ser. Global report on human settlements. London: Earthscan, 2011, vol. 2011.
- UN Habitat, *Prosperity of cities*, ser. The state of the world’s cities. New York: Routledge, 2013, vol. 2012/2013.
- United Nations, “SDG Indicators: Revised list of global Sustainable Development Goal indicators,” 17.05.2017. [Online]. Available: <https://unstats.un.org/sdgs/indicators/indicators-list/>
- United Nations, *World Urbanization Prospects: The 2011 Revision*. New York: United Nations, 2012.
- United Nations, *World economic and social survey 2013: Sustainable development challenges*, ser. Economic & social affairs. New York: United Nations, 2013, vol. 2013.
- United Nations, Department of Economic and Social Affairs, Population Division, Ed., *World Urbanization Prospects: The 2014 Revision, Highlights*. (ST/ESA/SER.A/352), 2014.

- United States Census Bureau, "About the Bureau," 03.04.2017. [Online]. Available: <https://www.census.gov/about.html>
- United States Census Bureau, "American Community Survey: Concepts and Definitions," 11.04.2017. [Online]. Available: <https://www.census.gov/programs-surveys/acs/geography-acs/concepts-definitions.html>
- United States Census Bureau, "American Community Survey: Information Guide," 11.04.2017. [Online]. Available: www.census.gov/acs
- United States Census Bureau, "Geographic Areas Reference Manual," 11.05.201. [Online]. Available: <https://www.census.gov/geo/reference/garm.html>
- United States Census Bureau, "2010 Census Data," 11.05.2017. [Online]. Available: <https://www.census.gov/2010census/data/>
- United States Census Bureau, "Guide to State and Local Census Geography," 11.05.2017. [Online]. Available: <https://www.census.gov/geo/reference/geoguide.html>
- United States Census Bureau, "2010 Census Urban and Rural Classification and Urban Area Criteria," 11.05.2107. [Online]. Available: <https://www.census.gov/geo/reference/ua/urban-rural-2010.html>
- United States Census Bureau, "American FactFinder," 12.05.2017. [Online]. Available: <https://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml>
- United States Census Bureau, *United States Summary: 2010: Population and Housing Units Counts*. Washington D.C.: U.S. Government Printing Office, 2012.
- United States Environmental Protection Agency, "TRI Explorer: 2015 Factsheet: State of Rhode Island." [Online]. Available: https://iaspub.epa.gov/triexplorer/tri_factsheet.factsheet_forstate?&pstate=RI&pyear=2015&pParent=TRI&pDataSet=TRIQ1
- United States Environmental Protection Agency, "Water and Energy Efficiency at Utilities and in the Home," 07.03.2017. [Online]. Available: <https://www.epa.gov/sustainable-water-infrastructure/water-and-energy-efficiency-utilities-and-home>
- United States Environmental Protection Agency, "Overview of the Clean Air Act and Air Pollution," 11.06.2017. [Online]. Available: <https://www.epa.gov/clean-air-act-overview>
- United States Environmental Protection Agency, *The Plain English Guide to the Clean Air Act*. Cincinnati: National Service Center for Environmental Publications, 2007.

- United States Environmental Protection Agency, *Heating and Cooling Degree Days: Climate Change Indicators in the United States*. Cincinnati: National Service Center for Environmental Publications, 2016.
- United States Geological Survey, “Using the USGS Landsat 8 Product,” 04.05.2017. [Online]. Available: <https://landsat.usgs.gov/using-usgs-landsat-8-product>
- United States Geological Survey, “Water Use Data available from USGS,” 05.06.2017. [Online]. Available: <https://water.usgs.gov/watuse/data/index.html>
- United States Geological Survey, “Earth Explorer,” 20.03.2017. [Online]. Available: <https://earthexplorer.usgs.gov/>
- United States Geological Survey, *LANDSAT 8 Data Users Handbook: Version 2.0*. Sioux Falls, South Dakota: USGS, 2016.
- United States Geological Survey, “About: Who We Are,” 25.06.2017. [Online]. Available: <https://www.usgs.gov/about/about-us/who-we-are>
- United States Green Building Council, “LEED For Cities Pilot: Performance Score to LEED Certification,” 02.06.2017. [Online]. Available: <http://www.usgbc.org/cityperformance>
- United States Green Building Council, “LEED Projects,” 13.05.2017. [Online]. Available: <http://www.usgbc.org/projects>
- U.S. Department of Transportation, “Geospatial at the Bureau of Transportation Statistics,” 20.03.2017. [Online]. Available: <http://osav-usdot.opendata.arcgis.com/>
- Venkatesh, G., Chan, A., and Brattebø, H., “Understanding the water-energy-carbon nexus in urban water utilities: Comparison of four city case studies and the relevant influencing factors,” *Energy*, vol. 75, pp. 153–166, 2014.
- Virginia W. Maclaren, “Urban Sustainability Reporting,” *Journal of the American Planning Association*, vol. 62, no. 2, pp. 184–202, 1996. [Online]. Available: <http://dx.doi.org/10.1080/01944369608975684>
- Vogt, C., Zimmerman, M., and Brekke, K., *Operationalizing the Urban Nexus: Towards resource-efficient and integrated cities and metropolitan regions*. Eschborn: Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH, 2014.
- Walker, V. R. and Beck, M. B., “Understanding the metabolism of urban-rural ecosystems,” *Urban Ecosystems*, vol. 15, pp. 809–848, 2012.

- Webber, M. E., *The United Nations World Water Development Report 4: The global nexus of energy and water*, ser. United Nations world water development report. Paris: UNESCO, 2012, vol. 4,3.
- Weinstein, M. P. and Turner, R. E., *Sustainability science: The emerging paradigm and the urban environment*. New York, NY: Springer New York, 2012.
- Weng, Q., Lu, D., and Schubring, J., “Estimation of land surface temperature–vegetation abundance relationship for urban heat island studies,” *Remote Sensing of Environment*, vol. 89, no. 4, pp. 467–483, 2004.
- Wolman, A., “The Metabolism of Cities,” *Scientific American Inc.*, 1965.
- World Commission on Environment and Development, *Report of the World Commission on Environment and Development: Our Common Future*. Nairobi: United Nations, 1987. [Online]. Available: <http://www.un-documents.net/our-common-future.pdf>
- Zhao-Liang Li et al., “Satellite-derived land surface temperature: Current status and perspectives,” *Remote Sensing of Environment*, vol. 131, pp. 14–37, 2013.