The early recognition of environmental impacts of human activities in developing countries

Author(s):
Binder, Claudia R.

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The Early Recognition of Environmental Impacts of Human Activities in Developing Countries

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zur Erlangung des Titels
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der
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vorgelegt von:

Claudia R. Binder
Dipl. Natw. ETH
geboren am 14. Mai, 1966
von Illnau/Effretikon

Angenommen auf Antrag von
Prof. Dr. Peter Baccini, Referent
Ing. Roland Schertenleib, Korreferent
Prof. Dr. Rolf Kappel, Korreferent

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Summary

In urban regions of developing countries, resource depletion and environmental pollution have been accelerating during the last decades. These problems are due to the rapid population growth at an average of 3.5% per annum and the increasing consumption per capita. In the 19th century, industrialized countries experienced similar problems during the period of industrialization. However, they experienced these problems over a period of 100 years, while developing countries are experiencing these problems in one generation. It has been shown that short-term technical measures can have immediate positive effects in reducing environmental pollution. But for long-term planning, it is of primary importance to develop tools which allow a better understanding of the resource demand and environmental impact of human activities.

In industrialized countries, Material Flux Analysis (MFA) has been shown to be a suitable instrument for the early recognition of environmental problems and the analysis of solutions to these problems. It has been shown that it is possible to combine data from market research on the one hand, with data from urban waste management on the other hand, to observe the metabolism of urban regions. In developing countries, however, this method has not been applied due to the poor availability of reliable data.

This thesis developed a tool for early recognition of resource demand and environmental impacts of human activities in developing countries. The specific research questions are:

- Can the method of MFA be applied to study the current demand and use of the natural resources in the region even with poor availability of reliable data?
- How should a monitoring concept be developed for early recognition of resource demand and environmental impacts due to changes in the regional metabolism?
- What will be the impacts of different consumption scenarios on the regional material management system (e.g. resource depletion, environmental pollution)?
- To which extent can technical measures mitigate these impacts?

Tunja, a municipality of 114,000 inhabitants in Colombia, was chosen as the study area to apply the methodology of MFA. The system border was defined as the geographical boundary of the municipality and five subsystems: water, food, durables, paper/cardboard and energy were selected. These subsystems were based on the four human activities "to nourish", "to clean", "to reside and work" and "to transport and communicate" as defined by Baccini and Brunner, (1991). The data collection was carried out by students of the UNIBOYACA for their diploma theses. Mathematical models based on Baccini and Bader (1996) were used for developing scenarios for water and solids.
The two main conclusions of this thesis are:

1. **In Spite of Poor Data Availability and Quality, Material Flux Analysis can be Applied to Regions in Developing Countries.**

   It is possible to develop and validate material flux systems for the subsystems, water, food and durables; (i) the subsystem water is determined by measuring precipitation, water consumption, surface water input and surface water output and validated by the balances of the indicator elements Phosphorous and Carbon. (ii) the subsystem food is determined by measuring the food consumption at the supply processes and validated by comparing the results with data of waste composition. (iii) the subsystem durables is determined by measuring input, stock, lifetime of durables (c) and standard deviation of the lifetime (σ) in a survey and calculating the output-flux of durables using a dynamic model based on the measured parameters. This model is robust with respect to changes in the parameters.

2. **MFA and its mathematical description can be used for**
   (a) *setting up monitoring concepts*
   (b) *the early recognition of resource demand and environmental impacts*
   (c) *evaluating the effect of technical measures in mitigating these impacts*

   Monitoring concepts have to be set up specifically for each study area. In Tunja, monitoring has to focus on the following fluxes; (i) monitoring of surface water quality has to focus on the regional consumption of water, food and detergents, (ii) monitoring of groundwater quantity has to focus on measurements of the water table in order to determine seasonal fluctuations (iii) monitoring of waste composition has to focus on monitoring the supply processes and monitoring the quantity and composition of new durables consumed.

   The early recognition of resource demand and environmental impacts and the evaluation of measures have to be based on the analysis of scenarios; (i) for water, population growth will lead to supply problems and increasing carbon and phosphorous concentration in surface water. This is due to the hydrological conditions of the municipality having a small amount of local water resources and a low dilution capacity for waste water. The reduction of water consumption in order to mitigate the supply problems, will lead to a further increase in the concentrations of carbon and phosphorous in surface water. This effect is reduced with increasing degree of sewage treatment. However, using even the most developed technology, the quality of the surface water leaving the region will still not meet the WHO standards for raw drinking water quality, (ii) for solids, even though the input of durables and packaging is going to increase, the organic part in waste will still remain dominant. If the municipality wants to decrease the total amount of household waste, it has to focus on the reduction of the organic part of waste.
Zusammenfassung


In Industrieländern hat sich gezeigt, dass die Stoffflussanalyse (SFA) ein geeignetes Instrument zur Früherkennung von Ressourcenbedarf, Umweltverschmutzung und zur Evaluation technischer Massnahmen ist. Mit Hilfe der SFA kann der Metabolismus einer Region durch die Kombination von Daten aus der Marktanalyse und Daten von Entsorgungsprozessen analysiert werden. Diese Methode ist bisher in Entwicklungsländern noch nicht angewendet worden.

In dieser Dissertation wird gezeigt, wie die Methode der Stoffflussanalyse als Instrument zur Früherkennung von Umweltproblemen in urbanen Regionen in Entwicklungsländern angewendet werden kann. Folgende Problemstellungen werden in dieser Arbeit diskutiert:

- Kann die Stoffflussanalyse auch bei schlechter Datenlage verwendet werden, um den Stoffhaushalt von urbanen Regionen zu charakterisieren?
- Wie müssen Monitoringkonzepte für urbane Systeme erstellt werden, um anthropogene Einflüsse auf die Umwelt früh erkennen zu können?
- Welches sind die Auswirkungen unterschiedlicher Konsumszenarien auf das Stoffhaushaltssystem?
- Was ist das Potential technischer Massnahmen, um diese Auswirkungen zu minimieren?

Zusammenfassung


Zwei Ergebnisse der Dissertation sind:

1 Die Methode der Stoffflussanalyse kann trotz schlechter Datenlage angewendet werden, um den Stoffhaushalt in urbanen Regionen von Entwicklungsländern zu charakterisieren.


2 Anhand der mathematischen Modellierung kann die SFA verwendet werden zur (a) Entwicklung von Monitoring Konzepten (b) Früherkennung von Umweltproblemen und (c) Evaluation technischer Massnahmen.

   Monitoring Konzepte müssen an die unterschiedlichen Randbedingungen der jeweiligen Region angepasst sein. Für den Fall von Tunja sollten folgende Messpunkte gewählt werden; (i) im Fall von "Wasser", um Aenderungen der Qualität und Quantität des Oberflächengewässers früh zu erkennen, muss der regionale Wasser-, Nahrungsmittel- und Waschmittelkonsum gemessen werden (ii) um eine Übernutzung des Grundwassers zu verhindern, muss der Grundwasserspiegel und seine saisonalen Schwankungen bestimmt und kontrolliert werden, (iii) im Falle von "festen Gütern" muss zur Früherkennung der Abfallzusammensetzung der Schwerpunkt auf Messungen des Konsums mittellebiger Güter und der regionalen Nahrungsmittelversorgungsstruktur gelegt werden.
Zusammenfassung

 Abbreviations

cap. Capita
CAR: Corporacion Autonoma Regional
CDS: Corporacion de Desarrollo Sostenible
DANE: Departamento Administrativo Nacional de Estadistica
DC: Developing Countries
EAAT: Empresa de Alcantarillado y Acueducto del Municipio de Tunja
EVT: Actual Evapotranspiration
FP: Fresh Products
GNP: Gross National Product
HDI: Human Development Index
IAE: International Energy Agency
IC: Industrialized Countries
ICBF: Instituto Colombiano de Bienestar Familiar
IGAC: Instituto Geografico Agustin Codazzi
Inh: Inhabitants
MFA: Material Flux Analysis
MP: Manufactured Products
PEVT: Potential Evapotranspiration
SINA: National Environmental System
STDV: Standard deviation
TS: Dry matter
UASBR: Upflow anaerobic sludge blanket reactor
UNDP: United Nation Development Program
WHO: World Health Organization
y: Year
Glossary

**Acopio**: Establishment where recycled goods are bought and sold to private enterprises.

**Activity**: Human activities define the material fluxes through the anthroposphere. The four activities "to nourish", "to clean", "to reside and work" and "to transport and communicate" are sufficient to describe the most important material fluxes within a region.

- "to nourish": Activity that comprises all processes and goods related to production and consumption of solid and liquid food.
- "to clean": Activity that comprises all the processes and goods used for maintaining human health, including washing, and providing environmental protection from pollution.
- "to reside and work": Activity that comprises all processes and goods which are set up to build and maintain residential units, working and recreation facilities.
- "to transport and communicate": Activity that comprises all processes and goods used for transporting persons and materials and for exchanging information.

**Anthroposphere**: The anthroposphere is an open system where humans carry out their activities and establish their living environment. It interacts with the environmental compartments air, soil and water, thereby importing energy and raw material and exporting waste components.

**Anthropogenic**: Determined or created by anthropogenic activities.

**Calibration**: Estimation of model parameters using empirical data sets or data from literature.

**Departamento**: State

**Dilution capacity**: For anthropogenic fluxes; anthropogenic produced flux/total flux.

**Dry matter (TS)**: Weight of a good without its water content.

**Durables**: Goods that have a lifetime in households longer than one year is, e.g. television, car, table.

**Flux**: A flux is defined as the mass transfer from process 1 to process 2. It is measured in mass per time and area.

**Fresh products**: Fresh vegetables, fruit and meat.

**Geogenic**: In a natural state.

**Good**: A good consists of a material or material mixtures and has a defined function and value.

**Human Development Index (HDI)**: The HDI is a composite of three basic components of human development: longevity, knowledge and standard of living. Longevity is measured by life expectancy. Knowledge is measured by a
combination of adult literacy (two-thirds weight) and mean years of schooling (one-third weight). Standard of living is measured by purchasing power, based on GDP per capita adjusted for the local cost of living (purchasing power parity).

**Landfill leachate**: Liquid formed within a landfill. It is composed of liquids that enter the site, material that is leached from waste and the degradation products of this material.

**Material**: A material is a chemical element or its compound. Material fluxes are measured in mass per time and area. The "area" can be an entire region, a household or a person.

**Minifundio**: Small plot of land of about 1-5ha.

**Municipio**: Municipality.

**Process**: A process is defined as transportation, transformation or storage of goods, materials, energy or information. Mathematically it can be interpreted as a balance volume, i.e., a unit of volume which is balanced.

**Manufactured products**: e.g. cereals, dried legumes, sugar, milk and milk products.

**Recycling**: Utilization of different parts of a product to produce a new product.

**Region**: A region is a geographically defined area (territory), which can be differentiated in respect to its neighboring regions because of its topographical characteristics (mountains), agricultural importance or political borders. In this thesis region is mainly used as synonym to the geographical unit defined by a specific system border.

**Reuse**: Reutilization of a good for the same purpose.

**Robust**: A model is robust if variations of the parameters do not change significantly the results calculated by the model.

**Transfer-coefficient k**: The transfer-coefficient $k_{12}$ is the fraction of the total input into a process 1 which is transferred from the process 1 or into the process 2.

whereas: $k_1 + k_{12} + \ldots + k_{in} = 1$

**Technology Factor ($f_t$)**: The technology factor $f_t$ defines the efficiency of the use of resources. It is larger than 0 and smaller than 1.

**Validation**: A model is validated if it can be shown that the model assumptions are valid for different data sets. In a MFA system, the parameters input and transfer-coefficients of a process can be validated as follows: Using these parameters the output of the process is calculated. Additionally, the output of the process is measured. If both, the calculated and measured output are in agreement, the parameters have been validated.
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The Early Recognition of Environmental Impacts of Human Activities in Developing Countries

This thesis developed a tool for early recognition of resource depletion and environmental impacts of human activities in developing countries. It is based on the method of Material Flux Analysis (MFA) which was developed in industrialized countries. One major difficulty of the application of this method in developing countries is the availability of reliable data. This thesis showed, for the case of Tunja, Colombia, that it is possible to apply the method of MFA in developing countries. It is also shown that MFA and its mathematical description can be used for setting up monitoring concepts, for early recognition of resource depletion and environmental impacts and for evaluating technical measures to mitigate these impacts.
1. Introduction

1.1 Sustainable Development

Sustainable development has become a new "watchword" for assessing resource bases and human impacts on the natural environment. In the Brundtland Commission report, 1987, sustainable development was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

Although sustainable development is an acknowledged subject of much recent development thinking (see e.g. Repetto, 1986, Redclift, 1987, Turner, 1988), few efforts have been made to operationalize the concept and to show how it can be integrated into practical decision making. According to Pearce et. al, 1990, one of the key conditions for achieving sustainable development is that the total natural capital should not decline over time\(^1\), i.e., the consumption of natural resources should be in balance with the yield of the natural capital. Thus, for decision-making at a local level, it is necessary to know the present and future demand for natural resources, their supply possibilities and the effect of their disposal on the environment.

The primary resource demand of a region is dependent on the population density, the consumption per capita and the efficiency of the technology used to produce the consumed goods (see equation 1.1, Baccini & Bader, 1996):

\[
R_p = \frac{\text{Population density (inh./km}^2) \times \text{consumption per capita (kg(J) / inh.year)}}{\text{technology factor (f)}}
\]  

(1.1)

where

\(R_p\): primary resource demand of a region kg/km\(^2\) and year or J/km\(^2\) and year

\(f\): technology factor \(1 > f > 0\).

The largest increase in the demand for primary resources is most likely to occur in areas where population density and consumption per capita increase faster than the technology factor. This is particularly true for urban regions in developing countries (DC) where population growth is about 3.5%/year (World Bank, 1995) and increasing consumption per capita is expected. The introduction of new

\(^1\) For an excellent review on the definition of value of natural capital and weak and strong sustainability, see Pearce et. al., 1990.
technologies is likely to occur but is not necessarily enough to compensate for the increasing population and consumption rate.

1.2 Urban Regions in Developing Countries

During the last forty years, population in developing countries grew from 1.7 billion to 4 billion. In the 1980's population growth was largest in urban areas at about 6.7% per annum. In the period from 1990 to 1994 population growth in urban areas decreased from 6.7%/year to 3.5%/year (World Bank, 1995). While, in 1980, only about 48% of the population in lower-middle income countries was living in urban areas, in 1994, this number increased to 57%. In 1994, already 67% of the population was living in urban areas in Latin America and this number is likely to increase.

Cities played an important role in the development of industrialized countries (IC) during the industrialization era in the 19th century. They were the centers where development and modernization took place, because manpower and industry were concentrated there. The development was transmitted from the largest urban centers to rural and peripheral regions.

A similar development was expected to take place in DC after the Second World War. Even though rapid city growth and capital growth have taken place, the welfare of all social strata and the rural areas of the countries did not go hand in hand with this development (Potter, 1990; Portes, 1989). For example, due to the rapid and often uncontrolled urbanization, it has not been possible to supply the poor, living in urban areas, with clean water and sanitation facilities. Additionally, DC's lack of tools for evaluating development strategies on a long term have lead to resource depletion and resource pollution (UNDP, 1993; World Bank, 1994; WHO, 1992; Bower et. al., 1990, LaNier et. al., 1990).

During the 19th and beginning of the 20th century, industrialized countries had also experienced similar problems of resource depletion and pollution. However, the measures industrialized countries developed to reduce water, air and soil pollution addressed only the symptoms of these problems, by setting quality standards and controlling the emissions. These "end of pipe" measures were able to partly reduce and stabilize pollution, but they did not significantly alter the processes causing the pollution. To tackle the pollution problems on a long term, it is necessary to shift from the end of pipe pollution control or "late recognition" to pollution prevention or "early recognition" (Baccini et al, 1985; Richards et. al, 1994).

The example of the development of domestic sewage pollution in Europe shows that a significant reduction of pollution is only achieved by understanding the processes generating the fluxes to the environment and taking measures at the source. Figure 1.1 illustrates the efficiency of different pollution mitigation
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approaches (WHO, 1989). In relation to the socio-economic development four phases of problem evolution are identified: In phase I, agricultural society (0 to A), pollution increased linearly with population growth. In phase II, industrialization (A to B), pollution increased exponentially due to the starting industrialization. In phase III, B to C, pollution increased to C1 if no measures were taken and it stabilized to C3 if efficient end of pipe measures were taken. In phase IV, C to D, pollution decreased to the level of A due to implementation of control measures at the source.

![Conceptual model of pollution occurrence and control using domestic sewage pollution in Europe as an example.](image)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - A</td>
<td>pollution increases nearly linearly with population growth (rural society)</td>
</tr>
<tr>
<td>A - B</td>
<td>exponential increase of pollution with industrialization</td>
</tr>
<tr>
<td>B - C1</td>
<td>no pollution control enacted</td>
</tr>
<tr>
<td>B - C2</td>
<td>some controls installed (end of pipe)</td>
</tr>
<tr>
<td>B - C3</td>
<td>effective controls consistently employed (increasing efficiency of end of pipe)</td>
</tr>
<tr>
<td>C3 - D</td>
<td>recovery of pollution situation to a tolerable environmental status due to effective source control</td>
</tr>
</tbody>
</table>

Figure 1.1:
Conceptual model of pollution occurrence and control using domestic sewage pollution in Europe as an example.

*Source: WHO, 1989*

Developing countries are experiencing the problems in one generation which industrialized countries experienced over a period of 100 years (WHO, 1989). The approaches developing countries are taking to tackle these problems, are based on the "late recognition" and end of pipe technologies developed by industrialized countries. However, in DC's, the approach of "early recognition" is even more important than in IC's because of the large population growth and the increasing resource demand per capita. For example, given the current population growth rate of 3.5%, about 50% of the built environment in developing countries will be "new" in about one generation. Thus, the decisions of how to build in the present are decisive for the resource consumption and pollution in the future.
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The shift from a "late recognition" to an "early recognition" implies the development of tools that focus on the understanding of the processes of production and consumption occurring in the anthroposphere\(^2\). These tools have to be based on the knowledge of the metabolism of the anthroposphere, which shows the interrelationship between human activities, their material fluxes and the environment.

1.3 Metabolism of Urban Regions

Only a few studies have been carried out so far on the metabolism of regions. All of them were made in industrialized countries. On a national level, Lohm et al. (1993) describe the balance of lead and chromium in Sweden. They show that despite the decreasing production-related emissions, the accumulation of lead and chromium in soils and sediments is increasing and will continue to increase, due to the increasing fluxes from the stocks to the environment and uncontrolled consumption-related material fluxes.

On a regional level in the Rhine River Basin, Stigliani and Anderberg (1993) showed how environmental management of polluting fluxes could significantly be improved by managing the input fluxes into the river basin instead of looking only at the damages occurring in the river.

Brunner et al. (1990) studied, for the first time, the metabolism of a region by analyzing the material fluxes caused by households, agriculture, industry and commerce using the method of Material Flux Analysis (MFA). They found that (i) MFA was a suitable method to quantify the relevant fluxes from the anthroposphere to air, water and soil, (ii) it is possible to set priorities for pollution control on a short and long term using this quantification. Another important finding of this study was that, in the selected region, households cause the major fluxes due to their usage of goods and services and their method of disposal of solids.

In a study called Metapolis, Baccini et. al. (1993) quantified the consumption, stock and waste production of households in a city. They showed that it is possible to analyze the metabolism of a city by quantifying the consumption and disposal processes. In 1991, Baccini and Brunner published the first methodological description of MFA as a method to study the regional metabolism. Recently, a mathematical description of MFA was published by Baccini and Bader (1996).

All the studies mentioned above describe steady state models of regions and their respective metabolisms. Until now, no publications using a mathematically defined dynamic model for forecasting resource demand and environmental impacts of human activities have been made.

\(^2\) Space where humans carry out their activities Baccini and Brunner, 1991.
1.4 Aims and Questions of the Thesis

The main aim of this thesis is to develop a tool for early recognition of environmental impacts of human activities in urban regions of developing countries. The specific research questions are:

- Can the method of MFA be applied to study the current demand and use of the natural resources in the region even with poor availability of reliable data?
- How should a monitoring concept be developed for early recognition of resource demand and environmental impacts due to changes in the regional metabolism?
- What will be the impacts of different consumption scenarios on the regional material management system (e.g. resource depletion, environmental pollution)?
- To which extent can technical measures mitigate these impacts?

In choosing a university in a developing country as the partner institution, another aim was to improve the research capacity at this university. The capacity building\(^3\) is discussed qualitatively because no measurements were made to quantify it.

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\(^3\) In the context of this thesis, capacity building is the development of research capacity in universities of developing countries.
1.5 Contents of the thesis

The thesis consists of 5 chapters:

Chapter 2 concentrates on the methods used. It consists of (i) selection of the study area, (ii) description of the study area (iii) description of MFA and its mathematical description and (iv) application of MFA to the study area. Within the latter it describes the system analysis, the parameter choice, data collection and data measurements.

Chapter 3 analyzes the current demand and use of the natural resources in the region for the subsystems water, food and durables, calibrates the material flux models and validates parts of them.

Chapter 4 uses the models presented in Chapter 3 (i) to set up monitoring concepts for water and solid waste management, (ii) to forecast the impact of different scenarios on the environment and (iii) to evaluate the effect of technical measures to mitigate this impact.

Chapter 5 gives a qualitative analysis of the experiences with capacity building.
2 Methods

This chapter describes the methods used. It consists of a section which explains and describes the study area chosen, a small section which gives an introduction into the method of MFA and its application to regions and a section showing how the method of MFA was applied to the Municipality of Tunja.

2.1 Choice of the Study Area

2.1.1 Characterization of the Selected Country

2.1.1.1 Selection Criteria

The country chosen to carry out the project is Colombia, South America. Colombia was chosen because it (i) is representative of lower middle-income economies of DC, (ii) has a good educational level, which increases the probability for getting good data and (iii) has a good basis for a participatory project and a good potential for capacity building due to the personal background of the author, who has dual citizenship for Switzerland and Colombia and has lived in both countries.

2.1.1.2 Physical Characteristics

Colombia stretches from 4° South to 12° North of the equator and has an area of approximately 1,140,000 km². It has access to two oceans, the Atlantic on the northern side and the Pacific on the western side. Colombia is bordered by Panama in the North-West, Venezuela in the North-East, Brazil in the South-East, Peru in the South and Ecuador in the South-West (Figure 2.1). The Andes mountain chains that cross the whole continent from North to South are located in the western part of Colombia. They comprise about 45% of the country. They split into Cordillera Occidental, Cordillera Central and Cordillera Oriental. The rest of the country, vast lowlands, can be divided into two regions: the Llanos in the North and the Amazon in the South. The Llanos, about 250,000 km² is a huge open Savannah lying in the basin of the Orinoco. The Amazon, about 400,000 km² is a tropical jungle marked by a labyrinth of rivers.
Due to its proximity to the equator, Colombia has wet and dry seasons. Additionally, Colombia has a variety of different climates which are defined by their altitude, where the temperature falls about 6°C with every 1,000 m increase in altitude.

![Map of Colombia and its neighboring countries](image)

Figure 2.1: Colombia and its neighboring countries.

### 2.1.1.3 Demographic Characteristics and Urban Development

**Demographic Characteristics.** The population of Colombia is 32 millions (DANE, 1993). The average population growth rate has been declining from 2.5%/year between 1965 and 1980 to 2.1%/year between 1980 and 1988. About 90% of the population lives in the western part of Colombia, the population density in this region ranges from 10 to 250 inh/km². The other 10% of the population lives in the rest of the country, in this case the population density smaller than 5 inh/km². The average population density is about 23 inh/km².
Urban Development. About 72% of the population in Colombia lives in urban centers, which are growing at about 2.7% per annum. The degree of urbanization in Colombia is comparable to Peru, higher than Bolivia and Ecuador and smaller than Venezuela (Table 2.1). In contrast to other countries of the continent, usually dominated by one metropolis, Colombia has four major regional centers, namely Bogotá, Medellín, Cali and Barranquilla\(^1\) (Figure 2.1). These cities are all located in the western part of the country and each of them has over one million inhabitants.

Table 2.1:
Urbanization in Colombia and other lower-middle income economies in Latin America.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Colombia</td>
<td>72</td>
<td>2.7</td>
</tr>
<tr>
<td>Bolivia</td>
<td>58</td>
<td>3.2</td>
</tr>
<tr>
<td>Ecuador</td>
<td>58</td>
<td>3.6</td>
</tr>
<tr>
<td>Peru</td>
<td>72</td>
<td>2.6</td>
</tr>
<tr>
<td>Venezuela</td>
<td>92</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Source: World Bank, 1996

During the period from 1951 to 1973, population growth in Colombia mainly took place in cities of more than 500,000 inhabitants, while in the period from 1973 to 1985 population growth was dominant in the smaller cities (Figure 2.2). The percentage of the population living in cities larger than 500,000 inhabitants increased from 16% to 41% between 1951 to 1973 and decreased from 41% to 30% between 1973 and 1985. Accordingly, the middle size cities (20,000 to 99,000 inhabitants) increased their share of the total population from 18% in 1973 to 27% in 1985.

\(^1\) IGAC, 1990
2.1.1.4 Socio-economic Characteristics

Socio-economic Development. According to its GNP per capita, Colombia is ranked as a lower-middle income economy country. In 1994, Colombia's GNP per capita was US$ 1,670, which is about the average of this group. The annual GNP growth during the years 1985 to 1994 was the largest of the Latin American countries in this group (Table 2.2). The Human Development Index (HDI) composed of the indicators, life expectancy, adult illiteracy and GNP, rank Colombia as a country with high human development, similar to Venezuela. The ratio of GNP per capita and HDI shows that for its GNP Colombia has a high human development index.

Table 2.2: GNP per capita and HDI of Colombia and other lower-middle income economy countries in Latin America.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Colombia</td>
<td>1,670</td>
<td>2.4</td>
<td>70</td>
<td>9</td>
<td>0.813</td>
</tr>
<tr>
<td>Bolivia</td>
<td>770</td>
<td>1.7</td>
<td>60</td>
<td>17</td>
<td>0.530</td>
</tr>
<tr>
<td>Ecuador</td>
<td>1,280</td>
<td>0.9</td>
<td>69</td>
<td>10</td>
<td>0.718</td>
</tr>
<tr>
<td>Peru</td>
<td>2,110</td>
<td>-2.0</td>
<td>65</td>
<td>11</td>
<td>0.642</td>
</tr>
<tr>
<td>Venezuela</td>
<td>2,760</td>
<td>0.7</td>
<td>71</td>
<td>9</td>
<td>0.820</td>
</tr>
</tbody>
</table>

Political System. Colombia has been developing from a two hegemony centralized state, as it was during the years 1948 to 1972, towards a democratic decentralized state. Within this development, only two aspects that have influenced the regional structure and development will be mentioned here. The first is the municipal autonomy and the second the National Environmental System.

1. During the government periods of Belisario Betancourt (1982-1986), Virgilio Barco (1986-1990) and Cesar Gaviria (1990-1994), reforms were implemented to increase the financial and political autonomy of the municipalities. For example, the municipalities have to grant the population access to public services according to the national aims, construct public buildings according to local progress, develop guidelines for regional planning and improve the cultural and social conditions for the population (Gobierno de Colombia, 1993). They give a part of their revenue to the central government, from where it is redistributed to the municipalities according to population and specific needs. One of the most important reforms to increase stability, legitimacy, participation and responsibility of the municipalities was the institutionalization of popular elections on the municipal level (Martz, 1992). The first popular elections took place in 1988. The mayors are elected for a three year period with no possibility of reelection.

2. The National Environmental System (SINA) was created in 1993 by Law 99. The SINA is headed by the Ministry of the Environment and consists of (i) scientific and research institutes, (ii) regional authorities "corporaciones autónomas regionales" (CAR), and "corporaciones de desarrollo sostenible" (CDS) (iii) departmental and local authorities and (iv) municipalities with over one million inhabitants, also called environmental management agencies (Figure 2.3).

![Organogram of the National Environmental System (SINA) of Colombia.](image)

Source: Ministerio del Medio Ambiente, 1995

The SINA's main function is to develop and implement a national policy for regional environmental planning and management and for the sustainable use of renewable natural resources. Within this aim it develops policies and guidelines for (i) land zoning for agriculture, forestry and urban settlements, (ii) use of soils and (iii) management of water resources incorporating the results of the different research institutes.
Chapter 2: Methods

The implementation and enforcement of these guidelines is decentralized to a regional level and occurs via the CARs and CDSs. These regional authorities are defined by geographical criteria, such as water catchment area, bio-region or ecosystem-related areas and cover over-municipal and over-departmental regions. Within their jurisdiction of responsibility, the CARs and CDSs also advise departments and municipalities on specific strategies for environmental protection and use and management of renewable resources. The CARs and CDSs are statutory bodies with administrative, legal and financial autonomy within their regions. They receive funding out of local taxes, such as mineral royalties, real estate taxes and environmental charges.

At the departmental and municipal levels of government, a set of local environmental management functions complementary to those of the CARs are to be exercised. Law 99 gives a special status to the major urban centers with populations of over one million inhabitants, i.e. Bogota, Cali, Medellin and Barranquilla, which, assigned the same function as the CARs, are to establish environmental institutions and undertake the environmental functions within their jurisdictions.
2.1.2 Characterization of the Selected Municipality

2.1.2.1 Selection Criteria

The selection of the municipality was made according to the following criteria:

- **population, socio-economic structure**
  The municipality should have around 100,000 inhabitants. Additionally, the different socio-economic strata should be clearly differentiable from each other with macroscopic criteria. This stratification represents one of the most important differences vis à vis industrialized countries.

- **economic structure**
  In order to develop the methodology, the metabolism of the municipality should be as simple as possible. It should be dominated by households and their activities, because one of the main differences between DC's and IC's is their socio-economic structure. Too many different industries would lead to an increase in the complexity of the model which is not necessary for developing the methodology.

- **partner institutions, infrastructure and data availability**
  The local university and the local government should be interested in learning and developing new methodologies and supporting the project with infrastructure and personnel power. Also, basic data concerning water and energy consumption and waste management should be readily available.

- **political aspects**
  First, the municipality should be politically stable to ensure the completion of the project. Second, the municipality should not have such urgent problems that would influence the emphasis the project towards finding a solution to these problems.

Five regions were analyzed according to the mentioned criteria. The municipality of Tunja was found to fit best to the criteria mentioned above (Table 2.3).
<table>
<thead>
<tr>
<th></th>
<th>Tunja</th>
<th>Duitama</th>
<th>Sogamoso</th>
<th>Facatativá</th>
<th>Ibague</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Population</strong></td>
<td>~ 110,000</td>
<td>~ 80,000</td>
<td>~ 90,000</td>
<td>~ 60,000</td>
<td>~ 320,000</td>
</tr>
<tr>
<td><strong>Social Structure</strong></td>
<td>clear stratification</td>
<td>clear stratification</td>
<td>clear stratification</td>
<td>clear stratification</td>
<td>clear stratification</td>
</tr>
<tr>
<td><strong>Economic Structure¹</strong></td>
<td>tertiary sector</td>
<td>trade and commerce</td>
<td>heavy industry</td>
<td>agriculture</td>
<td>industry and commerce</td>
</tr>
<tr>
<td><strong>Partner Institutions</strong></td>
<td>UNIBOYACA (Tunja)</td>
<td>UNIBOYACA (Tunja)</td>
<td>Universidad Pedagógica y Tecnológica</td>
<td>Universidad Nacional In Bogotá</td>
<td>Corporación Autónoma de Ibague</td>
</tr>
<tr>
<td><strong>Infrastructure, Partner Institution</strong></td>
<td>good</td>
<td>good</td>
<td>fair</td>
<td>good</td>
<td>fair</td>
</tr>
<tr>
<td><strong>Data Availability²</strong></td>
<td>fair</td>
<td>fair</td>
<td>poor</td>
<td>very poor</td>
<td>poor</td>
</tr>
<tr>
<td><strong>Security</strong></td>
<td>very good</td>
<td>good</td>
<td>fair</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td><strong>Urgent Environmental Problems</strong></td>
<td>none</td>
<td>solid waste management</td>
<td>industrial pollution (basically air)</td>
<td>none</td>
<td>solid waste management, industrial water pollution</td>
</tr>
</tbody>
</table>

1: dominant economic branch

2: data availability in comparison with industrialized countries
2.1.2.2 Physical Characteristics

Location. Tunja, the capital of the Departamento de Boyacá, is located in the eastern chain of the Andes at an altitude of 2,800 m above sea level, has an area of 117 km² and a population of 114,000 (DANE, 1994). The municipality lies in a valley that is 15 km long, 4.5 km wide and has a slope with an inclination of 1/100 in a northerly direction. The lateral sides rise up to 3,200 m (west) and 2,800/2,900 (east). The distance from Bogotá is about 150 km.

There are two main rivers in the region, the Río Chulo that originates in the rural part and the Río La Vega that originates in another catchment area and enters the region at the urban part of Tunja (Figure 2.4). The urban area of Tunja is located on both sides of the Río Chulo.

Climate. Due to the altitude and geographical location, the average temperature in Tunja is 13°C, with variations down to 5°C at night and up to 20°C during the day. There are two wet and two dry seasons. The wet seasons are in April/May and Oct./Nov. The average precipitation is 590 mm per year and varies monthly from 10 mm to 85 mm as shown in Figure 2.5.
Chapter 2: Methods

Figure 2.5:

Source: HIMAT, 1993

The rate of potential evapotranspiration (PEVT) in Tunja is nearly equal to the regional precipitation (P) at 100%. The ratio is of PEVT to P is comparable to the ratio of regions located at the same height in the Andes (Table 2.4)

Table 2.4:
Precipitation and potential evapotranspiration of different cities in the Andes

<table>
<thead>
<tr>
<th>City</th>
<th>Country</th>
<th>m above sea level</th>
<th>Precipitation (P)</th>
<th>PEVT1</th>
<th>PEVT/P2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bogotá</td>
<td>Colombia</td>
<td>2,556</td>
<td>939</td>
<td>704</td>
<td>75</td>
</tr>
<tr>
<td>Huancayo</td>
<td>Perú</td>
<td>3,380</td>
<td>724</td>
<td>640</td>
<td>88</td>
</tr>
<tr>
<td>San Gabriel3</td>
<td>Ecuador</td>
<td>2,860</td>
<td>937</td>
<td>1,076</td>
<td>115</td>
</tr>
<tr>
<td>Tunja</td>
<td>Colombia</td>
<td>2,850</td>
<td>707</td>
<td>7054</td>
<td>100</td>
</tr>
</tbody>
</table>

1: PEVT: potential evapotranspiration
2: PEVT/P: ratio potential evapotranspiration to precipitation (P)

Source: Müller and Richter, 1980

Hydrogeology. Geologically, the region lies in a synclinal valley. It has three main aquifers (Figure 2.6). The first is located in the shallow alluvium, the second in the Formación Bogotá and the third in the Formación Cacho. The characteristics of the different aquifers are shown in Table 2.5. The aquifers

---

2 However, the actual evapotranspiration (EVT) may differ significantly for the different regions, because it is dependent on parameters such as vegetation and humidity. The EVT is estimated to be significantly smaller than the PEVT. However, no data of EVT exists.

3 1968

4 based on the equation: \( \text{PET} = \text{ET}_{\text{tank}} K, (K=0.6), [\text{Calixto, Valcarcel, 1994}] \)
Currently used for urban water supply are located in the Formación Bogotá and in the Formación Cacho. Both aquifers are more than 100 m below the soil surface (Figure 2.6).

![Geological stratification of the catchment area of Tunja.](image)

Figure: 2.6
Geological stratification of the catchment area of Tunja.

(I): Qal, Qc, Qac, Qd, quaternary depositions with a magnitude of 1 to 9 m
(II): Tb, Formación Bogotá: contains one aquifer with a magnitude of 10 to 40 m
(III): Tc, Formación Cacho: contains two aquifers with a magnitude of 30 to 70 m each
Ktg, Formación Guaduas: sand clay formation, contains no aquifer
(IV): Formación Guadalupe: contains aquifers in not known magnitudes.

Source: Alarcón & Rodríguez, 1993

Table 2.5:
Characteristics of the different aquifers.

<table>
<thead>
<tr>
<th>Geologic formation</th>
<th>Lithology of the different strata</th>
<th>Thickness [m]</th>
<th>Porosity [%]</th>
<th>Hydraulic conductivity [m/s]²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow alluvium</td>
<td>Silt and sand</td>
<td>0.1-10</td>
<td>20-30</td>
<td>(5 \times 10^{-5})</td>
</tr>
<tr>
<td>Formación Bogotá</td>
<td>Layers of sandstone, and conglomerates with silt (up to 400m)</td>
<td>10-40</td>
<td>10-18</td>
<td>(3 \times 10^{-6})</td>
</tr>
<tr>
<td>Formación Cacho</td>
<td>Two sandstone strata divided by a silt stratum</td>
<td>30-70</td>
<td>12-25</td>
<td>(1.7 \times 10^{-5})</td>
</tr>
</tbody>
</table>

1: Porosity of potential groundwater carriers
2: Mean values

Source: Alarcón, Rodríguez, 1993
Land Use. About 54% of the land of the municipality is used for pasture, 26% is arable land, 12% urban area and 9% unproductive land, including forests, water and eroded hills. Even though the urban area covers only 12%, it holds 94% of the inhabitants. The arable land is characterized by agriculture on minifundios, land plots of about 1-5 ha, where potatoes, wheat, oats and maize are produced.

Table 2.6: Land use in the Municipality of Tunja.

<table>
<thead>
<tr>
<th>Area [km²]</th>
<th>Proportion [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>14</td>
</tr>
<tr>
<td>Arable land</td>
<td>30</td>
</tr>
<tr>
<td>Pasture (extensive agriculture)</td>
<td>63</td>
</tr>
<tr>
<td>Unproductive</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>117</td>
</tr>
</tbody>
</table>

1: Numbers may not add to 100 because of rounding

*Source: Hidrotec, 1992*

### 2.1.2.3 Demographic Characteristics and Urban Development

History. Several independent Indian cultures, separated from each other through the Andes mountain chain, lived in Colombia in the Pre-Colombian period. The most advanced culture, the Muiscas, also known as the Chibcha, occupied the territory of today's Departamentos of Cundinamarca and Boyacá. At the time of the Conquest, the Muiscas had the largest indigenous population of 500,000 inhabitants and were known for their wealth. They had a well-developed agriculture and artisanry and mined salt and emeralds that they exchanged with other cultures. When the Spanish reached the interior of the country, the Muiscas were divided into two tribes, the southern ruled by the Zipa from Bacatá, today Bogotá, and the northern ruled by the Zaque from Hunza, today Tunja.

In 1539, Gonzalo Suárez Rendón founded Tunja at the old Chibcha site of Hunza. During the XVI century, the Provincia of Tunja, today Departamento de Boyacá, was culturally, economically and politically the second most important region after the capital, Bogotá. The importance of Tunja was based on the following aspects. First, it was the center of food and textile supply for the mining regions and for Bogotá. Second, it was an important trading center because it lay on the route from the coast to Bogotá. Tunja's importance and prosperity were also reflected in the architecture. During the XVI and XVII centuries, Tunja became the city with the best built houses because culturally interested people of the high society settled there.

During the XVIII century, Tunja began to lose its importance. This was due to (i) the growing scarcity of water and wood, (ii) the decreasing demand for locally
produced textiles due to the import of textiles and (iii) the discovery of new and better trading routes between the coast and Bogotá.

In the second half of the XX century, Tunja's importance began to increase again, mostly with the discovery of new water sources, the installation of water pipes and the discovery of coal. The development took place mainly at the educational and administrative levels; schools and universities were constructed, but only a few industries were started. Since then, Tunja has been developing into a regional university center and a regional administrative center (Correa, 1989).

**Demographic Characteristics.** Tunja's population is dominantly Mestiza, an ethnic mixture of Spanish and Indian. This gives the people from Tunja a Hispanic-Chibcha identity that has influenced their values, beliefs and feelings until now (Ocampo, 1989).

Tunja's population growth was quite large during the 1920's and 1930's, but stagnated during the 1940's due to the decreasing economic growth. With the economic recovery in the 1950's, the population started growing again, increasing from about 20,000 inhabitants in 1950 to about 100,000 in the early 1990's (DANE, 1985).

![Demographic development of Tunja from 1925 to 1995.](source: DANE, 1985)

**Urban Development.** Tunja's urban structure is clearly dominated by Spanish architecture. The Spanish buildings were placed on a square of 80m by 80m. In the middle of the city was the Plaza Municipal that was constructed where the main trading center of the Indians had been. The growth of the city took place
around this core. The church, the municipal buildings and the houses of the most prominent people were constructed around the Plaza, which played an important role in urban life, political and religious affairs and was also the central place for water supply. In 1610, the city had 330 houses, 4 temples and 6 hermitages. Until 1946, the city growth took place mainly around the core of the city. After 1946, wealthier people started moving to the northern areas of the city, leaving the center to people from the middle and lower strata. Since then, the city has been growing into the northern part of the municipality. According to the plans of the local government, this development is likely to continue. Additionally, the local government is trying to encourage the construction of settlements on the eastern side of the city (Figure 2.8) (Hidrotec, 1992).

Figure 2.8:
Urban structure and projected growth for Tunja.
Source: Hidrotec, 1992

2.1.2.4 Socio-economic Characteristics

Employment Structure. About 60% of the employees of the formal economy work in the service sector. Compared to other municipalities, such as Duitama, Ibagué and Bogotá, the service sector in Tunja employs about 15% more people than the other municipalities (Table 2.7). A possible explanation is Tunja's function as a regional center for education and administration. The industrial sector employs only 8% of the employees which is about half the amount of people employed in the other municipalities.
Methods/Choice of the Study Area

Table 2.7:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>% employees</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commerce</td>
<td>29</td>
<td>39</td>
<td>37</td>
<td>27</td>
</tr>
<tr>
<td>Industry</td>
<td>8.2</td>
<td>14</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>Services</td>
<td>57</td>
<td>41</td>
<td>43</td>
<td>42</td>
</tr>
<tr>
<td>Others</td>
<td>6.2</td>
<td>5.6</td>
<td>6.1</td>
<td>6.9</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

1: Numbers may not add to 100 because of rounding

Source: DANE, 1990

Socio-economic Structure. The criteria shown in Table 2.8 are used as socio-economic indicators to define six socio-economic strata in Colombia. These criteria were developed to allow for sliding fees for water and energy according to the social strata.

Table 2.8:
Criteria for the definition of the six socio-economic strata in Colombia.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Stratum 1</th>
<th>Stratum 2</th>
<th>Stratum 3</th>
<th>Stratum 4</th>
<th>Strata 5 + 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition</td>
<td>low lower class</td>
<td>lower class</td>
<td>lower middle class</td>
<td>middle class</td>
<td>upper middle and upper class</td>
</tr>
<tr>
<td>Condition of the building</td>
<td>provisional</td>
<td>not finished</td>
<td>half finished</td>
<td>finished</td>
<td>finished</td>
</tr>
<tr>
<td>Urbanization form</td>
<td>not planned (&quot;invasion&quot;)</td>
<td>peripheral districts</td>
<td>planned</td>
<td>planned by urbanization companies</td>
<td>resident districts with sophisticated buildings</td>
</tr>
<tr>
<td>Public services</td>
<td>lack of more than two</td>
<td>drinking water and sewerage</td>
<td>all, except phone</td>
<td>all</td>
<td>all</td>
</tr>
<tr>
<td>Roads, public transport</td>
<td>no roads bad access</td>
<td>no tarred roads, poor access</td>
<td>tarred roads, fair access</td>
<td>tarred roads, good access</td>
<td>As stratum 4 with green areas and parking facilities</td>
</tr>
<tr>
<td>NR. of Households per house</td>
<td>&gt;3</td>
<td>3</td>
<td>&gt;1 and &lt;3</td>
<td>partly &gt;1</td>
<td>1</td>
</tr>
</tbody>
</table>

Source: DANE, 1985

According to these criteria, in urban Tunja, the lower middle class, stratum 3, is the dominant class constituting about 62% of the urban population. The middle class, stratum 4, constitutes 27% of the population. Because strata 1 and 6 account for less than 1% of the population, they are added to strata 2 and 5 respectively (Table 2.9).
Chapter 2: Methods

The stratification of Tunja is typical for cities of similar size and economic structure in Latin America (Portes, 1989). Portes found that in cities with increasing tertiary sector, the middle income strata also increase their share of the population. In cities with a population larger than one million inhabitants, the dominant strata are the low lower and lower class (>40%).

Table 2.9:
Stratification of the urban part of Tunja.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>2,070</th>
<th>13,300</th>
<th>5,920</th>
<th>360</th>
<th>21,650</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household</td>
<td>10</td>
<td>62</td>
<td>27</td>
<td>2</td>
<td>100</td>
</tr>
</tbody>
</table>

1: Numbers may not add to 100 because of rounding

Source: EAAT, 1993

Socio-economic Structure and Income. It is assumed that the stratification criteria of the Colombian government (Table 2.8) relates to the income of households. The household survey carried out in Tunja, 1993, showed that the average income of the socio-economic strata, as defined above, differs significantly among the socio-economic strata (Figure 2.9). Thus, the stratification criteria of the Colombian government are sufficient for differentiating among the different social strata.

10^3 Pesos/HH.month

Figure 2.9:
Monthly household income of the different socio-economic strata (certainty 95%).
HH: household

Source: Survey, 1993
Public Services. Table 2.10 shows the coverage of public services in urban and rural Tunja. In the urban part, the coverage is very good and significantly higher than the coverage in the rural areas. The average coverage in the Municipality of Tunja is higher than in Colombia and higher than in other lower-middle income economies.

Table 2.10:
A comparison of coverage of public services in Tunja, Colombia, and other lower-middle income economies.

<table>
<thead>
<tr>
<th></th>
<th>Water Supply (%)</th>
<th>Sanitation (%)</th>
<th>Electric Energy (%)</th>
<th>Waste Collection (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban¹ Tunja</td>
<td>93</td>
<td>92</td>
<td>96</td>
<td>n/d</td>
</tr>
<tr>
<td>Rural¹ Tunja</td>
<td>33</td>
<td>3</td>
<td>68</td>
<td>n/d</td>
</tr>
<tr>
<td>Average¹ Tunja</td>
<td>90</td>
<td>87</td>
<td>95</td>
<td>70</td>
</tr>
<tr>
<td>Average² Tunja</td>
<td>88</td>
<td>87</td>
<td>87</td>
<td>84</td>
</tr>
<tr>
<td>Colombia¹</td>
<td>70</td>
<td>59</td>
<td>78</td>
<td>n/d</td>
</tr>
<tr>
<td>Bolivia³</td>
<td>46</td>
<td>44</td>
<td>n/d</td>
<td>n/d</td>
</tr>
<tr>
<td>Ecuador³</td>
<td>58</td>
<td>54</td>
<td>n/d</td>
<td>n/d</td>
</tr>
<tr>
<td>Perú³</td>
<td>58</td>
<td>45</td>
<td>n/d</td>
<td>n/d</td>
</tr>
<tr>
<td>Venezuela³</td>
<td>89</td>
<td>55</td>
<td>n/d</td>
<td>n/d</td>
</tr>
</tbody>
</table>

n/d: no data

Sources: 1: DANE, 1985
2: EAAT, 1995
3: World Bank, 1996

Water Supply. The water supply company, Empresa de Alcantarillado y Acueducto Tunja (EAAT), supplies 90% of the households (rural and urban) and the whole service and industry sector with water. Tunja has two main water sources (i) surface water from a reservoir located at 3,200 m above sea level in another catchment area and (ii) groundwater extracted from the lower aquifer located mainly in the Formación Bogotá. The water from the reservoir is treated and stored in several tanks around the city. The groundwater is transported directly to the households after pumping. The other 10% of households (mostly rural households) is supplied by own wells extracting water from the upper aquifer (Figure 2.6).

Only about 60% of the produced water is accounted for, 20% is assumed to be illegally obtained water and the rest is assumed to be lost in the distribution system (EAAT, 1993). During the last few years, Tunja has experienced severe water shortages and regular interruptions of the water supply.

Sanitation. Approximately 92% of the urban and 3% of the rural population are connected to a sewer system. The sewage is discharged into the Río Chulo without any treatment. Thus, the surface water leaving Tunja is heavily contaminated with sewage. In 1991, the farmers of the downstream region litigated
against Tunja because they were receiving surface water of bad quality. They claimed for a surface water which has drinking water quality.

Energy. The main energy sources used are: coal, gasoline and propane gas and electricity. Coal is mainly used for brick production and for cooking in restaurants. Propane gas and electricity are used for cooking and gasoline is used for transportation.

Waste Management. About 70% of the population is served with regular waste collection. Tunja produces waste at about 0.33 kg per capita and day which adds to 49 t per day or $18 \times 10^3$ t per annum. Households produce around 80% of the total waste (Gorraiz et al., 1988). The waste is disposed of on a dumping site and irregularly covered with soil.
Material Flux Analysis

2.2 Material Flux Analysis

2.2.1 Basic Framework

Material Flux Analysis (MFA) is a method to determine, describe and analyze the metabolism of e.g. industries, regions. It analyzes the flux of different materials through a defined space, within a certain time. The methods used to determine these fluxes are based on natural sciences (Baccini & Brunner 1991, Baccini & Bader 1996). The application of the method consists of the following steps:

- System analysis, consisting of the definition of a system border\(^1\), processes\(^2\) and goods\(^3\)
- Measurement of the goods fluxes and element concentrations
- Calculation of the goods and element fluxes of the whole system
- Schematic presentation and interpretation of the results.

2.2.2 Material Flux Analysis in Regions

The metabolism of a region can be described by four basic processes (Figure 2.10):

(i) process **Supply** which supplies the region with natural resources and which imports consumption goods,

(ii) process **Production/Consumption** which uses the natural resources to produce goods and which consumes the produced and the imported goods,

(iii) process **Waste Management** which cleans the waste produced by the other processes and

(iv) process **Environment** which consists of soil, water and air.

---

\(^1\)The system border defines the boundaries of the system.

\(^2\)Processes are defined as transportation, transformation or storage of goods, materials, energy or information. Mathematically a process is a balance volume.

\(^3\)Goods consist of a material or material mixtures and have a defined function and value.
The system analysis, i.e. the selection of system border, processes and goods depends on the question to be answered. Additionally, to set up a system analysis, it is necessary to know the relationship between the selected processes. These leads to characteristic features of each system. Based on these, it is possible to determine the minimum amount of data needed to quantify the system.

Thus, the data needed to answer different questions will be different. The possibility to choose a system with defined characteristic features is the advantage of MFA in comparison to specific models. Latter often need a defined set of data to answer a specific question.
2.2.3 Mathematical Description of MFA Systems

The mathematical description of MFA-systems allows for (i) data analysis, (ii) setting up of monitoring concepts and (iii) forecasting. Each model is specific for the system chosen. The development of a mathematical model for a specific system consists of the following steps (Baccini and Bader, 1996):

**General mathematical description:**

a) Complete description of the system using **system variables**, which are determined by the system analysis.

b) Determination of the **set of general equations**, (balance equations) which describe the general interactions and are valid for all systems.

The general mathematical description is applied (i) for calculating the best estimates for the variables and (ii) for modelling.

c) Development of the model. This step consists of choosing the **system parameters** and the **specific model equations**. The system variables are now a function of the system parameters.

Based on each specific model, monitoring concepts and forecasting-scenarios can be investigated. In the following a short description of the mathematical formalism is given. In Chapter 4 the specific model assumptions are described for the different subsystems.

### 2.2.3.1 General Mathematical Description

- **System variables** (dependant)

  The system variables describe an MFA system completely in time and space. They reflect the characteristic features of the system considered. The variables of a MFA system are:

  \[ M_j(t) : \text{amount of material in } V_j \]

  \[ A_{ij}(t) : \text{material flow from } V_r \text{ to } V_j \]

  \[ V_r : \text{selected balance volume (Process)} \]

- **General equations** (balance equations for the processes)

  These equations are valid for all systems. They define that for materials, elements and energy the input flux equals the output flux plus the flux to or from the stocks.

  \[ \frac{dM_j(t)}{dt} = \sum_r A_{ij} - \sum_s A_{js} \]
2.2.3.2 Modelling

- **System parameters (P)** (independent)
  
The system parameters are model specific. They represent the qualities characterizing the system. They should not be mixed up with the system variables which describe the system completely.

- **Model specific equations**
  
  These equations are model specific and are usually non-linear. They define the relationship between parameters and variables. They correspond to the model assumptions. The mathematical form is independent of the modelling approach chosen.

\[ F(M^{(j)}, A_n, P_v) = 0 \]

Therefore, a model with **N processes** is defined by the following three vectors:

**System variables**

\[ X := (X_1, \ldots, X_{N_{tot}}) = (M^{(j)}, A_n) \]  
vector of the unknown variables

**System parameters**

\[ P := (p_1, \ldots, p_M) \]  
vector of the system parameters

**Functions**

\[ F := (F_1, \ldots, F_{N_{tot}}) \]  
vector of the functions

The complete model is described by the following equations:

\[ F_1(X_1, \ldots, X_{N_{tot}}; p_1, \ldots, p_M) = 0 \]

\[ \vdots \]

\[ F_{N_{tot}}(X_1, \ldots, X_{N_{tot}}; p_1, \ldots, p_M) = 0 \]

or simplified:

\[ F(X, P) = 0 \]
2.2.3.3 Application of Mathematical Models

Mathematical models can be applied (i) to set up measurement programs, (ii) to set up monitoring concepts and (iii) to develop and study forecasting scenarios. In the following only the first two application will be discussed.

To set up a measurement program it is necessary to know (i) which fluxes have to be measured and (ii) how accurate the data has to be. Thus, the key to set up a measurement program is to analyze which parameter changes have the largest effects on the system (Bader & Baccini, 1996).

To set up a monitoring concept it is necessary to know (i) which changes in the system can be measured and (ii) where those changes can be measured. Thus, the key to set up a monitoring concept is to compare measurement errors of variables with changes in variables due to specific or random parameter variation.

Error propagation and sensitivity analysis are two indispensable tools to set up measurement and monitoring concepts because they analyze (i) the influence of random errors of the parameters on the variables and (ii) the effect of a systematic change of one parameter on the variables.

2.2.3.3.1 Error Propagation

Error propagation analyzes the effect of parameter deviations on the variables. Errors can be classified into two different types: systematic and random errors. A systematic error is a change of a variable due to a "directed" or specific measurable error of a parameter. A random error is a change in a variable due to a random variation of a parameter. In this thesis the effects of the random errors on the variables are of special interest, due to the expected large uncertainty and fluctuation of the parameters. To calculate the error propagation the first approximation of the gauss error propagation equation (equation 2.1) was chosen (Baccini & Bader, 1996):

\[
(\sigma_{x_j})^2 = \sum_i \left(\frac{\partial X_j}{\partial \rho_i}\right)^2 \sigma_{\rho_i}^2
\]  

(2.1)

\(X\): variable, \(\sigma_{x_j}\): average error of the variable,
\(p\): parameter, \(\sigma_{\rho_i}\): average error of the parameter.

Error propagation answers the following questions:

- Which random errors of the parameters can be detected?
- Where can natural or anthropogenic changes of the system be measured?
2.2.3.3.2 Sensitivity Analysis

Sensitivity analysis studies the sensitivity of a variable with respect to specific variations of the parameters. It allows for quantifying the effect of a defined parameter change (e.g. variation of 10%) on a variable. The equation describing the absolute sensitivity of a variable to a one unit change in a parameter is shown in equation 2.2a.

The relative sensitivity function (equation 2.2b) is used more often because it is normalized. This allows the comparison of the sensitivity of a variable to different parameters. It can be seen that the absolute sensitivity (equation 2.2a) is the basis for both the calculation of the relative sensitivity and the error propagation in first order.

\[ S_{i,j}^{(\text{abs})} = \frac{\partial X_i}{\partial p_j} \quad \text{absolute sensitivity} \quad (2.2a) \]

\[ S_{i,j}^{(\text{rel})} = \frac{\partial X_i}{\partial p_j} \cdot \frac{\Delta p_j}{X_i} \quad \text{relative sensitivity} \quad (2.2b) \]

\( X \): variable, \( p \): parameter

Knowing (i) the influence of a parameter on a variable and (ii) the measurement error of the variable, it can be determined which variables have to be measured in order to detect the effect of changes of the parameter.

2.2.3.3 Parameter Variation

Another important tool is the parameter variation. The parameter variation plays a significant role if (i) the effect of large changes of parameters on variables are analyzed and (ii) the effect of these changes is not likely to be linear. Parameter variation approximates numerically the shape of the function \( X_i = f(p_j) \) by variation of the parameter within a determined range\(^4\).

\(^4\)Sensitivity analysis only approximates the slope at a defined point.
2.3 Material Flux Analysis of Tunja

2.3.1. System analysis

System border

The system border was defined as the geographical boundary of the municipality. Within the geographical boundaries of the municipality, system borders are defined for the different subsystems chosen.

Selected Processes and Goods:

The system, municipality of Tunja, consists of four groups of processes and their subprocesses (Figure 2.10), leading to a total of 11 processes and 23 goods fluxes (Figure 2.11).

The process Supply consists of paper/cardboard, durables, food, energy and water; the process Production/Consumption consists of household/service/industry; the process Waste Management consists of recycling/reuse and landfill; and the process Environment consists of several processes relating to water and soil, namely soil/upper aquifer, groundwater/lower aquifer and surface water.

![System of the Municipality of Tunja](image)

Figure 2.11: System of the Municipality of Tunja.

---

5The atmosphere is located outside the system border and is not quantified.
2.3.2 Subsystems:

Five subsystems were selected to develop the methodology. They were based on the four human activities\(^6\) as defined by Baccini & Brunner, (1991). The subsystems selected were:

- Subsystem Water which is part of the activity "to clean"
- Subsystem Food which is part of the activity "to nourish"
- Subsystem Durables which is part of the activity "to reside"
- Subsystem Paper/Cardboard which is part of the activity "to communicate"\(^7\)
- Subsystem Energy which is part of the activity "to transport"\(^8\).

In the following all the subsystems are analyzed according to the scheme presented above; system analysis consisting of (i) system border, (ii) processes, i.e. supply, consumption/production, waste management and environment processes and (iii) goods. Additionally, the choice of indicators and the method used to collect and measure the data is presented.

---

\(^6\)According to Baccini and Brunner (1991) the four activities "to nourish", "to clean", "to reside and work" and "to transport and communicate" are chosen to describe the most important material fluxes within a region.

\(^7\)The data basis for the Subsystem Paper/Cardboard was not sufficient to fully characterize and validate the material fluxes. The methods used to collect the data and first results are discussed in Annex D.

\(^8\)The data basis for the Subsystem Energy was not sufficient to fully characterize and validate the material fluxes. The methods used to collect the data and first results are discussed in Annex E.
2.3.3. Subsystem Water; "to Clean"

2.3.3.1 System Analysis

The system consists of 5 processes and 16 fluxes (Figure 2.12). Only the system border and the selected processes will be discussed.

System Border

For the subsystem water, the system border is defined by the catchment area in the south, east and west and by the political boundary on the northern part of the municipality (74km²).

Figure 2.12:
Subsystem water; *: Measurement points.

Selected Processes:

The subsystem water consists of one supply, one production/consumption and three environment processes. The environment processes characterize the different water compartments and soil.
Supply:
The process Supply consists of Water-Supply which operates through the water supply company of the municipality, EAAT, and supplies Households, Services and all Industries of the municipality with water.

Consumption:
The process Consumption is Household/Services/Industry, where Households consume 84% and Services 13% and Industry 3% of the total water accounted for (see also 2.1.2.4).

Environment:
The process Environment consists of Soil/Upper Aquifer, Groundwater/Lower Aquifer, Surface Water and External Surface Water.

Soil/Upper Aquifer (0-10m) consists of two subprocesses Soil and Upper Aquifer. Soil includes 1m of pedosphere, where there is evapotranspiration, interception and CO₂ fixation. Upper Aquifer is located just below the Soil, varies between 1m and 9m and is used as a water source by 8% of the urban and 90% of the rural population (Figure 2.6).

The Groundwater/Lower Aquifer (50-300m) consists of the two main aquifers, Formación Bogotá (II) and Formación Cacho (III) and constitutes 15% of the water sources of the municipality.

Surface Water consists of the Río Chulo which originates in the rural part, south, of the municipality and flows north, passing across the whole urban area and collecting the untreated waste water. The whole length of the river within the municipality is about 10 km, of which 80% are through the urban area and 3 km of those are canalized.

The External Surface Water consists of the Río La Vega which originates in another catchment area and merges with the Río Chulo in the northern part of urban Tunja.

The waste management process Landfill was not integrated into the system for the subsystem water because the probability of contamination of groundwater due to landfill leachates is less than 1% the probability of contamination of groundwater due to sewage⁹.

Choice of Indicators
Phosphorous (P) and Carbon (C) were selected as the indicator elements taking into account three aspects. First, the indicator elements had to be measurable with the infrastructure available at the UNIBOYACA in Tunja, so that monitoring could be continued. Second, they had to reflect the human activities

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⁹ The estimations of leachate fluxes were made according to Baccini et., al. (1987) and Belevi & Baccini (1989). A comparison between leachate fluxes and sewage fluxes is shown in Chapter 3.
taking place in the region. Third, they had to reflect pollution and nutrients contamination in water. Studies of urban regions in industrialized countries have shown that the phosphorous (P) content in sewage originates in feces and washing water and thus, the P-flux can be correlated to the amount of food and detergents consumed (Baccini et al., 1993). Carbon (C) is a good indicator of organic pollution and can also be correlated with the human activities "to nourish" and "to clean".

2.3.3.2 Collection and Measurement of Data

Using the system analysis shown in Figure 2.12, the data was classified into (i) data that has already been measured and can be obtained from national or regional statistics, such as precipitation and water consumption, (ii) data that has to be measured, such as water flow and phosphorous and carbon concentrations in surface water and (iii) data that can be calculated from the measured data. The data which was measured is marked in Figure 2.12 with *. The data was collected and measured by four undergraduate students of the UNIBOYACA for their diploma theses.

a) Water flow data

In Figure 2.13, the measurement points are shown. At measurement points M1 and M3, water flow was determined by depth and flow velocity measurements. At these measurement points, the river bed was cleaned and leveled in order to obtain a homogeneous flow area. Depth gauges were installed afterwards and their height calibrated. The water velocity measurements in m/s were carried out using a floating object over a distance of 1 meter. The velocity was calibrated by comparing the velocity of the floating body with the velocity measured with a hydrometric propeller. The correction factor found was 0.8. Variations in the daily water flow were measured by monitoring the water flow every 30 minutes for 24 hours in the wet and dry seasons. Variations in the monthly water flow were measured by monitoring the water flow at the same time once a day during one month in the wet season and one month in the dry season. The annual water flow (mio m³/catchment area and year) was determined using the monthly data assuming a wet period of 5 and a dry period of 7 months according to the variation in precipitation.

Water flow at points M2 and M410 was determined using a measuring weir. To estimate possible infiltration rates, the daily water flow at different sites of the river was measured by installing gauges at different points along the river and measuring the velocity with floating objects.

\[^{10}\text{flow from urban area.}\]
b) Phosphorous and carbon concentrations in surface water

**Sampling method.** Water samples to determine the phosphorous and carbon concentrations in surface water were taken at all measurement points using a bottle previously cleaned with sulfuric acid\(^{11}\). At point M3 the bottle was submerged at three different levels 10, 20 and 30 cm below the water table. At the measurement points where the water level was less than 20 cm deep, only one sample was taken. Mixed daily samples were taken by proportionally mixing the different samples.

**Analysis of phosphorous.** The samples were filtered using a 45μm filter. The dissolved phosphorous was measured using the ascorbic acid method (APHA, 1992). The total P content was calculated based on the assumption that, in sewage, the dissolved P fraction is 50% ± 10% of the total P concentration (Boller, 1994).

**Analysis of carbon.** Chemical Oxygen Demand (COD) was measured from the unfiltered sample using Hatch COD digestion reagent vials for low and high range. The Carbon concentration as TOC (total organic carbon) was calculated from measured COD using a factor of TOC: COD = 1:3 according to Boller, (1994).

c) Phosphorous and Carbon loads calculated at household level

The P and C loads were calculated by measuring the mass fluxes of the goods containing P and C in households, food and detergents, and multiplying them times the concentration of P and C in this goods.

---

\(^{11}\)Cleaning with sulfuric acid is used to remove rests of phosphorous.
**Mass fluxes.** Food fluxes were determined by measuring the food input into the municipality at the supply processes (see Chapter 2.3.4.2). Detergent fluxes were determined by multiplying the amount of washing machines in the region times an average consumption per household, which was assumed to be half the amount that measured in Swiss households.

**P and C concentrations.** P and C concentrations in food were taken from Souci et al. (1992). Concentrations of the commonly used detergents in the municipality were measured by dissolving 10 g of detergent in 100 ml of water and measuring P and C.

In Tables 2.11 to 2.14 the data sources and their corresponding estimated error margins are shown.

<table>
<thead>
<tr>
<th>Good</th>
<th>Data source</th>
<th>Error margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (P)</td>
<td>HIMAT, Thiessen polygons</td>
<td>5%</td>
</tr>
<tr>
<td>Drinking water1</td>
<td>EAAT</td>
<td>5%</td>
</tr>
<tr>
<td>GW extraction</td>
<td>EAAT</td>
<td>5%</td>
</tr>
<tr>
<td>Drinking water2</td>
<td>EAAT</td>
<td>10%</td>
</tr>
<tr>
<td>Losses</td>
<td>EAAT</td>
<td>10%</td>
</tr>
<tr>
<td>Surface water input</td>
<td>water flow measurements during wet and dry season, each one month.</td>
<td>20%</td>
</tr>
<tr>
<td>Surface water output</td>
<td>water flow measurements during wet and dry season, each one month.</td>
<td>30%</td>
</tr>
</tbody>
</table>
Table 2.12: 
Equations and assumptions made for the calculation of fluxes in the subsystem water.

<table>
<thead>
<tr>
<th>Good Flux</th>
<th>Data Source</th>
<th>Method/Assumptions</th>
<th>Error Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evapotranspiration (EVT)</td>
<td>(HIMAT, 1993)</td>
<td>Measured values and formula of TURC for regional evapotranspiration. Including evapotranspiration caused by irrigation: $EVT_{tot} = ETP_{regional} + EVT_{irrigation}$</td>
<td>10%</td>
</tr>
<tr>
<td>Fountain water</td>
<td>(World Bank, 1992)</td>
<td>Distance from water source correlates with the amount of water consumed. Here: 125 l/cap. d</td>
<td>20%</td>
</tr>
<tr>
<td>Sewage / sewage losses</td>
<td>(EAAT, 1993)</td>
<td>Estimation according to quality of sewage system 80% sewage, 20% losses</td>
<td>10%</td>
</tr>
<tr>
<td>Run off</td>
<td>US Soil Conservation Service</td>
<td>$N_d = \left[\left(\frac{N}{25.4}\right) - \left(\frac{200}{CN}\right) + 2\right]^2 \times 25.4$  [N_d = (P-EVT)] [N = (P-EVT)] [CN = \text{max. soil water storage capacity}]</td>
<td>10%</td>
</tr>
<tr>
<td>Irrigation</td>
<td>(HIMAT, 1993) theoretical water need of cultures</td>
<td>Assumption: watering to 85% of theoretical need - root crops and cereals: whole cultivated area - pasture land: 15% of the area</td>
<td>20%</td>
</tr>
<tr>
<td>Infiltration</td>
<td>(Alarcán &amp; Suárez, 1991)</td>
<td>Infiltration areas according to geological card 8 km²: Formación Bogotá 8.8 km²: Formación Cacho Assumption: Infiltration quantity: $P-EVT$</td>
<td>20%</td>
</tr>
<tr>
<td>Groundwater stock (GR)</td>
<td>(Alarcán &amp; Suárez, 1991); (Dracos, 1980)</td>
<td>Calculation with two different methods: 1) $GR = A \times h \times P$  2) $GR = t \times \text{infiltration}$, $t = \frac{X}{t_{res}}$  [A: \text{flow area, } h: \text{thickness, } P: \text{porosity}]  [k: \text{hydraulic conductivity, } t: \text{residence time,}]  [X: \text{length of the studied aquifer}]</td>
<td>40%</td>
</tr>
<tr>
<td>GW output2</td>
<td>Darcy, $Q = A \times k \times i$ (parameter definition see above)</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>Leachate</td>
<td>(Baccini et al, 1987), (Belevi, Baccini, 1989)</td>
<td>Leachate amount is $P-EVT$, area: 7ha, Concentration of element in leachate: $c = c_0 \times e^{v \times c_0 \times c}$  [c_0: \text{mean concentration of element after intensive reactor phase, } V: \text{leakage volume, } Mm: \text{element stock in landfill}]</td>
<td>30%</td>
</tr>
</tbody>
</table>
Table 2.13:
Measurement program for determining P- and C-concentrations in water.

<table>
<thead>
<tr>
<th>Good</th>
<th>Frequency</th>
<th>Date</th>
<th>Error Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface water input</td>
<td>Daily (1x)</td>
<td>27.9.93, 20.10.93, 3.11.93, 17.11.93</td>
<td>20%</td>
</tr>
<tr>
<td>Drinking water inlet and water extraction</td>
<td>Daily (1x)</td>
<td>27.9.93, 20.10.93, 3.11.93, 17.11.93</td>
<td>20%</td>
</tr>
<tr>
<td>Surface water output</td>
<td>Every hour Daily (1x)</td>
<td>14.12.93 (one day) 18.1.94 - 18.2.94</td>
<td>30%</td>
</tr>
<tr>
<td>Irrigation</td>
<td>Spot checks</td>
<td>27.9.93, 20.10.93, 3.11.93, 17.11.93</td>
<td>40%</td>
</tr>
</tbody>
</table>

Table 2.14:
Determination of the P- and C- fluxes in the anthroposphere.

<table>
<thead>
<tr>
<th>Good</th>
<th>Data Source</th>
<th>Method/Assumptions</th>
<th>Error Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food P-content</td>
<td>FAO (Food balances sheet 1984 -1986), 1991</td>
<td>see 2.3.3.2</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>FAO, [Souci et al., 1989]</td>
<td></td>
<td>10%</td>
</tr>
<tr>
<td>Detergents P-content</td>
<td>[Baccini et al, 1993]</td>
<td>Measurement of the most commonly purchased detergents</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10%</td>
</tr>
<tr>
<td>Fertilizer</td>
<td>[ICA, 1986]</td>
<td></td>
<td>50%</td>
</tr>
<tr>
<td>Agricultural production</td>
<td>[IGAC, 1990], [Gorraiz, 1994], [Rodriguez, 1992]</td>
<td>Average values</td>
<td>10%</td>
</tr>
</tbody>
</table>
2.3.4 Subsystem Food; "to Nourish"

2.3.4.1 System Analysis

The system consists of 6 processes and 16 goods (Figure 2.14). Only the system border and the selected processes will be discussed.

System Border

For the subsystem food, the system border is the urban part of the municipality of Tunja.

![Subsystem food diagram](image)

Figure 2.14: Subsystem food.
FP: Fresh Products, MP: Manufactured Products, Meat: Includes fish and eggs (see below)
*: Measured fluxes.

Selected Processes

The subsystem food consists of three supply processes, one consumption process, one waste management process and one environment process.
Subsystem Food; "to Nourish"

Supply:
The process Supply consists of the processes Market Place, Supermarkets and Specialized Shops\textsuperscript{12}. The Market Place supplies the inhabitants of Tunja with fresh products\textsuperscript{13}. Additionally, it is a regional trade center for fresh products. The Supermarkets supply the inhabitants with fresh and manufactured products\textsuperscript{14}. They obtain the fresh products from the Market Place and import most of the manufactured products. The Specialized Shops supply the municipality with imported manufactured products and locally produced meats. They include grain houses and butchers.

Consumption:
The process Consumption is Household/Restaurant. Households and Restaurants are considered to be one consumption unit, because it is assumed that, similar to industrialized countries\textsuperscript{15}, Households consume about 90\% of the food and Restaurants consume only about 10\%.

Waste Management:
The process Waste Management is Landfill where the municipal solid waste is deposited.

Environment:
The process Environment is Surface Water. Surface Water consists of the Rio Chulo (see 2.3.3.1).

Choice of Indicators
Phosphorous (P) and carbon (C) are good indicators for the activity "to nourish".

2.3.4.2 Collection and Measurement of Data
The data of food consumption was surveyed at the supply processes. The different food supply processes were specific for the different food types (Table 2.15). Additionally, as a control, the waste composition of the different social strata was measured. The unit selected to compare the mass fluxes of the different food

\textsuperscript{12} Small Shops (similar to petty commodities) are not included in the system analysis because they supply themselves either from the Supermarkets or the Specialized Shops and thus their flux is included in the measurements of the input into Supermarkets and Specialized Shops (Martinez et. al, 1994).

\textsuperscript{13} Fresh products comprise fresh vegetables, fresh fruit and meat.

\textsuperscript{14} Manufactured products comprise cereals, dried legumes, sugar, milk and milk products.

\textsuperscript{15} Baccini et al., 1993.
types is dry matter. The data was collected and measured by six undergraduate students of the UNIBOYACA. The data which was measured is marked in Figure 2.14 with *.

Table 2.15: Food groups and their main supply processes.

<table>
<thead>
<tr>
<th>Food group</th>
<th>Definition</th>
<th>Main supply process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh products</td>
<td>Fresh vegetables, fresh fruit and meat</td>
<td>Market Place</td>
</tr>
<tr>
<td>Manufactured</td>
<td>Cereals, dried legumes, sugar, milk and milk products</td>
<td>Supermarkets and Specialized Shops</td>
</tr>
</tbody>
</table>

a) Mass Fluxes

**Market Place.** The amount of fresh products consumed in Tunja was determined as the difference between the amount of products entering and the amount of products leaving the municipality via the Market Place. The Market Place was surveyed during the wholesaler's supply period (Wednesday - Friday). Surveys took place on 25.08.93 - 27.08.94, 30.9.93 - 1.10.93 and 29.10.93 - 1.11.93. Each entrance to the Market Place was surveyed by 4-5 people who recorded the numbers of the license plates of the trucks, amount, package and origin and destiny of the transported products. The weight per package and product was measured separately. The total food entering and leaving the municipality was calculated as the amount of each product in certain package times its weight.

**Supermarkets and Specialized Shops.** The amount of manufactured products consumed in Tunja was determined by surveying the most important Specialized Shops and Supermarkets. The information was recorded over six months and contained: amount, packages, weight and origin of each product.

The amount of veal and pork consumed in Tunja was determined using monthly slaughter data. The amount of imported chicken, fish and eggs was estimated using national statistics. It was assumed that meat consumption increases with growing wealth (Mohan, 1980).

b) Element Concentration

The concentration of the elements P and C in food were calculated using published data (Souci et. al, 1990, see also Annex B).
2.3.4.3 Purchasing Habits and Waste Production:

The purchasing habits of Households of the different food groups were surveyed in the household survey described in Chapter 2.3.5.2.

Waste production and composition were surveyed using a sample of different social strata. The sample size was calculated according to the following formula [Collazos, 1989]:

\[
    n = \frac{N \cdot t^2 \cdot S^2}{N \cdot d^2 + t^2 \cdot S^2}
\]

(2.3)

where:

- \(n\): Sample size
- \(N\): Total sample (here: Total of each strata)
- \(t\): Factor for 95% certainty
- \(S\): Variance; here 1.4 according to data from Gorraiz et. al., (1988)
- \(d\): Error margin

The sample size for the different social strata is shown in Table 2.16:

Table 2.16:
Sample size for the survey of waste composition for the different social strata.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>54</td>
</tr>
<tr>
<td>4</td>
<td>63</td>
</tr>
<tr>
<td>3</td>
<td>64</td>
</tr>
<tr>
<td>2</td>
<td>62</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>243</strong></td>
</tr>
</tbody>
</table>

Households were surveyed twice. The samples consisted of the waste of a whole week taken in two different months. The waste was collected the same day the official collection would have taken place. On the day of sampling, the number of people living during that week in that household was recorded. The waste of each household was collected in a separate bag and weighed. The waste from one district was put together and divided into 8 categories; recyclable plastic, non recyclable plastic, glass, cardboard, paper, tin-plates, textiles, organic matter and others.
Chapter 2: Methods

A short summary of the measured data is presented in Table 2.17:

<table>
<thead>
<tr>
<th>Measurement Point</th>
<th>Measurements/Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh Products</td>
<td>3 surveys at the Market Place, measurement of input and output to Tunja (Martinez et al., 1994)</td>
</tr>
<tr>
<td>Manufactured</td>
<td>Surveys at Supermarkets and Specialized Shops, Average sales over 6 months (Martinez et al., 1994)</td>
</tr>
<tr>
<td>Meat</td>
<td>Surveys at the slaughterhouse (Martinez et al., 1994; FAO, 1990)</td>
</tr>
<tr>
<td>Purchasing</td>
<td>Household survey by socio-economic strata</td>
</tr>
<tr>
<td>Waste Composition</td>
<td>Household survey by socio-economic strata during two weeks (Forrero and Sanchez, 1994)</td>
</tr>
</tbody>
</table>
2.3.5 Subsystem Durables; "to Reside"

2.3.5.1 System Analysis

The system consists of 6 processes and 16 goods (Figure 2.15). Only the system border and the selected processes will be discussed.

System border

For the subsystem durables, the system border is the urban part of the municipality of Tunja.

Selected Processes

The subsystem durables consists of four consumption processes related to the four socio-economic strata in Tunja (see 2.1.2.4) and two waste management processes (Figure 2.15)\(^\text{16}\).

\(^\text{16}\)The supply processes are located outside the system border.
Consumption:

The process Consumption is composed of Households 2, 3, 4, 5 which correspond to the socio-economic strata of Tunja as defined in 2.1.2.4. Strata 1 and 6 were added to strata 2 and 5 respectively because they constitute less than 1% of the total population.

Waste Management:

The process Waste Management consists of Reuse/Recycling and Landfill. Reuse/Recycling is a distribution process, where the used durables are sold or given away and reused again by Households from the same or another strata or are collected to be exported for Recycling. The durables which are neither reused nor recycled are disposed of at Landfill.

2.3.5.2 Collection and Measurement of Data

The flux of durables into and storage in Households was measured using a survey of social strata. The survey was developed in co-operation with Mrs. M. Gómez and Mrs. B. Gómez. The survey was carried out by social science students of the UNIBOYACA under supervision of Mrs. H. Garcia.

The classification into the different strata was made according to the Colombian criteria (Table 2.8). To validate the applicability of the Colombian criteria for the classification of the different social strata questions with respect to income and expenditures were included in the survey. The following groups of durables, characterizing the activity "to reside" were analyzed:

- Furniture (table, bed)
- Electrical appliances (washing machine, TV)
- Vehicles (car, bus, bicycle).

Sample Size. The sample size was calculated according to the following equation (Kaplitza, 1975):

\[ n = t^2 \cdot \frac{p(p-1)}{\alpha^2} \]  

where:  
- \( n \): sample size  
- \( t \): certainty factor (here: 95%)  
- \( p \): percentage of answers (here: 0.7)  
- \( \alpha \): first grade error (here: 0.05)

The sample size by socio-economic strata was determined proportionally to their population share (Table 2.18). The sample size per district was determined.
proportionally to the number of Households living in the district. For stratum 5, a larger sample size was chosen so that the different social strata could be compared.

Table 2.18:
Sample size of the different social strata.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Inhabitants</th>
<th>Household (HH)</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>%</td>
<td>Total</td>
</tr>
<tr>
<td>5</td>
<td>1,735</td>
<td>350</td>
<td>22^a</td>
</tr>
<tr>
<td>4</td>
<td>28,287</td>
<td>5,780</td>
<td>83</td>
</tr>
<tr>
<td>3</td>
<td>64,174</td>
<td>12,990</td>
<td>204</td>
</tr>
<tr>
<td>2</td>
<td>9,843</td>
<td>2,020</td>
<td>37</td>
</tr>
<tr>
<td>Total</td>
<td>104,039</td>
<td>21,140</td>
<td>332</td>
</tr>
</tbody>
</table>

^a For stratum 5 a larger sample size was chosen so that the different social strata could also be compared.

Sample choice. To select the samples, the city districts were classified into different social strata according to the Colombian criteria. Districts that included more than one social stratum were classified according to their predominant strata. Only districts with one social stratum were chosen for the survey. Small comparative samples were taken from the other districts. In total, surveys were carried out in 50 districts out of 88. To increase the probability of response, the samples were selected with the help of district organizations and friends. Some samples were also chosen randomly. The proportion of the different sample choices was 1:1:1. The survey was made in the form of standardized interviews, which were carried out by a team of two people and lasted 15 - 25 min.

2.3.5.3 Data Analysis

Dynamic Model for Durables

The output of durables from Households is delayed in relation to the input because durables have a lifetime which is longer than one year. A dynamic input-output model was used to calculate the output of durables from households. This model allows the calculation of the output by using an input function and a transfer function. Both functions were determined with the data obtained in the survey described below. The mathematical description is based on the formalism presented in Chapter 2.2.3.
Chapter 2: Methods

System variables:

\( O(t_{op}) \) output flux at the time \( t \)

\( M^{(0)}(t) \) stock at time \( t \)

\( I(t_{ip}) \) input at time \( t_{ip} \)

System parameters:

\( \tau_0 \) lifetime of the different goods

\( \sigma_0 \) standard deviation (STDV) of \( \tau \)

\[ k_{rs}(t_{op}, t_{ip}) \text{ input-output transfer function} = \frac{1}{N_0} e^{-\frac{(t_{op} - t_{ip} - \tau_0)^2}{2\sigma_0^2}} \]

where,

\[ N_0(t_{ip}) = \int_0^\infty e^{-\frac{(t-t_0)^2}{2\sigma_0^2}} dt \text{ norming factor} \]

Model equations

Output function

\[ O(t_{op}) = \int_{-\infty}^{t_{ip}} I(t_{ip}) k(t_{op}, t_{ip}) dt_{ip} \quad (2.5) \]

Calculation of the Input function

\[ I(t_{ip}) = \frac{\Delta M(t; t_{ip}, t_{ip} + \Delta t) / \Delta t}{(1 - \int_{t_{ip}}^t k(t_{op}, t_{ip}) dt_{op})} \quad (2.6) \]

where:

\( \Delta M(t; t_{ip}, t_{ip} + \Delta t) \) is the part of the input at the time \( t_{ip} \) that still remains in the stock of household at time \( t \).

\( \tau_0 \) is the lifetime of the good, \( \sigma_0 \) is the STDV of \( \tau_0 \).
Interpretation

Input at a time \( t_{ip} < t \)

At a time \( t \) later than \( t_{ip} \), the input at time \( t_{ip} \) cannot be measured. However, the part of the input which is still in the stock at time \( t \) \( (\Delta M(t; t_{ip}, t_{ip} + \Delta t)) \) can be measured. The input at a time \( t_{ip} \) can be calculated using equation 2.6, if \( \Delta M(t; t_{ip}, t_{ip} + \Delta t) \), the lifetime and STDV of the goods in the stock are known (Bader, 1995).

Transfer-function \( k(t_{op}, t_{ip}) \)

The transfer-function is a function of \( \tau_0 \), \( \sigma_0 \) and \( t_{op} \) and \( t_{ip} \). The transfer-function is assumed to be Gauss distributed as shown in Figure 2.16. For a given input at a time \( t_{ip} \), the total output in a time interval \([t_{ip}, t_{op}]\) originating from the input at time \( t_{ip} \) is equal to the area below the curve for the time interval \( t_{ip} \) to \( t_{op} \). Accordingly, \( \Delta M(t; t_{ip}, t_{ip} + \Delta t) \) measured in Household at a time \( t \), \( (t_{ip} < t < t_{op}) \) corresponds to the total area minus the area below the curve for the time interval \( t_{ip} \) to \( t \). This is equal to the area for the time interval \( t_{op} \) to \( t \).

![Figure 2.16: Output transfer function \( k_{rs}(t_{op}, t_{ip}) \); \( \tau_0 \): lifetime, \( \sigma_0 \): STDV of \( \tau_0 \).](image)
Chapter 2: Methods

Definition of the data needed

Based on the modeling approach presented, the following parameters had to be measured:

\[ \Delta M(t_p, t) \] part of the input at the time \( t_p \) that still remains in the households

\[ t - t_p \] residence time of the good

\( \tau_0 \) lifetime of the good

\( \sigma_0 \) STDV of \( \tau_0 \)

In Table 2.19, the questions used to determine the parameters of the model described above are shown (for the durable table). The complete questionnaire is shown in Annex C. The error margin of the answers cannot be directly determined because effects such as social desirability and knowledge about older pieces of furniture were not analyzed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Question (for the durable table)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verification of social strata</td>
<td>Income and expenditure pattern of households</td>
</tr>
</tbody>
</table>
| \( \Delta M(t_p, t) \) part of \( I(t_p) \) that still remains in households | How many tables do you possess?  
Quantity and brief characterization; e.g. wood, metal. |
| Residence time in household at the time \( t \) | How long have you had your table?  
Answer: in time categories 5, 10, 15, 20, >20 years                                            |
| Lifetime of table \( \tau \) and STDV of lifetime \( \sigma \) | If you had a table earlier, how long did you have it?  
Answer: in time categories 5, 10, 15, 20, >20 years                                               |
| Output-transfer coefficient                   | What did you do with your old table?  
Answer: e.g. sold, present, waste, e.g. to friends, relatives                                     |
3. Results

This section analyzes the results for the subsystems "water", "food" and "durables". For each subsystem the mass fluxes and their validation are presented.

3.1 Subsystem Water; "to Clean"

For the subsystem water, the water balance of the catchment area is shown. It focuses in particular on (i) the anthropogenic demand vis à vis the local and neighboring water resources and (ii) the dilution capacity of surface water with respect to waste water.

3.1.1 Mass Fluxes

3.1.1.1 Water Balance

Figure 3.1 shows the water balance of the catchment area for the year 1993. The error margin of the fluxes is mainly determined by the random errors, which vary between 5% and 30% (see 2.3.3.2).
Chapter 3: Results

The largest input flux into the catchment area is precipitation (Atmosphere to Soil/Upper Aquifer) and the largest output flux is evapotranspiration (Soil/Upper Aquifer to Atmosphere). Evapotranspiration consists of the actual evaporation from precipitation (about 76%) and the evapotranspiration from irrigation of plants. The total evapotranspiration is about 84% of the precipitation, which is typical for regions located in the Andes at the same altitude (Müller & Richter, 1980). Thus, the net precipitation, total precipitation minus evapotranspiration, is only 7 mio m$^3$/year.

The second largest input flux at 8.5 mio m$^3$/year is the drinking water1 (Figure 3.1) from an external reservoir to Water-Supply. It constitutes 85% of the total flux into Water-Supply; the other 15% is extracted from Groundwater/Lower Aquifer located in the municipality. Thus, the municipality can only satisfy 15% of its drinking water demand with its own water sources and is dependent on water sources from neighboring regions. In the urban area, about 6 mio m$^3$/year are consumed by 90% of the population, which corresponds to a per capita consumption of 160 l/day.

The second largest output flux of the system is the output flux from Surface Water that is composed of runoff, waste water from Household/Services/Industry and the SW-input from external surface water. The quality of the surface water is determined by (i) the dilution capacity$^1$ of the surface water for waste water and (ii) the quality of waste water of the consumption processes. The flux of untreated waste water from Household/Services/Industry to Surface Water constitutes about 30% of the total flux to Surface Water leading to a dilution capacity for waste water of about 3. Thus, the quality of the output flux from Surface Water is mainly determined by the quality of waste water from Household/Services/Industry.

About 20% of waste water from Household/Services/Industry infiltrates into Soil/Upper Aquifer due to leakages in the sewer system and flows to the neighboring region.

The infiltration rate into the Lower Aquifer at about 2 mio m$^3$/year and the extraction rate of the Lower Aquifer at about 1.5 mio m$^3$/year are in the same order of magnitude, showing that the Lower Aquifer is not being overexploited. The actual stock of the Lower Aquifer is about 1,000 mio m$^3$, that is about 100 times larger than the current infiltration and extraction rates indicating a residence time for the water in the lower aquifer of about 100 years. This fact has been confirmed by isotope measurements which showed that the water in the Lower Aquifer is at least 100 years old (Jimenez & Valero, 1990).

---

1For anthropogenic fluxes; anthropogenic polluted flux/total flux.
3.1.1.2 Phosphorous and Carbon Balances

For both elements, P and C, the flux from Household/Services/Industry to Surface Water is the most important flux constituting about 90% of the total P and 70% of the total C flux into Surface Water. Thus, the P and C balances verify the finding of the water balance that the quality of waste water from Household/Services/Industry determines the quality of the surface water leaving the region. The concentration of P in the surface water increases by 100 times while passing through the urban area and C increases by 40 times.

3.1.1.2.1 Phosphorous Balance

The largest P-inputs into the catchment area are fertilizer into Soil/Upper Aquifer and food and detergents into Household/Services/Industry (Figure 3.2). In Soil, P originates from the agricultural production, i.e. activity "to nourish". The input-flux to Soil is fertilizer and the output-flux agricultural products. However, the larger part of the P-input remains in the Soil building a stock. In Households, the P-flux originates from the consumption of food and detergents used in the activities "to nourish" and "to clean". The P-flux from to the activity "to nourish" is about twice as much as the P-flux from "to clean".

![Diagram](image)

Figure 3.2:
Phosphorous balance for the catchment area in t/year (for fluxes) and t (for stocks). For details see Annex A.
The P-flux from Household/Services/Industry into Surface Water constitutes 90% of the total P-flux into Surface Water, the contribution of soil erosion being only 10%. Therefore, the quality of waste water of Household/Industry determines the P content in Surface Water.

The output-flux from Household to Landfill is organic waste constituting only 5% of the total output flux of Household. Thus, for recycling of P as for example fertilizer, it is important to focus on the P content of waste water instead of focusing on organic waste.

3.1.1.2.2 Carbon Balance

The largest C-input is the food input into Household/Services/Industry. It is one order of magnitude larger than the input of detergents. The largest output flux from Household/Services/Industry is the gas-flux into Atmosphere (breath). The second largest output fluxes from Household are the fluxes into Landfill and Surface Water which are about one tenth the size of the flux from Household/Services/Industry into Atmosphere.

The C-flux from Household/Services/Industry into Surface Water constitutes about 70% of the total C-flux into Surface Water with run off, including soil erosion, accounting for the other 30%. Thus, the quality of surface water is determined by the quality of waste water from Household/Services/Industry.

Figure 3.3: Carbon balance for the catchment area in t/year (for fluxes) and t (for stocks). For details see Annex A.
3.1.1.3 Groundwater Contamination

Measurements of parameters in the Upper Aquifer, such as solids, chlorine and sulfates have shown, that the water in the wells located in the urban part of Tunja is contaminated (Alarcón & Suárez, 1991). This contamination is due to the location of the Upper Aquifer which is only about 1 m below the surface (Figure 2.6). Therefore there is a high probability for groundwater contamination due to infiltration of sewage and landfill leachates.

The contribution of landfill leachate to the P and C balance is marginal if the P and C balances are considered as a whole. However, the C-concentration, as DOC, of landfill leachate is twice the C-concentration of sewage and the P-concentration of landfill leachate is in the same order of magnitude as the P-concentration of sewage (Table 3.1). Thus, landfill leachate can cause local contamination of the Upper Aquifer, deteriorating the quality of drinking water sources located near this pollution source.

Contamination of the Lower Aquifer due to sewage losses or landfill leachate has not been found until now (Alarcón & Suárez, 1991) because the Lower Aquifer is protected by layers of silt and clay with a magnitude from 100 to 200 m. However, a local contamination might be possible due to badly sealed groundwater wells.

Table 3.1:
Water-flux, P and C concentrations and fluxes caused by landfill leachates and sewage losses.

<table>
<thead>
<tr>
<th></th>
<th>Landfill leachates¹</th>
<th>Sewage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water flux (mio m³/year)</td>
<td>0.01</td>
<td>1.6</td>
</tr>
<tr>
<td>P-conc. (mg/l)</td>
<td>6.8²</td>
<td>15³</td>
</tr>
<tr>
<td>P-flux (t/year)</td>
<td>0.07</td>
<td>28</td>
</tr>
<tr>
<td>C-conc. (mg DOC/l)</td>
<td>750</td>
<td>420</td>
</tr>
<tr>
<td>C-flux (t DOC/year)</td>
<td>7.5</td>
<td>1,200</td>
</tr>
</tbody>
</table>

¹: according to Belevi & Baccini (1989)
²: dissolved P
³: total P
3.1.2 Calibration and Validation

3.1.2.1 Calibration of the Dilution Capacity

In this study area, dilution capacity is defined as the capacity of the surface water to dilute waste water from Household/Services/Industry. The dilution capacity of surface water is calibrated by comparing:

(i) the dilution capacity obtained using the water balance with
(ii) the dilution capacity obtained using the P- and C- concentrations in waste water and surface water.

<table>
<thead>
<tr>
<th></th>
<th>Waste water&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Surface water before urban area&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Surface water leaving the region&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Dilution capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water flux mio m&lt;sup&gt;3&lt;/sup&gt;/y</td>
<td>4.7 ± 0.5</td>
<td>0.6 ± 0.1</td>
<td>14.4 ± 2.8</td>
<td>3.1 ± 0.8</td>
</tr>
<tr>
<td>[P]&lt;sub&gt;tot&lt;/sub&gt; mg/l</td>
<td>15 ± 4</td>
<td>0.01</td>
<td>6.5 ± 0.5</td>
<td>2.3 ± 0.7</td>
</tr>
<tr>
<td>[TOC] mg/l</td>
<td>140 ± 20</td>
<td>0.3</td>
<td>77 ± 10</td>
<td>1.8 ± 0.6</td>
</tr>
</tbody>
</table>

          2: Calixto & Valcarcel, 1994

The dilution capacity calculated using the water flux is about 3, while the dilution capacity calculated using the concentrations in waste water and surface water is about 2.3 for P and 1.8 for C (Table 3.2). For P and C, the lower dilution capacity is due to the additional input of P and C to Surface Water caused by soil erosion. Soil erosion constitutes about 10% of the total P and 30% of the total C input to Surface Water. Taking this into account, the three data series are in agreement and show a similar dilution capacity, between 2 and 3, for waste water.

The variation of more than 20% for P and C concentrations in sewage is due to large daily fluctuations and the comparatively small number of samples taken.
3.1.2.2 Validation of Model Assumptions

The model assumptions for the water, P and C-fluxes are validated by comparing
(i) the P and C fluxes calculated from the measured inputs (food and detergents)
and the transfer coefficients with
(ii) the P and C fluxes calculated from the measured data in surface water output.

For both elements, the model assumptions can be validated (Table 3.3). For P, the error range is smaller if the flux is calculated using the measured input and transfer coefficients than using measurements of surface water. For C, the error range is larger for the fluxes calculated from inputs and transfer coefficients. This is due to the uncertainty of the transfer coefficient which determines the rate of erosion. However, it can be seen that, even with a low amount of data and relatively high error margins, a system can be set up and validated by measuring or estimating the system parameters (input and transfer coefficients), calculating the output using these parameters and comparing the calculated output values to output measurements (see also Baccini et. al, 1993).

Table 3.3:
P and C fluxes calculated from measured inputs and transfer coefficients and P and C fluxes calculated from measurements in surface water.

<table>
<thead>
<tr>
<th>Calculated fluxes from measured inputs and transfer coefficients</th>
<th>P- Flux (t/catchment area.year)</th>
<th>C-Flux (TOC) (t/catchment area.year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;to nourish&quot; (excreta)</td>
<td>77 ± 19</td>
<td>1,200 ± 460</td>
</tr>
<tr>
<td>&quot;to clean&quot; (washing water)</td>
<td>66 ± 5</td>
<td>550 ± 46</td>
</tr>
<tr>
<td>Irrigation (losses)</td>
<td>39 ± 17</td>
<td>820 ± 200</td>
</tr>
<tr>
<td>Sewage leakages (losses)</td>
<td>-19 ± 2</td>
<td>-390 ± 40</td>
</tr>
<tr>
<td>Erosion (Baccini &amp; von Steiger, 1993)</td>
<td>-24 ± 5</td>
<td>-400 ± 70</td>
</tr>
<tr>
<td>14 ± 1</td>
<td>600 ± 400</td>
<td></td>
</tr>
<tr>
<td>Calculated fluxes from measured values in surface water</td>
<td>82 ± 30</td>
<td>1,100 ± 360</td>
</tr>
<tr>
<td>(concentration and water flux)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.1.2.3 Validation of the Infiltration Flux to Groundwater/Lower Aquifer

The infiltration flux into Groundwater/Lower Aquifer was validated by comparing

(i) the infiltration calculated using the infiltration area and net precipitation with

(ii) the infiltration calculated as the theoretical groundwater flow out of the catchment area.

Latter was calculated using slope, flow area and porosity of the aquifer according to Darcy (see Chapter 2, Table 2.12).

The infiltration fluxes into Groundwater/Lower Aquifer which were calculated using the two methods lie in the same order of magnitude. The maximum extraction rate where the groundwater stock is still in balance lies between 0.5 and 3.4 mio m$^3$/year.

Table 3.4: Groundwater stock and infiltration into Groundwater/Lower Aquifer.

<table>
<thead>
<tr>
<th>Stock (mio m$^3$)</th>
<th>Infiltration mio m$^3$/y (Infiltration areas)</th>
<th>Infiltration mio m$^3$/y (Darcy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formación Bogotá</td>
<td>100 ± 50</td>
<td>1.2 ± 0.6</td>
</tr>
<tr>
<td>Formación Cacho (upper level)</td>
<td>500 ± 200</td>
<td>0.6 ± 0.2</td>
</tr>
<tr>
<td>Formación Cacho (lower level)</td>
<td>500 ± 200</td>
<td>0.6 ± 0.2</td>
</tr>
<tr>
<td>Total</td>
<td>1,200 ± 500</td>
<td>2.4 ± 1.0</td>
</tr>
</tbody>
</table>
3.1.3 Conclusions

- The water balance can be determined by measuring precipitation, water consumption, surface water input and surface water output. In areas without major industries, Phosphorus and Carbon are appropriate indicators to validate the fluxes.

- The municipality can only satisfy about 15% of the current water demand with its own water sources. Thus, the municipality is dependant on a "Hinterland" for its water supply.

- The low regional geogenic water input leads to a dilution capacity for sewage that is smaller than 3. Therefore, the quantity and quality of surface water is mainly determined by the anthropogenic use of water.

- The Lower Aquifer is exploited in a sustainable way, because the amount of regenerating groundwater and extracted groundwater are in the same order of magnitude.
3.2 Subsystem Food; "to Nourish"

For the subsystem food, the food flux of the municipality of Tunja is shown. It focuses on the food supply structure, the retail structure, the nutrition pattern and its development, and the influence of these parameters on the waste composition in Tunja.

3.2.1 Mass Fluxes

3.2.1.1 Food Supply Structure of Tunja

The food supply structure of Tunja consists of Market Place, Supermarkets and Specialized Shops (Figure 3.4).

Figure 3.4: Food flux of the urban part of Tunja in kgTS/cap.year (packaging not included). For details see Annex B. Error margin: fresh products: 20-25%, manufactured products: 10%.
Subsystem Food; "to Nourish"

Fresh products enter the municipality via the Market Place and constitute about 62% of the total food input into Tunja. About 80% of the fresh products are produced in the Departamento de Boyacá, the remainder being imported from other Departamentos. About 50% of the total input of fresh products is consumed in Tunja. The other 50% is exported to other regions. Potatoes, the main agricultural product of the central part of Boyacá, constitute about 80% of the fresh products input into the Market Place.

The large percentage of exported products shows that the Market Place of Tunja not only supplies the "Tunjanos" with fresh products but also functions as an interregional market. This function is due to (i) the availability of storage room for potatoes, (ii) the short distance for local producers compared to Bogotá, which would be the next nearest wholesale market¹ and (iii) the location in the transport corridor Cucutá, Bucaramanga and Bogotá.

Manufactured products, which enter the municipality via Specialized Shops and Supermarkets, constitute about 38% of the input flux into Tunja. The manufactured products are mainly imported from Bogotá due to the limited food processing industry in Boyacá.

The main output of the system is off gas from Households into Atmosphere. The output-fluxes from Households to Landfill and Surface Water are about 20% of the total output-flux of Households. The organic part of household waste constitutes more than 90% of the organic waste input into Landfill, the proportion of the flux of Market Place to Landfill being less than 10%.

### 3.2.1.2 Retail Structure

Households buy their food in equal amounts at Market Place, Specialized Shops, and Supermarkets. There is a preference for buying a specific food type in a specific shop, e.g. fresh products in Market Place, cereals, meat and milk in Specialized Shops, other manufactured food such as sugars and oils in Supermarket (Figure 3.5).

¹see also Rodriguez, 1992
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Figure 3.5:
Food retail structure of the municipality of Tunja for different food types. Specialized Shops include corn houses, butcher and little shops. others: e.g oils, sugars, coffee.

The retail structure is similar for Households 2, 3 and 4 and different for Household 5. Households 2, 3 and 4 purchase their food in similar shops, while Household 5 has significantly different purchasing customs. Household 5 buys about 50% of its food in Supermarkets, while the other strata only buy around 35% of their food in Supermarkets. Similarly, people from Household 5 tend to buy less food in Specialized Shops (13% compared to 20%) and Market Place (35% compared to about 40%).

Table 3.5:
Purchase customs of the different social strata in Tunja (in percent).

<table>
<thead>
<tr>
<th></th>
<th>Household 2 (%)</th>
<th>Household 3 (%)</th>
<th>Household 4 (%)</th>
<th>Household 5 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market Place</td>
<td>43</td>
<td>41</td>
<td>43</td>
<td>35</td>
</tr>
<tr>
<td>Specialized Shops</td>
<td>21</td>
<td>22</td>
<td>17</td>
<td>13</td>
</tr>
<tr>
<td>Supermarket</td>
<td>33</td>
<td>35</td>
<td>38</td>
<td>49</td>
</tr>
<tr>
<td>No Response</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Households 2,3,4, which constitute 98% of the population, purchase from Market Place and Specialized Shops a pattern which is typical for intermediate cities in DC's (Drakakis-Smith, 1990). Drakakis-Smith also found that the consumption pattern is dependant on the socio-economic strata. Lower strata tend to buy their
food in Market Places and Specialized Shops, while higher strata prefer to buy their food in Supermarkets. This pattern is also observed in Tunja, though less pronounced. However, with growing population, larger differences among the social strata and an increase of the share of supermarkets can be expected. In large cities of DC's (>1 mio inhabitants) changes towards a central supply system (mainly Supermarkets) have been observed. In Hong Kong for example, the number of supermarkets in the urban area rose from 65 in the mid 1970s to 650 in the mid 1980s. During that time, supermarkets increased their share in the food retail market to 55 % (Drakakis-Smith, 1990).

3.2.1.3 Nutrition Pattern

The typical daily diet of a person in Tunja is a mixture of the Indian diet (i.e. maize, tubers, legumes and fruit) and the Spanish diet (i.e. wheat, rice, bananas, sugar, meat and coffee). It is based on products grown in Tunja and its neighboring regions and consists mostly of tubers and cereals which constitute each about 27% of the total food consumed. The protein sources are legumes at 12%, meat and milk at 10% of the total food consumed (Figure 3.6).

Figure 3.6: Typical diet of a person in Tunja (in percent of TS).
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A comparison of the diet in 1972\textsuperscript{2} and in 1993 shows that the nutritional habits of the population has not changed significantly (Figure 3.7). In 1972, the basis of the diet, cereals and tubers, was the same as in 1993, showing that the traditional nutritional customs were maintained. The increased food consumption is in agreement with the per day increase in calorie intake: per day calorie intake in Colombia has risen from 2175 kcal/cap.d in 1965 to 2542 kcal/cap.d in 1986 (World Bank, 1991).

Figure 3.7: Daily food consumption per capita in 1972 and 1993 in Tunja and 1993 in Switzerland.

Sources: ICBF, 1972
Martinez et al., 1994
Sekretariat des Schweizerischen Bauernverbandes, 1995

A comparison between the nutritional habits in Tunja (1993) and the Swiss nutritional habits (1993) shows that a larger amount of tubers and legumes is consumed in Tunja, while the Swiss consume more meat, milk and fruit (Figure 3.7). The total amount of dry matter consumed is about 580 gTS/cap.day in Tunja and 700 g/cap.day in Switzerland.

\textsuperscript{2}ICBF, 1972
3.2.1.4 Self-sufficiency

The strong orientation towards locally grown products in the diet of the inhabitants of Tunja raises the question of the level of self-sufficiency for basic food products. The comparison of the estimated agricultural production in rural Tunja and the current food consumption of urban Tunja shows that the municipality is able to satisfy its needs for tubers completely, for cereals to a degree of about 70% and for meat to about 30% (Table 3.6).

Table 3.6: Current demand and local production of food in Tunja.

<table>
<thead>
<tr>
<th></th>
<th>Current demand [10E^3 tTS/y]</th>
<th>Actual Production [10E^3 tTS/y]^a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereals</td>
<td>6,000</td>
<td>4,300</td>
</tr>
<tr>
<td>Tubers</td>
<td>6,500</td>
<td>9,200</td>
</tr>
<tr>
<td>Legumes</td>
<td>2,800</td>
<td>110</td>
</tr>
<tr>
<td>Meat</td>
<td>32</td>
<td>21^b</td>
</tr>
</tbody>
</table>

^a Productivity 1984-1987 (Rodriguez, 1992)
^b Only cattle and pig production (chicken and fish are imported), (DANE, 1991)

Sources: Rodriguez, 1992
DANE, 1991
3.2.2 Calibration and Validation

3.2.2.1 Validation of "food" flux

The "food" flux was validated by comparing:

(i) the amount of organic waste calculated using input data and the transfer coefficient from Household/Restaurants to Landfill with

(ii) the amount of organic matter measured in household waste

The input was measured as food consumption. The transfer coefficient was determined as the non-edible fraction of food according to Souci et. al. (1989).

The calculated amount of organic matter in waste at 118 kg/cap.y with an error of 24 kg/cap.y and the measured amount of organic matter in household waste at 94 kg/cap.y with an error of 9 kg/cap.y. are about equal within the error margins. Thus, the consumption data and transfer coefficients selected were validated.

3.2.2.2 Income and Purchase Customs

Income and purchase customs determine the amount of packaging in waste. This relationship is analyzed by comparing the purchase customs of the different socio-economic strata with the amount of packaging in waste. Household 5 has different purchase customs than the other socio-economic strata (Table 3.5). Consequently, Household 5 produced about 3 times more glass and tin waste than Households 2, 3 and 4 which have similar amounts of packaging in waste. Thus, income and purchase customs determine the amount of packaging in waste.
3.2.3 Conclusions

- A regional food system can be analyzed by measuring the food consumption at the supply processes. The system is validated by comparing the calculated amount of organic matter in waste with measurements on waste composition.
- Income and purchase pattern are closely linked to the amount of packaging found in waste and differ significantly among Household 5 and the other Households.
- The nutritional customs of the municipality are dominated by Household 2, 3 and 4, because they constitute about 98% of the population. They are based on regionally grown products.
- The retail structure is specific for the different food groups. Fresh products are mainly bought in Market Place, grains and meat in Specialized Shops and manufactured products in Supermarket.
3.3 Subsystem Durables; "to Reside"

For the subsystem durables, the flux of durables the municipality of Tunja is shown. The following aspects regarding durables in households will be discussed:

- The relationship among input and stock, output-transfer-coefficients and income.
- The role of reuse and recycling of durables in the flux of durables.
- The sensitivity of the model used to calculate the output of durables.

3.3.1 Differences Between the Social Strata

a) Input and Stock

The input and stock of durables increases with increasing income (Figure 3.9). Household 3 has double the input/stock of Household 2, Household 4 has three times the input/stock of Household 2 and Household 5 has five times the input/stock of Household 2. The largest differences between the Households were found for vehicles; the input/stock of Household 5 is ten times larger than the input/stock of Household 2.

![Figure 3.9: Input and stock in kg/cap.year and kg/cap. of Households in Tunja (1993)\(^1\) and a Swiss average household (1991)\(^2\). HH: household. Sources: 1: Survey 1993 2: Baccini et. al, 1993]
A comparison of the input/stock of Household 5 with the Swiss average Household shows that Household 5 has not yet reached the input and the stock per capita of the Swiss Households (Figure 3.9). The input and stock of furniture and electrical appliances in Household 5 are 1/2 the input and 1/3 the stock of Swiss Households. The smaller difference between the stocks of Household 5 and the stocks of Swiss Households is due to (i) the smaller degree of substitution of new durables by old durables in Household 5 than in Swiss Households, (ii) the larger residence time of durables in Household 5 than in Swiss Households and (iii) the household size which is 5 persons per household in Household 5 and 2.1 persons per household in Swiss Households. The household size influences only durables which are household and not person-related such as washing machines, ovens. In this case, a person in Tunja needs only half the amount of durables as a person in Switzerland.

b) Stock Growth

For furniture and electrical appliances, the yearly stock growth of about 4% is similar across the different socio-economic strata and about 4 times larger than the yearly stock growth in Switzerland (Table 3.7). Quantitatively, in Households 2 and 3, stock growth is mainly due to the growth of the furniture stock, in Households 4 and 5, stock growth of vehicles is dominant.

Table 3.7:

<table>
<thead>
<tr>
<th>Household Types</th>
<th>Stock in kg/cap and Change in Stock in kg/cap.y</th>
<th>Change in Stock in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household 2</td>
<td>65 + 3.4</td>
<td>17 + 0.8</td>
</tr>
<tr>
<td>Household 3</td>
<td>103 + 5</td>
<td>30 + 1</td>
</tr>
<tr>
<td>Household 4</td>
<td>133 + 3.2</td>
<td>40 + 1.8</td>
</tr>
<tr>
<td>Household 5</td>
<td>155 + 5</td>
<td>52 + 2.8</td>
</tr>
<tr>
<td>Swiss Household</td>
<td>241 + 2.8</td>
<td>144 +2.8</td>
</tr>
</tbody>
</table>

1: Stock growth was calculated as described in Chapter 2.3.5.3.
2: Data for the year 1991 (Baccini et. al., 1993). For comparability reasons, only the items which were surveyed in Tunja were taken into account.
c) Output transfer-coefficients of Households

The most important transfer-coefficient is the output transfer-coefficient from Households to Reuse which is largest for vehicles at 95%, followed by furniture at 90% and electrical appliances at 80%. Thus, only 5% of the total output is waste (Table 3.8). The share of durables which is given or sold to relatives and friends is about 90% of the output of furniture and electrical appliances and 60% of the output of vehicles, indicating that the reuse of durables takes place mainly within the same socio-economic strata. The amount of durables given away as charity increases with increasing income (see Annex C).

Vehicles are either reused or recycled. The high reuse rate at about 95% indicates that the vehicles are still useful, while some electrical appliances and furnitures are not. Additionally, the low transfer-coefficient to Landfill suggests that the possibility of recycling seems larger for parts of vehicles than for electrical appliances and furniture.

Table 3.8:
Output transfer-coefficients from Households to Reuse, Recycling and Landfill for the different groups of durables in Tunja (in percent).

<table>
<thead>
<tr>
<th></th>
<th>Reuse (%)</th>
<th>Recycling (%)</th>
<th>Waste (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furniture</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Household 2</td>
<td>92</td>
<td>8.4</td>
<td>0</td>
</tr>
<tr>
<td>Household 3</td>
<td>84</td>
<td>12</td>
<td>4.6</td>
</tr>
<tr>
<td>Household 4</td>
<td>92</td>
<td>5.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Household 5</td>
<td>90</td>
<td>4.5</td>
<td>5.2</td>
</tr>
<tr>
<td>Elec. Appl.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Household 2</td>
<td>56</td>
<td>32</td>
<td>12</td>
</tr>
<tr>
<td>Household 3</td>
<td>83</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Household 4</td>
<td>83</td>
<td>9.6</td>
<td>7.5</td>
</tr>
<tr>
<td>Household 5</td>
<td>90</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Vehicles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Household 2</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Household 3</td>
<td>88</td>
<td>8.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Household 4</td>
<td>98</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Household 5</td>
<td>97</td>
<td>5.6</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: Survey, 1993
3.3.2 Mass Fluxes

The total input into Households is composed of imported and reused durables\(^3\). Based on Table 3.8 it is assumed that in Household 2 only around 20% of the total input consists of new durables, while in Household 5 the total input is new.

![Diagram showing fluxes and stocks of durables in Households 2 to 5.](image-url)

Figure 3.10: Flux of durables in urban Tunja. fluxes: kg/cap.year, stocks: kg/cap.

The input fluxes to Households 3 and 4 constitute about 93% of the total input flux, which corresponds to their population share of 89%. The total stock in urban Tunja is dominated by the stocks of Households 3 and 4. The stocks of Households are more than one order of magnitude larger than the input into Households. Stock growth is about 75% of the input of Household 2 and about 50% of the input of Households 3, 4 and 5.

Reuse, which prolongs the lifetime of goods in a region, plays an important role in the whole flux of durables, because the flux of reused goods into Households is in the same order of magnitude as the input flux of new durables. The largest

\(^3\)see Chapter 2.3.5.3
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fluxes concerning reused goods are the fluxes from and to Households 3 and 4. Changes in the amount of reused goods consumed by these Households will have a large influence on the flux of goods being recycled and the flux to Landfill.

3.3.3 Calibration and Plausibility of the Model

For the subsystem durables, it is not appropriate to use the approach used to validate the subsystem food\(^4\). Due to the small transfer-coefficients to Landfill, the amount of durables that are disposed of as waste is only about 0.2 kg/cap.year which is less than 1% of the total amount of waste produced, i.e. 130 kg/cap.year. This means that durables cannot be measured in a household waste survey. Therefore, the approach taken to validate this system was to test the selected input-model for its plausibility and the output-model for its sensitivity with respect to errors of the parameters.

3.3.3.1 Parameter Estimation of the Input Model

The model chosen to calculate the input and output of durables in function of their lifetime \(\tau\) and the standard deviation of the lifetime \(\sigma\) was presented in Chapter 2.3.5.3. The data basis for this model is derived from the results of the household survey, 1993. The parameters \(\tau\) and \(\sigma\) were calibrated by calculating the input of the last 20 years for different values of \(\tau\) and \(\sigma\) and comparing it to the estimated input found in Latin American studies. Four sets of parameters were studied. The model cases are shown in Table 3.9.

Table 3.9: Values of \(\tau\) (lifetime) and \(\sigma\) (STDV of lifetime) used to calibrate the input-output model for electrical appliances in Tunja.

<table>
<thead>
<tr>
<th></th>
<th>(\tau)</th>
<th>(\sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Case 2</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Case 3</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>Case 4</td>
<td>18</td>
<td>12</td>
</tr>
</tbody>
</table>

\(\tau_0, \sigma_0\) (result from survey)

1\(\times \tau_0\) and 2\(\times \sigma_0\)

2\(\times \tau_0\) and 1\(\times \sigma_0\)

2\(\times \tau_0\) and 2\(\times \sigma_0\)

\(^4\)i.e. calculating the output by using the input and the transfer coefficients and validating these model assumption by measuring the output.
The development of the input of electrical appliances for Household 3 using the different cases is shown in Figure 3.11. Case 1 was discarded because it shows a threefold reduction in input from 1973 up to 1993 which was not considered to be plausible. In cases 2 to 4, input doubles from 1970 to 1975 and 1975 to 1980, the input of case 2 being double the one of cases 3 and 4. After 1985, in cases 3 and 4, the input remains constant, while in case 2, the input reduces slightly.

In Latin American studies, data of the consumption of durables in Brazil show that the percentage of households with an income similar to Households 2 and 3 owning one refrigerator, rose from 35% in 1967/68 to 57% in 1974, and the percentage owning at least one television from 21% in 1967/68 to 58% in 1974 (Filgueira, 1981). This means an input increase between 30% and 60% during 6 years, meaning an increase of around 10%/year. This input growth rate is in agreement with the input growth rates found for cases 3 and 4.

The evaluation of the same cases for the other strata and durables shows that case 4 is the most appropriate across all strata and types of durables. This lifetime is in agreement with the average lifetime of durables in developing countries found by Binswanger (1982), (see Annex C). Therefore, for further calculations, the lifetime $\tau$ was chosen as $2^*\tau_0$ and its standard-deviation $\sigma$ as $2^*\sigma_0$ leading to a maximum error of 50% for $\tau$ and $\sigma$ and of 20% for the input.
3.3.3.2 Sensitivity Analysis of the Output Flux

Sensitivity analysis is used to analyze the influence of changes in the parameters on the output-flux. The output-flux is the dependant variable and \( \tau \) (lifetime of the good), \( \sigma \) (STDV of the lifetime) and \( I_{ip} \) (Input at the time \( ip \)) are the parameters. In Table 3.10 the relative sensitivity of the output-flux is shown for a 20% change of \( \tau \), \( \sigma \) and \( I_{ip} \).

For nearly all socio-economic strata and durables a 20% change in a parameter causes less than a 20% change in the output-flux. The output-flux has the largest sensitivity to changes in the lifetime of the durables, \( \tau \), followed by \( \sigma \) and the inputs at the time \( t_0 < t \). The sensitivity of the output-flux is larger for Households 2 and 3 than for Households 4 and 5 and is largest for furniture.

Table 3.10:
Output change in percent if the parameters \( \tau \) (lifetime), \( \sigma \) (STDV of lifetime) and \( I_{ip} \) (input) are varied by 20%.

<table>
<thead>
<tr>
<th></th>
<th>( \tau )</th>
<th>( \sigma )</th>
<th>( I(-17.5)^1 )</th>
<th>( I(-12.5)^2 )</th>
<th>( I(-7.5)^3 )</th>
<th>( I(-2.5)^4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furniture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Household 2</td>
<td>29</td>
<td>20</td>
<td>4.6</td>
<td>5.2</td>
<td>5.8</td>
<td>4.4</td>
</tr>
<tr>
<td>Household 3</td>
<td>28</td>
<td>18</td>
<td>5</td>
<td>6.4</td>
<td>5.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Household 4</td>
<td>5</td>
<td>11</td>
<td>6</td>
<td>6.5</td>
<td>4.8</td>
<td>2.7</td>
</tr>
<tr>
<td>Household 5</td>
<td>8.6</td>
<td>6</td>
<td>4</td>
<td>6</td>
<td>5.7</td>
<td>4.4</td>
</tr>
<tr>
<td>Elec. appl.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Household 2</td>
<td>18</td>
<td>11</td>
<td>3.4</td>
<td>6.5</td>
<td>5.9</td>
<td>4.3</td>
</tr>
<tr>
<td>Household 3</td>
<td>18</td>
<td>12</td>
<td>3.8</td>
<td>6</td>
<td>6.2</td>
<td>4</td>
</tr>
<tr>
<td>Household 4</td>
<td>13</td>
<td>10</td>
<td>3.8</td>
<td>5.7</td>
<td>6.2</td>
<td>4.3</td>
</tr>
<tr>
<td>Household 5</td>
<td>23</td>
<td>17</td>
<td>4.3</td>
<td>5.9</td>
<td>6</td>
<td>3.9</td>
</tr>
<tr>
<td>Vehicles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Household 2</td>
<td>14</td>
<td>21</td>
<td>—</td>
<td>—</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>Household 3</td>
<td>8</td>
<td>10</td>
<td>—</td>
<td>6.3</td>
<td>8.4</td>
<td>5.3</td>
</tr>
<tr>
<td>Household 4</td>
<td>4</td>
<td>18</td>
<td>—</td>
<td>8.4</td>
<td>8.2</td>
<td>6.4</td>
</tr>
<tr>
<td>Household 5</td>
<td>12</td>
<td>23</td>
<td>—</td>
<td>5.3</td>
<td>9</td>
<td>7.7</td>
</tr>
</tbody>
</table>

1: Input at time \( t - 17.5 \) years; 2: Input at time \( t - 12.5 \) years; 3: Input at time \( t - 7.5 \) years; 4: Input at time \( t - 2.5 \) years.
3.3.3.3 Error Propagation

Error propagation analyzes the robustness\textsuperscript{5} of the model with respect to errors of the parameters. The error propagation was calculated for a 20% error of all parameters using the Gauss equation (see Chapter 2.2.3.3).

The model used to calculate the output-flux of durables is robust for errors of the parameters because the error of the total output flux of durables is smaller than 20%. For the different groups of durables the error is between 15% and 35%. The largest errors are found for Households 2 and 3 and the durable furniture.

Figure 3.12: Error of the output flux of the different groups of durables from Households for a 20% change of the parameters $\tau$ (lifetime), $\sigma$ (STDV of lifetime) and $l_p$ (input).

\textsuperscript{5}A model is robust if variations of the parameters do not change significantly the results calculated by the model.
3.3.4 Conclusions:

- The reuse of goods plays an important role in the whole flux of durables (40%) and takes place mainly among people from the middle income strata (strata 3 and 4).

- The consumption per capita and year and the stock per capita in Households differ significantly among the different socio-economic strata and increase with increasing income. The total input-flux into the region is determined by the middle income strata, which also have the largest population share.

- The output-flux of durables can be calculated using a dynamic model with three parameters, i.e. input, lifetime ($\tau$) and standard deviation of lifetime ($\sigma$).

- The most sensitive parameters of the model are $\tau$ and $\sigma$. The model is robust with respect to changes in these parameters, because an error of 20% leads to an error of less than 20% in the total output flux.
4. Using Material Flux Analysis for Early Recognition

In this Chapter the material balances which were elaborated in Chapter 3 are used (i) for setting up monitoring concepts, (ii) for the early recognition of the environmental impacts of different development scenarios and (iii) to evaluate the effect of technical measures to mitigate these impacts. Two topics will be analyzed: the regional water management and the management of materials in private households. In the latter, the subsystems "food" and "durables" are summarized to a subsystem "solids".

4.1 Regional Water Management

Three examples were chosen to illustrate the application of MFA for regional water management: (i) set up of monitoring concepts for surface water and groundwater, (ii) forecasting of the development of surface water quality and quantity and (iii) evaluation of the effect of different technical measures for improving surface water quality.

4.1.1 Mathematical Model

A mathematical model is used to address these topics. Figure 4.1 shows the system for the water model showing the variables as used for the mathematical modeling.
Chapter 4: Using Material Flux Analysis for Early Recognition

Figure 4.1: System for the mathematical model for the subsystem water.

The following gives a short overview of the variables, parameters and equations used to describe the model\(^1\).

**Variables**

\[ M^{(1)}, \ldots, M^{(5)} \]  
5 stock change of balance volume (landfill excluded)

\( I_1, I_2a, I_2b, I_3a, I_3b, I_5 \)  
6 input fluxes

\( A_j \)  
10 internal fluxes

\( O_{2a}, O_{2b}, O_{2c}, O_3, O_4, O_5 \)  
6 output fluxes

**Parameters**

\( P_1, \ldots, P_6 \)  
6 input fluxes

\( P_7, \ldots, P_{18} \)  
18 transfer coefficients

\( P_{19} \)  
second output transfer coefficient for evapotranspiration

\(^1\) A complete set of equations is given in Annex A.
Model specific equations (Model assumption)

A modified input-output model is used to characterize the system. In the following only the equations which do not correspond to an input-output model are shown.

a) **Stock change** for all processes except *Groundwater/Lower Aquifer* are all 0.
   \[ M^{(1)} = M^{(1)} = M^{(3)} = M^{(5)} = 0 \]  
   (4.1)

b) Definition of the infiltration rate \( A_{24} \) and the evapotranspiration \( O_3 \)
   \[ A_{24} = ((1 - k_{O_3}) \cdot I_2) \cdot 0.23 \]
   \[ O_3 = I_2 \cdot k_{O_3} + A_{52} \cdot 0.9 \]  
   (4.2)

### 4.1.2 Evaluating Monitoring Concepts

#### 4.1.2.1 Monitoring of Groundwater/Lower Aquifer

The monitoring concept for *Groundwater/Lower Aquifer* was developed by analyzing the sensitivity of the groundwater level to a 100% increase in the extraction rate of groundwater. A 100% increase of the current extraction rate in the aquifer in the Formacion Bogota (Figure 2.6) will lead to a lowering of the groundwater level of around 40 cm, assuming a homogeneous reduction through the whole aquifer (Table 4.1). Thus, monitoring the groundwater level allows the determination of overexploitation of this aquifer.

A 100% increase in the current extraction rate from the aquifer of the Formacion Cacho will lead to a lowering of the groundwater level of about 5 cm. This lowering could be in the same order of magnitude as fluctuations in the groundwater level due to dry and wet seasons. Therefore, changes in the groundwater level can only be detected if the seasonal fluctuations are known.

Table 4.1:
Sensitivity of the groundwater stock and groundwater levels of the aquifers to a 100% increase in the extraction rate in Tunja.

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>Extraction rate (mio m³/y)</th>
<th>Stock reduction (mio m³/y)</th>
<th>Stock reduction (%)</th>
<th>Reduction of groundwater level (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formación Bogotá</td>
<td>2.4</td>
<td>1.2</td>
<td>1%</td>
<td>40</td>
</tr>
<tr>
<td>Formación Cacho</td>
<td>1.2</td>
<td>0.6</td>
<td>0.12%</td>
<td>5</td>
</tr>
</tbody>
</table>
4.1.2.2 Monitoring of Surface Water

Error propagation and sensitivity analysis were used to develop a monitoring concept for the quality of surface water (see Chapter 2.2.3.3).

Propagation of random errors.

Error propagation was analyzed for parameters which have large errors. The following parameters with their maximum random error were chosen:

- transfer coefficient Water-Supply - Soil/Upper Aquifer determining the flux supply losses with a maximum random error of 50%,
- transfer coefficient Household - Soil/Upper Aquifer determining the flux sewage losses with a maximum random error of 100% and
- transfer coefficient Soil/Upper Aquifer - Surface Water determining the flux runoff with a maximum random error of 50%.

Random error of the transfer coefficient Water-Supply - Soil/Upper Aquifer: A random error in the transfer coefficient Water-Supply - Soil/Upper Aquifer leads to errors in the fluxes, supply losses, drinking water, sewage, sewage losses, groundwater output, irrigation, surface water output, fountain water and runoff (Figure 4.2a). A comparison of the induced errors (Figure 4.2a) with the measurement errors (Figure 4.2b) shows that the induced errors are smaller than the measurement errors of the affected fluxes, except for drinking water and sewage. Thus, estimates of the transfer coefficient defining the flux supply losses can be verified by measurements of the fluxes drinking water or sewage.
Regional Water Management

Figure 4.2:
Induced errors of the variables due to a random error of the transfer coefficient Water-Supply to Soil/Upper Aquifer and measurement errors of the variables of water balance. X-axis: Value in mio m³/catchment area.year, Y-axis: Probability.

Random error of the transfer coefficient Household - Soil/Upper Aquifer: A random error in the transfer coefficient Household - Soil/Upper Aquifer leads to errors in the fluxes, sewage losses, sewage, groundwater output2, irrigation, surface water output, fountain water and run off (Figure 4.3a). A comparison of the induced errors (Figure 4.3a) with the measurement errors (Figure
4.3b) shows that the induced errors are smaller than the measurement errors of the affected fluxes, except for sewage. Thus, estimates of the transfer coefficient defining the flux sewage losses, can only be verified by measurements of the flux sewage.

![Diagram of induced and measurement errors for different variables](image)

Figure 4.3:
Induced errors of the variables due to a random error of the transfer coefficient Household to Soil/Upper Aquifer and measurement errors of the variables of water balance. X-axis: Value in mio m\(^3\)/catchment area/year, Y-axis: Probability.

**Random error of the transfer coefficient Soil/Upper Aquifer - Surface Water.** A random error of the transfer coefficient Soil/Upper Aquifer - Surface Water, has an effect on the fluxes fountain water, run off, irrigation and surface water output, evaporation and groundwater output. A comparison of the induced errors with the measurement errors shows that the induced errors are solely larger than the measurement errors of the affected fluxes for irrigation and for surface water export. Thus, estimates of the transfer coefficient defining the flux supply...
losses can be verified by measurements of the fluxes irrigation or surface water output.

**Sensitivity Analysis**

**Water.** The relative sensitivity of the flux surface water output was analyzed using a 10% change in the parameters. The results of the sensitivity analysis are shown for the parameters which have an effect that is larger than 1% of the flux of surface water output (Figure 4.4).

![Absolute change of the flux surface water output (variable) for a 10% change and for the error of the system parameters (Unit: mio m$^3$/year).](image)

The largest sensitivities are found for precipitation and run off (geogenic processes). Changes of 10% in these parameters affect the flux surface water output by about 1 mio m$^3$/year (7%). The second largest sensitivities are found for the parameters related to the consumption of water (anthropogenic processes). Changes of 10% in drinking water1, drinking water2 and sewage affect the flux surface water output by 3%.
Chapter 4: Using Material Flux Analysis for Early Recognition

The measurement error of the flux surface water output is about 30% or 4.2 mio m³/year. The effect of changes in drinking water on the flux surface water output cannot be determined by monitoring the flux surface water output because: a 10% change in drinking water leads to a 3% change in the flux surface water output, which has a measurement error of 30%. Thus, changes of up to nearly 100% in drinking water are still in the margin of the measurement error of this flux and can therefore not be detected by monitoring this flux.

**Phosphorous and Carbon.** The results of the sensitivity analysis for phosphorous and carbon for a 10% change in the parameters are depicted in Figure 4.5 a, b. In contrast to water, the P and C fluxes of surface water output are influenced mainly by the anthropogenic activities "to nourish" and "to clean". In the case of P, the largest sensitivities are found for food input at about 4t/year and detergent input at about 2t/year. The second largest sensitivities are found for the transfer coefficients determining sewage losses and irrigation. A 10% increase of these transfer coefficients would lead to a decrease of the P-flux of surface water of about 2t/year. A similar pattern is also shown for C.

![Graphs showing absolute change for P and C-flux of variable surface water output for a 10% change in system parameters.](image)

**Figure 4.5:** Absolute change for the P and C-flux of the variable surface water output for a 10% change in the system parameters. Unit: t/year.
The measurement errors of the P and C-fluxes of surface water are at about 30 t/year for P and at about 360 t/year for C. A comparison of these errors with the results of the sensitivity analysis shows that even if there is a 100% change in food or detergent consumption, this change cannot be observed by monitoring the P and C-fluxes at surface water output.

In urban regions of developing countries, the largest changes regarding water, phosphorous and carbon fluxes are expected to occur in the anthroposphere, i.e. increased water demand per capita, population growth, increased consumption of detergents per capita. Therefore, to recognize changes in the quality and quantity of surface water, monitoring has to focus on the input fluxes and the changes in transfer coefficients. Latter could be due to infrastructure changes within the region. For example: an improved sewerage system will lead to a decrease in sewage losses.

Thus, the following monitoring concept is recommended for the early recognition of water pollution and overexploitation of the aquifer:

- Monitoring of the inputs: water, detergents, food and precipitation
- Monitoring of changes in infrastructure of the municipality, i.e. improvement of water supply system and decrease in sewage losses
- Monitoring of the water levels of the aquifers.
4.1.3 Evaluating Measures to Achieve and Preserve Regional Water Quality

Scenarios are used to forecast the development of surface water by the year 2020 and to analyze and the effects of technical measures to improve the surface water quality. The following questions will be addressed:
1. What will be the quality of surface water in Tunja by the year 2020?
2. How can different sewage treatment techniques influence this quality?

4.1.3.1 Assumptions

The following assumptions are made
(i) economic growth will take place mainly in the tertiary sector (education and tourism)
(ii) population growth of 2.7% per year will continue, leading to a doubling of the population by the year 2020
(iii) per capita consumption of food and detergents will stay constant
(iv) losses in the supply of drinking water will be reduced from 40% to 20% and
(v) the aquifer will not be overexploited.

4.1.3.2 Scenarios

The effect of the installation of three different types of sewage treatment techniques, changes in water consumption per capita and sewage losses were analyzed using carbon as an indicator element. The different types of sewage treatment chosen were septic tank, upflow anaerobic sludge blanket reactor (UASBR) and an activated sludge plant. For water consumption and sewage losses, plausible minimum and maximum values were selected. Table 4.2 shows the analyzed scenarios.

Table 4.2: Scenarios to analyze the development of the surface water quality in the year 2020 in Tunja.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Water consum. min/max (l/inh.day)</th>
<th>Sewage losses min/max (%)</th>
<th>Sewage treatment</th>
<th>Carbon elimination (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>80/160</td>
<td>0/20</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>80/160</td>
<td>0/20</td>
<td>septic tank</td>
<td>30</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>80/160</td>
<td>0/20</td>
<td>UASBR</td>
<td>65-70</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>80/160</td>
<td>0/20</td>
<td>activated sludge plant</td>
<td>90</td>
</tr>
</tbody>
</table>

1: UASBR: Upflow anaerobic sludge blanket reactor
2: Diaz, 1995
3: Metcalf & Eddy, 1991
In scenario 1, assuming maximum water consumption and maximum sewage losses, and if no sewage treatment facilities are installed the C concentration in surface water will increase from 85 mgC/l in 1993 to 120 mgC/l in 2020. For minimum water consumption and no sewage losses, it will further increase to 180 mgC/l (Figure 4.6).

In scenario 2, assuming maximum water consumption and maximum sewage losses, the installation of septic tanks will decrease the C concentration in the surface water to 94 mgC/l. Thus, the C concentration will be reduced in comparison to scenario 1, however, it will still be in the same order of magnitude than in 1993. If minimum water consumption and no sewage losses are assumed, the concentration of carbon will increase to 130 mg/l.

In scenario 3, assuming maximum water consumption and maximum sewage losses, the installation of an anaerobic sludge reactor will decrease the C concentration in the surface water to 43 mgC/l, which is about 50% of the C concentration in 1993. Assuming minimum water consumption and no sewage losses, the C concentration will increase to about 60mgC/l which is still about 20% less that in 1993.

In scenario 4, assuming maximum water consumption and maximum sewage losses, the installation of an aerobic activated sludge plant, the concentration of carbon in the surface water decreases to 20 mgC/l which is nearly one order of magnitude lower that in 1993. However, it still will be one order of magnitude higher than the geogenic value of 1 mg/l.
magnitude larger than the geogenic value. Assuming minimum water consumption and no sewage losses, the C concentration will increase only to about 26 mgC/l, which is still in the same range as the concentration assuming maximum water consumption and maximum sewage losses.

Due to the limited regional water resources and assuming a doubling of the population into the year 2020, a reduction of water consumption per capita seems unavoidable. The reduced water consumption per capita will increase the C concentration in surface water. The effects on surface water quality will be worst if no sewage treatment facilities are installed. An increasing effectivity of the sewage treatment will mitigate the negative impact of the reduced water consumption per capita.

4.14 Conclusions

- MFA and its mathematical formulation can be applied as an instrument to develop monitoring concepts and evaluate technical measures.
- In Tunja, monitoring has to focus on the consumption of water, food and detergents in order to detect changes in quality and quantity of surface water.
- The reduction of water consumption will lead to an increase of carbon concentration in surface water. This effect is reduced with improved sewage treatment.
4.2 Management of Materials in Private Households

Two examples were chosen to illustrate the application of MFA for material management in private households; (i) the set up and evaluation of monitoring concepts and (ii) the evaluation of management concepts for solid waste management. The following questions will be addressed:

- If income per capita increases according to GNP growth, how will the consumption of solids and consequently the quantity and quality of waste change until the year 2010?
- How is a monitoring concept to be set up to recognize changes in waste composition?
- Which measures are necessary in order to minimize the flux of solids into landfill?

4.2.1 Fluxes of Solids

The total flux of solids, including short- and long-lived solids, is depicted in Figure 4.7. For foods and durables the results presented in Chapter 3 were used. For packaging\(^2\); it was assumed that about 30% of the packaging material is recycled (Gonzales & Cadena, 1992, Forrero & Sanchez, 1994). Packaging includes paper, tin, glass and plastic.

\(^2\)Only the packaging material related to food consumption is taken into account. According to Baccini et al, 1993, it constitutes about 90% of the total packaging materials.
The flux of solids is determined by the food flux. Food constitutes the largest input flux, accounting for 94% of the total input of solids with packaging at about 5% and durables at only 1%.

The largest output is the off gas into Atmosphere. The output flux from Households to Landfill is composed of 80% organic matter consisting of food scraps, about 20% of packaging and less than 1% of durables. The output flux from Households to Recycling is basically composed of packaging.

The stock of durables in households is ten times larger than the yearly input and is increasing at about 5% per year. Reuse plays a significant role in the flux of durables, because the amount of reused durables is similar to the import of durables.
4.2.2 Mathematical Model

Figure 4.8 shows the system for the model for solids showing the variables chosen for the mathematical model.

The following shows the system variables and parameters and gives a short overview of the equations used to describe the model.

**Variables**

- $\dot{M}^{(1)}, \ldots, \dot{M}^{(7)}$: 7 stock change of balance volume
- $I_1, \ldots, I_3$: 3 input fluxes
- $A_{jn}$: 7 internal fluxes
- $O_3, O_4, O_5, O_7$: 4 output fluxes
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Parameters

- $P_1, P_2$: 2 input fluxes into processes 2 and 3
- $P_3$: 1 total input flux $I_{tot}^{(1)}$ into process 1
- $P_4, \ldots, P_{10}$: 7 internal transfer coefficients
- $P_{11}, \ldots, P_{14}$: 4 output transfer coefficients

Model specific equations (Model assumptions)

A modified input-output model is used to characterize the system. In the following only the equations which do not correspond to a typical input-output model are shown.

a) **Stock change** for processes Food Consumption, Packaging Consumption, Reuse/Recycling and Surface Water is 0.

$$\dot{M}^{(2)} = \dot{M}^{(3)} = \dot{M}^{(4)} = \dot{M}^{(7)} = 0 \quad (4.3)$$

b) The total **input** into Durables Consumption $I_{tot}^{(9)}$ is defined as the sum of the input flux of durables into the system ($I_1$) and the flux $A_{41}$ from Reuse/Recycling to Durables Consumption (see also 2.3.5.2).

$$I_{tot}^{(9)} = I_1 + A_{41} \quad (4.4)$$
4.2.3 Evaluating Monitoring Concepts

To set up a monitoring concept for solid waste management, three aspects have to be taken into account, (i) the sensitivity of the fluxes of solids to increasing income, (ii) the effect of changes of these fluxes on waste composition and (iii) the key parameters for managing solid waste.

4.2.3.1 Changes in Fluxes of Solids as a Result of Increasing Income

The fluxes which are sensitive to increasing income are determined by comparing the current fluxes in Tunja with fluxes of a region with higher income. Here, the fluxes of solids of Tunja are compared to the fluxes of solids in St. Gallen\(^4\) (Figure 4.9).

The main differences on the input side between St. Gallen and Tunja are found for durables and for packaging materials\(^5\); (i) the consumption of durables in St. Gallen is 10 times larger than in Tunja, (ii) the stock of durables in households in St. Gallen is about 10 times larger than in Tunja and (iii) the amount of packaging consumed in St. Gallen is twice as large as in Tunja.

The main differences on the output side between St. Gallen and Tunja are found for the transfer coefficients Household to Recycling and Household to Landfill/Incineration. These transfer coefficients determine the amount of recycled deposited or incinerated solids, i.e. while 65% of the solid output is recycled in St. Gallen, it is only 12% in Tunja. This means that only 35% of the total solid output in St. Gallen must be incinerated, while in Tunja almost the whole solid output (88%) must be deposited. This higher rate of recycling in St. Gallen requires an appropriate recycling infrastructure and education of the population.

Thus, it is postulated that, with increasing income in Tunja, the input of durables and packaging will increase. The development of new infrastructure, for example recycling, will determine the value of the transfer coefficients to Recycling and Landfill and consequently the amount of solid waste deposited in Landfill.

\(^4\)St. Gallen, Switzerland, is a city with similar characteristics as Tunja with regard to socio-economic structure (predominantly middle income class) and population.

\(^5\)Only the packaging material related to food consumption is taken into account. According to Baccini et al, 1993, they constitute about 90% of the total packaging materials.
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Figure 4.9:
Comparison of the fluxes of solids in Tunja and in St. Gallen.
4.2.3.2 Sensitivity Analysis

The sensitivity analysis for the variable Landfill stock shows which parameters influence the current composition of the Landfill stock. The parameters with the largest influence on the composition of Landfill stock are: food input, transfer coefficient Food Consumption to Landfill, packaging input and transfer coefficient Packaging Consumption to Landfill. The influence of the food related parameters is equal and about 5 times larger than the influence of the packaging related parameters (Table 4.4). Changes in the input flux of durables have a very small influence on the total waste amount; the influence is about 100 times smaller than the effect of the input flux of food. Thus, currently, according to the sensitivity analysis, changes in the amount of food consumption have the largest influence on the total flux into Landfill.

Table 4.4
Absolute change of Landfill stock (kg/cap.year) with respect to a 10% change in the parameters for Tunja.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effect of 10% change in parameter (kg/cap.year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food input</td>
<td>9.4</td>
</tr>
<tr>
<td>Transfer coefficient Food Consumption to Landfill</td>
<td>9.4</td>
</tr>
<tr>
<td>Packaging input</td>
<td>2.1</td>
</tr>
<tr>
<td>Transfer coefficient Packaging Consumption to Landfill</td>
<td>2.1</td>
</tr>
<tr>
<td>Durables</td>
<td>0.01</td>
</tr>
</tbody>
</table>

4.2.3.3 Monitoring the Current Composition of Waste

The monitoring concept of the current waste composition is developed by comparing:
(i) the propagation of measurement errors on the input side, e.g. food input, with
(ii) the measurement errors on the output side, e.g. composition of household waste in Landfill.
This comparison shows that for monitoring the organic content in waste, measurements of the composition of household waste are appropriate. The reason is that the measurement error of organic waste at 10% is smaller than the propagation error calculating organic waste using food consumption data at 20% (Table 4.5).

Table 4.5
Propagation errors of input measurements and measurement errors of household waste composition for Tunja.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Error in input measurement (%)</th>
<th>Error propagation</th>
<th>Measurement error of household waste at Landfill (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food¹</td>
<td>20 %</td>
<td>18.8</td>
<td>10 %</td>
</tr>
<tr>
<td>Packaging</td>
<td>20 %²</td>
<td>4.2</td>
<td>20 %²</td>
</tr>
<tr>
<td>Durables</td>
<td>20 %⁴</td>
<td>0.02</td>
<td>18 %</td>
</tr>
</tbody>
</table>

1: food input leads to organic matter in waste
2: was not determined in this study, assumption about 20%
3: including the error of non quantifiable recycling of materials
4: including errors in input, lifetime and STDV of lifetime (all errors are 20%)
5: it was not possible to measure any output of durables into Landfill.

To determine the current amount of packaging in waste, one can measure either the household waste composition or the products consumed in the Supermarkets. The measurement of the amount of packaging material in household waste was quite accurate, with an error of 10%. However, this measurement did not give any information on the amount of recycled packaging materials, making the error range for the total flux 10-30%. The error of determining the amount of packaging in Supermarkets is equal to the error of food input into Supermarkets at about 20%. Thus, both errors are about equal and monitoring of packaging can be made either by measuring household waste or by measuring food consumption at Supermarkets.

The current amount of durables in waste can only be determined accurately by measuring the input and modeling the output of durables using the parameters input, lifetime and STDV of lifetime. The input of durables was quantified in a household survey. The errors of the input, lifetime and STDV of lifetime were around 20% (see Chapter 3.3). The propagation of these errors causes an error of the total output flux to landfill of only 18%. The error of measurements of durables in waste is about 100%.
4.2.3.4 Monitoring the Future Composition of Waste

According to Figures 4.9a) and 4.9b), the largest changes in input which affect the composition of solid waste are the inputs of durables and packaging. Monitoring the future amount of durables in waste has to concentrate on monitoring the current consumption and composition of the durables and on estimating lifetime and the transfer coefficient to Reuse.

Monitoring the total consumption of packaging materials has to concentrate on monitoring the packaged products sold in Supermarkets. In addition, spot measurements of the amount of packaging materials in household waste allow the determination of the current and the potential amount of packaging that can be recycled.

Measures taken to enhance recycling will change the transfer coefficients between the consumption processes and landfill, thus, changing the composition of the deposited waste. To evaluate the potential and effect of such measures it is necessary to monitor (i) the current and potential input of durables and packaging and (ii) the amount of already recycled materials. The latter can be determined by monitoring recyclable products at household waste or by measuring the amount of recycled products which are used as raw materials by the recycling company. In combination with the knowledge of the potential amount of recyclable solids in the municipality, a recycling program can be developed which takes into account the development and changes of consumption.

Thus, the following monitoring concept is recommended for the early recognition of waste composition and evaluation of recycling potential:

- Monitoring the products sold in Supermarkets and their packaging.
- Monitoring the consumption and composition of durables.
- Monitoring the amount of recycled solids either at recycling companies or as a fraction of solid waste.
4.2.4 Evaluating Concepts for Solid Waste Management

Concepts for solid waste management into the year 2010 are evaluated by (i) quantifying the potential effect of increasing income per capita on the material fluxes and (ii) quantifying the effect of measures on the quantity and composition of solid waste.

4.2.4.1 Assumptions

4.2.4.1.1 Population Growth in Tunja

It is assumed that population will continue growing at a rate of 2.7% per year leading to about 170,000 inhabitants by the year 2010.

4.2.4.1.2 Development of Income per Capita

The increase of income per capita expected by the year 2010 is estimated according to the 2.4% GNP growth per capita in Colombia during the years 1985 to 1994 (World Bank, 1996). This growth rate will lead to an income increase of about 50% from 1993 to 2010. Thus, stratum 2 will have an income slightly higher than the present stratum 3 and stratum 3 an income slightly higher than the present stratum 4. The income of stratum 4 will remain lower than the income of the present stratum 5.

Table 4.6:
Changes in income of the different socio-economic strata for a GNP growth rate of 2.4%/year in Tunja.

<table>
<thead>
<tr>
<th>Socio-economic strata</th>
<th>1993(^1) US$/cap.year</th>
<th>2010 GNP growth rate 2.4%/year; US$/cap.y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratum 2</td>
<td>310</td>
<td>450</td>
</tr>
<tr>
<td>Stratum 3</td>
<td>380</td>
<td>560</td>
</tr>
<tr>
<td>Stratum 4</td>
<td>490</td>
<td>720</td>
</tr>
<tr>
<td>Stratum 5</td>
<td>800</td>
<td>1,190</td>
</tr>
</tbody>
</table>

\(^1\) Source: Survey, 1993

4.2.4.1.3 Food

Based on Figures 4.9a) and 4.9b), it is assumed that the food consumption in kg/cap.year, and thus the per capita amount of organic matter in waste will remain constant into the year 2010.
4.2.4.1.4 Packaging

The amount of packaging in waste relates to the amount of food bought in Supermarkets which in turn depends on the socio-economic strata (Figure 3.8). For Tunja, a significant difference of the amount of packaging in waste was only found between Households 2, 3, 4 on the one hand and Household 5 on the other hand. Thus, no reliable model could be developed which links income to the amount of packaging in waste. Studies of waste development in Switzerland showed that the total amount of waste increased during the last 30 years at the same rate as GNP growth and has now reached a saturation level. Based on this, it is assumed, for Tunja, that the amount of packaging in waste will increase by about 2.4%/year leading to a 50% increase by the year 2010. The error margin of this estimation is 30%.

4.2.4.1.5 Durables

The results in Chapter 3.3 indicate that the consumption and the stock of durables per capita increases with increasing income. Four modelling approaches were used to analyze the relationship between income and consumption/stock of durables. The four selected approaches are (i) a linear model which analyzes the relationship between income and stock, (ii) a logistic growth model which analyzes the relationship between income and consumption, (iii) a polynomial model which analyzes the relationship between income and stock, and (iv) a discrete choice model which was only applied for vehicles. The results of the estimations for the different models are shown in Annex C.

All models show that income has a significant influence on consumption/stock of durables. However, the explanatory power is relatively low. This could be due to the following: (i) The sample was chosen in order to characterize the metabolism of the region. Thus, the larger part of the sample corresponds to the middle income social strata. Even though, for stratum 5, the sample size taken corresponded to a higher share than its population share, it seems that the variability within households in stratum 5 is very high. Thus, the selected sample does not include enough observations to characterize the relationship between income and consumption/stock of higher-income households. (ii) Weight of durables and their composition are indispensable in characterizing the metabolism of the region. However, these indicators might not be adequate to measure the relationship between income and consumption/stock. For example, it could be the case that as income increases, households buy more furniture but the weight of the furniture they buy is lower. This could alter the relationship between income and consumption/stock because households with low and high income might have the same weight of stock. (iii) Variables such as prices of durables were not included in the survey. These variables are important determinants of the demand for durables.
Chapter 4: Using Material Flux Analysis for Early Recognition

The logistic growth model was chosen for developing the scenarios for the following reasons: (i) according to Deaton and Muellbauer (1980), it is appropriate for modeling the relationship between income and consumption; (ii) it assumes saturation of consumption and stock with increasing income. The linear model is quite accurate for modeling income-stock relationships of low income households, because in Tunja those households still are in the linear growth phase. However, a linear model does not model saturation of the stock growth which has to be expected for higher-income households; (iii) the polynomial model mimics saturation of stock growth up to a certain income level, where the model shows nearly exponential growth. The saturation level is lower than the one obtained with the logistic growth model. So, in order to estimate a maximum scenario, the logistic growth model was preferred over the polynomial model.

For the development of the scenarios, four different approaches were evaluated. They used the two sets of parameters estimated for the logistic growth model and additionally each of them analyzed the effect of different GNP/capita growth rates at 1.6%/year and 2.4%/year. The average of the four model approaches had a STDV of 13% to 20% and was used to estimate the fluxes of durables by the year 2010.

Growth of Input, Stock and Output. The growth of input, stock and output is linear for Households 2, 3, 4 and 5 (Figures 4.10a, b, c). Input growth is about 9 kg/cap.year for all Households.

The stock growth is between 100 to 125 kg/cap.year for Households 2, 3, and 4 and more than 200 kg/cap for Household 5. In the year 2010, the stock change will be about 2.5%/year for Household 2, 2.3%/year for Household 3 and about 1.3%/year for Households 4 and 5. Until then, no saturation of input or stock growth will have occurred.

The output of Households 2, 3 and 4 increases about 5 kg/cap during the 15 years. For Household 5, the increase of the output will be 15 kg/cap which is about 3 times larger than for Households 2, 3 and 4.

---

6 see Annex C

7 According to the GNP growth rate from 1980 to 1990
Management of Materials in Private Households

Figure 4.10:
Growth of input, stock and output of durables for the different socio-economic strata from 1995 to 2010 in Tunja.
4.2.4.2 Scenarios of Waste Composition

Based on the above quantifications, two scenarios until the year 2010 are discussed. In these scenarios, the transfer coefficients Consumption of Durables to Reuse and Packaging Consumption to Recycling are varied. The transfer coefficient Food Consumption to Landfill and the household solid waste fraction "others" are kept constant. In scenario 1, it is assumed that 70% of the packaging is recycled and that 95%, i.e. the rate of 1993, of the durables are reused. In scenario 2, only 30%, i.e. the rate of 1993, of the packaging is recycled and 10% of the durables are reused (Table 4.7).

In scenario 1, the flux of waste to Landfill in 2010 falls by around 10% compared to the flux of waste to Landfill in 1993, the base year. This means, that if the current reuse rate of durables of 95% stays constant, an increased recycling of packaging from 30% to 70% will lead to a reduction of 10% of the flux of waste from Households to Landfill. In this case, organic matter constitutes about 80%, packaging about 12% and durables less than 1% of the waste in Landfill.

In scenario 2, the flux of waste to Landfill in 2010 increases about 20% compared with the flux of waste to Landfill in 1993. In this case, organic matter constitutes about 60%, packaging about 22% and durables about 10% of the waste in Landfill. The amount of durables in waste is nearly 100 times larger than in scenario 1.

Table 4.7: Scenarios for waste composition assuming maximum and minimum reuse and recycling rates (Assumption: the amount of "other" in waste is constant at 14 kg/cap.year).

<table>
<thead>
<tr>
<th></th>
<th>Durables waste kg/cap.y (%)</th>
<th>Pack. waste kg/cap.y (%)</th>
<th>Organic waste kg/cap.y (%)</th>
<th>Other kg/cap.y (%)</th>
<th>Total kg/cap.y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>0.2 (&lt;1%)</td>
<td>26 (19%)</td>
<td>95 (70%)</td>
<td>14 (10%)</td>
<td>135</td>
</tr>
<tr>
<td>2020, scenario 1</td>
<td>0.4 (&lt;1%)</td>
<td>17 (13%)</td>
<td>95 (76%)</td>
<td>14 (11%)</td>
<td>127</td>
</tr>
<tr>
<td>2020, scenario 2</td>
<td>15 (9%)</td>
<td>39 (24%)</td>
<td>95 (58%)</td>
<td>14 (9%)</td>
<td>163</td>
</tr>
</tbody>
</table>

Scenarios 1 and 2 show that, even with increased growth in consumption of durables and packaging, the main part of solid waste will be organic matter. Thus, if the municipality wants to minimize the total amount of waste produced, it has to focus on recycling or treating the organic part of waste for the next 15 years, e.g. by separate collection and correspondent composting.

If the reuse rate of durables decreases and the recycling of packaging materials stays constant, as suggested in scenario 2, the amount of durables and packaging in the waste in 2010 will significantly increase in comparison to 1993.
Assuming that 30% of the durables consist of metals, the metals flux caused by depositing durables in the landfill would be about 770t/year in 2010 (assuming constant population growth). Packaging material will cause a metal flux due to the depositing of tin of about 80 t/year by 2010. Thus, if a recycling program for metals is to be established, it should focus on the recycling of durables.

4.2.4 Conclusions

- Monitoring of future waste composition has to focus on the consumption and composition of durables and the food supply pattern. Additionally, the amount of recycled goods has to be monitored at the recycling companies, in order to determine the current amount of recycled goods and the potential for recycling within the municipality or broader region.

- The organic part of waste will remain dominant for the next 15 years. Thus, if the municipality wants to decrease the flux of household waste to Landfill, it has to put priority on the reduction of the organic part (e.g. by separate collection and correspondent composting).

- Material management has to focus on the management of durables (e.g. metals).
5 Experiences with Capacity Building

In the context of this thesis, capacity building is the development of local research capacity. Capacity building is one of the major aims of the Program "Environment and Development" of the Swiss National Science Foundation. It is a very difficult subject within the discussions of development strategies and few academic tools exist to measure the level of capacity building achieved. In choosing a university in a developing country as the partner institution, capacity building was implicitly included in this thesis.

A university was selected as the research partner institution because (i) it offers more continuity to a project than a government institution where the staff have a limited residence time of 2 to 3 years (ii) it provides the infrastructure and research capacity to support the continuation or development of similar projects and (iii) it offers the opportunity to influence the education of future professionals. A local university was chosen over a larger, more prestigious institution in a major city because the research methods should be developed utilizing the local capacity and infrastructure.

The research partner institution should contribute manpower (professors and students) to the project in exchange for an introduction to the methodology of MFA as well as support in the development of research projects. The approach taken for capacity building is divided into the following 6 phases:

Phase 1: Selection of the Subsystems and Draft of the Topics of the Theses (6 months)

This phase included a first screen of the region followed by the selection of the subsystems and definition of the various topics for the diploma theses. These topics were discussed with local professors.

Observation: In general the professors agreed with the proposed topics and were very supportive by collecting and sending data in order to develop the first draft of the topics of the theses. However, their specific feedback on the project's development and research questions was limited.

Phase 2: Introduction of MFA and Planning of the Field Measurements (3 months)

In this phase, MFA was introduced to local professors and students in an informal seminar. The initial draft of the system analyses for the different subsystems was jointly developed and the first measurement points were identified. Based on these system analyses the students created a framework for their theses topics and for data collection and measurement. The various measurement
methods were tested on the field. This framework was later discussed with Prof. P. Baccini.

**Observation:** The students were very motivated and very creative in developing low cost measurement methods. However, they lacked background knowledge and critical analytical training. The professors did not get as involved as the students in working with the methodology.

**Phase 3: Collection and Measurement of Data (3 months)**

In this phase, the students guided by the local professors collected and measured the data according to the developed framework. Intermediate results and problems were discussed by fax, air mail or phone.

**Observation:** The goal of this phase of the project was to assign the responsibility for data collection and measurement to the local research partners in order to develop their skills in this area. However, it was observed that the local professors had not completely understood the methodology and therefore had difficulties in advising the students.

**Phase 4: Discussion of First Results (3 weeks)**

The students presented their first results in a seminar. Measurement errors and missing data were discussed with the students and the local professors. Additionally, the interpretation of the collected data was emphasized. Based on these discussions the students finished their theses.

**Observation:** The results reflected the students' high level of commitment to obtain good quality data. However, in some cases, the quality of the data was not sufficient and the interpretation of the results was not good, mostly due to a lack of guidance from the local professors. This situation indicated that the briefing time employed to provide them with the necessary academic tools to lead the students had not been sufficient.

**Phase 5: National Workshop**

To disseminate the information gained during this project, a national workshop was carried out in November 1995. The professors summarized and presented the results of the diploma theses.

**Observation:** The preparation of the proceedings confronted the professors with the method and the interpretation of the results which had been weak in the diploma theses. They got motivated in trying to understand the method and interpret the results. It was also observed that they had developed a project in which the method was applied. The students, who also participated in the workshop, were able to give some input into the discussion. However, it was visible that the students had not further worked with the method because they had similar problems as the other participants of the workshop.
Chapter 5: Experiences with Capacity Building

Phase 6: Further Development

Two developments that indicate that the method will be further used have taken place. First, based on the crisis of water supply in Tunja, the dean of the university presented the mayor of Tunja different policies for dealing with the water supply crisis. For this presentation, he used the results of the theses of the diploma students which had been further analyzed and interpreted during the workshop. Second, they designed new projects in form of diploma theses based on the results of the work-shop.

Conclusions

The following conclusions are drawn from the experiences made with capacity building:

- The success of capacity building is determined by three factors; (i) motivation and time availability of professors and students of the partner university, (ii) duration and the amount of time invested in teaching and for advising the professors and students of the partner university, and (iii) the existing local research capacity.

- In local universities, capacity building should focus on increasing the research and analytical capacity of the professors to grant a long term academic development. Even though students have often more time and are very motivated, depending on their background knowledge, they have rarely the possibility to apply and further develop the learned methods. However, students play an important role as catalysts for involving local professors.
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Publications Resulting from this Dissertation


Organization of the Work-Shop: "Seminario Taller Internacional Modelo de Flujo de Materiales: Un Instrumento para la Identificación Temprana de Problemas Ambientales en Zonas Urbanas", Tunja 23 to 25. November, 1995; resulting publications:

Diaz J., Quevedo P., Gorraiz V., Binder C., 1995, Fundamentos e Introducción a la Metodología.


Gorraiz V., Orjuelo O., Rubiano O., Diaz J., Binder C., 1995, Flujo de Papel por el Municipio de Tunja.

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<td>14 May 1966</td>
<td>Born in Montreal, Canada</td>
</tr>
<tr>
<td>1973 - 1978</td>
<td>Elementary School in Eggersriet/Switzerland</td>
</tr>
<tr>
<td>1978 - 1984</td>
<td>High School in the German School in Bogotá/Colombia</td>
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<tr>
<td>1984 - 1985</td>
<td>College in Kantonsschule St. Gallen/Switzerland</td>
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<tr>
<td>1985 - 1990</td>
<td>M.Sc. in Biochemistry, Swiss Federal Institute of Technology, Zurich (ETH)</td>
</tr>
<tr>
<td>1990 - 1991</td>
<td>Introduction of composting in a rural area in Colombia in a Colombian-German Project of the Christlicher Friedensdienst</td>
</tr>
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<td>1991</td>
<td>Management position in an educational project in the Department of Environmental Sciences at the Swiss Federal Institute of Technology, Zurich</td>
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<tr>
<td>1991</td>
<td>Chemistry teacher at a junior college in the Kantonsschule St. Gallen/Switzerland</td>
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<tr>
<td>1991 - 1992</td>
<td>Specialist for waste management in envico AG (Environmental Consultancy), Zurich</td>
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<tr>
<td>1992 - 1996</td>
<td>PhD-student at the Chair of Resource and Waste Management, Swiss Federal Institute of Technology, Zurich and the Department of Sanitation in Developing Countries (SANDEC), Dubendorf</td>
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<tr>
<td>1992 - 1995</td>
<td>Teaching assistant at the Chair of Resource and Waste Management, Swiss Federal Institute of Technology, Zurich</td>
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Annexes

Annex A: Subsystem Water

Annex B: Subsystem Food

Annex C: Subsystem Durables

Annex D: Subsystem Paper/Cardboard

Annex E: Subsystem Energy

Annex F: Mathematical Model for Subsystem Solids
Annex A: Subsystem Water; "to Clean"

The Annex A consists of (i) data sheets for water, phosphorous and carbon balance including explanations of the estimations, calculations and errors and (ii) the mathematical model used for the calculation of the sensitivity analysis, and error propagation.
1 Data Sheet for the Calculation of Water, Phosphorous and Carbon-Fluxes
# Data Sheet for the Calculation of Water, P and C-Flux

## Stock

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<th>Processes</th>
<th>Mass-stock</th>
<th>Mass-stock (error)</th>
<th>P-stock</th>
<th>P-stock (error)</th>
<th>P-conc</th>
<th>P-conc (error)</th>
<th>C-stock</th>
<th>C-stock (error)</th>
<th>C-conc</th>
<th>C-conc (error)</th>
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<td>GW Lower Aquifer</td>
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<td>500</td>
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## Input fluxes

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<th>Flux (good)</th>
<th>Mass-flux (Error)</th>
<th>P-flux (Error)</th>
<th>P-conc (Error)</th>
<th>C-flux (Error)</th>
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<td>HH/SER/ID</td>
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<td>8.4</td>
<td>1.6</td>
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<td>72.5</td>
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## Internal fluxes

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<th>C-flux (Error)</th>
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<td>0.40</td>
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<td>Surface W</td>
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<td>Surface W</td>
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<td>1</td>
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<td>waste</td>
<td>Landfill</td>
<td>6</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>F</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>32</td>
<td>Output Fluxes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Process of origin</td>
<td>Flux (good)</td>
<td>Process of destiny</td>
<td>m³ m³/yr</td>
<td>Mass-flux</td>
</tr>
<tr>
<td>34</td>
<td>Surface W</td>
<td>SW-output</td>
<td>Ext. Surface W</td>
<td>14</td>
<td>4.2</td>
</tr>
<tr>
<td>35</td>
<td>Soil/Upper Aquifer</td>
<td>evaporation</td>
<td>Atmosphere</td>
<td>37</td>
<td>4</td>
</tr>
<tr>
<td>36</td>
<td>GW/ Lower Aquifer</td>
<td>GW - output1</td>
<td>Ext. GW1</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>HH/SERVID</td>
<td>respiration</td>
<td>Atmosphere</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>Soil/Upper Aquifer</td>
<td>GW - output2</td>
<td>Ext. GW2</td>
<td>3</td>
<td>0.6</td>
</tr>
<tr>
<td>39</td>
<td>Soil/Upper Aquifer</td>
<td>food</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Cell: D13
Note: Area=74sqkm [1] Prec. = 593 mm/a (1993, HiMAT)

Cell: F13
Note: P-conc see H13

Cell: H13
Note: P-conc: 0.015 mg/l, [Henseler et al, 1990], 0.5mg/l, [Frick: ], Assumption: 0.03mg/l, Error 0.01 mg/l

Cell: D14
Note: Average flux Rio La Vega: 60 l/s [Calixto, Valcarcel, 1994]. It was calculated from measured fluxes in September 51l/s, October 55 l/s (dry season) and November 82l/s (wet season). It was assumed that the dry season lasts 7 months and the wet season lasts 5 months.

Cell: F14
Note: P-conc see H14

Cell: H14
Note: [Calixto, Valcarcel, 1994], error 10%

Cell: J14
Note: C-conc see L14

Cell: L14
Note: [Calixto, Valcarcel, 1994], COD: 51 mg/l +/- 10 mg/l; COD: TOC= 3:1, [Boller, 1994]

Cell: D15
Note: Average import: 271 l/s, [EAAT], [Calixto, Valcarcel, 1994]

Cell: F15
Note: P-conc see H15

Cell: H15
Note: [Calixto, Valcarcel, 1994], error 10%

Cell: J15
Note: C-conc see L15

Cell: L15
Note: [Calixto, Valcarcel, 1994], 6 mgCOD/l, COD: TOC = 3:1, [Boller, 1994], error 10%

Cell: F16
P output in excreta: 56t/a, P in excreta according to age and food type [Ciba, 1970]: 70t/a. Assumption excreta: 63t/a +/-7t/a.
Total food consumption urban: (95%): 69t/a. Total food consumption rural (5%): 3.5t/a,
Total food consumption Tunja: 72.5t/a +/-7.5t/a

Cell: J16
Note: Food consumption in the urban area (95%) according to Ramirez et al., (1994); C content is 45% of dry matter

Cell: K16
Note: Error 10% [Ramirez et al.]

Cell: F17
Note: Assumption: Households with washing machine (79%), consume about 6.7 kg/cap.y (2/3 of swiss average consumption; Baccini et al., 1993): P content in detergents is: 8.7% [Varela S.A.]. Total P input into households with washing machine: 50tP/a +/-10t/a
For households without washing machine (21%) an average consumption of 2.5kg/cap.y was assumed. P content of these detergents: 9% [Diaz, personal communications, (1995)]. Total P from households without washing machine: 5t/a +/-1t/a.
Total P input of detergents: 55t/a +/-11t/a.
Total P input of detergents according to a survey of supermarkets: 22tP/a [Ramirez et al, 1994].
Assumption P input of detergents: 38.5 t/a +/-16.5t/a

Cell: J17
Note: Assumption: Households with washing machine (79%), consume about 6.7 kg/cap.y (2/3 of swiss average consumption; Baccini et al., 1993): C content in detergents is: 117g/kg (Baccini et al., 1993.). Total C from detergents: 670t/a +/-70t/a
For households without washing machine (21%) an average consumption of 2.5kg/cap.y was assumed. C-content of these detergents: 12% [Diaz,
personal communications, (1995)]. C-flux: 7tC/y +/- 1tC/y
Rural: Assumption equal consumption as urban households without washing machine: 1.7tC/y
Total C-input of detergents: 678tC/y.
C input from detergents according to a survey of supermarkets: 271tC/a [Ramirez et al, 1994].
Assumption for detergent consumption: 471 +/- 200
Amount of dirt from human 1260 gC/cap.y, dirt in clothes: 1780 gC/cap.y [Baccini et al., 1993]
Total dirt (urban + rural)= 346 tC/y.
Total C input: 817 tC/y

Cell: D22
Note: Average import: 47 l/s, (EAAT), [Calixto, Valcarcel, 1994]

Cell: F22
Note: P-conc see H22

Cell: H22
Note: [Calixto, Valcarcel, 1994], error 10%

Cell: J22
Note: C-conc see L22

Cell: L22
Note: [Calixto, Valcarcel, 1994], error 10%

Cell: D23
Note: Water consumption 5.8 mio m3/year, [EAAT], error 10% [Calixto, Valcarcel, 1994]

Cell: F23
Note: P-conc see H23

Cell: H23
Note: [Calixto, Valcarcel, 1994], error 10%
Note: [Calixto, Valcarcel, 1994], error 10%

10% of population is supplied with fountain water. Water consumption 100-150 l/inh.d, 0.42-0.62 mio m3/year

Note: Average P conc. in the upper aquifer: 0.5 mg/l. Assumption: 90% of the P which infiltrates is adsorbed to the soil. About 50% of the water extracted from the upper aquifer is not contaminated.

Note: Assumption based on [Alarcon, Suarey, 1991] and [Calixto, Valcarcel, 1994], error 10%

Losses in water supply 40% +/-5%, [EAAT], [Calixto, Valcarcel, 1994]

Note: [Calixto, Valcarcel, 1994], error 10%

Note: [Calixto, Valcarcel, 1994], error 10%

Cultivated area nearby Rio Chulo: 8.34 km2 [Calixto, Valcarcel, 1994], irrigation need according to water need of the different cultures [HIMAT], Assumption: 85% of this need is met (own estimations)
Note: Average ortho P-conc.: 4.1 mgP/l [Calixto, Valcarcel, 1994]. Ortho P is 50% +/-10% of total P-conc. [Boller 1994, Boller personal communications 1995],
Total P-conc. 8-10 mgP/l; Assumption: 9mgP/l.

Cell: H26
Note: 3-6mg/l dissolved orthophosphate. Mean value several measurement points: 4.1 mg/l [Calixto, Valcarcel, 1994], ortho P is 40-60% of total P-conc. [Boller 1994, Boller personal communications 1995].

Cell: L26
Note: [Calixto, Valcarcel, 1994], Average COD conc: 350 mg/l

Cell: D27
Note: 20% of sewage is lost due to damaged sewerage systems, [EAAT]

Cell: F27
Note: Total urban sewage: 101.5 t/a +/- 18 t/a, 20% sewage losses (see D30), sewage flux to surface water: 81.2 +/-14.4 t/a

Cell: G27
Note: see F27

Cell: J27
Note: Urban sewage: dirt and detergents: 817tC/a, excreta: 549 tC/a (Assumption 94% of the consumed food are respirated [Baccini et al, 1993].

Cell: L27
Note: Sewage measurement: 420 +/-60 mg COD/l, which is equivalent to 120-160 mg/l TOC

Cell: D28
Note: Area runoff calculated according to US Soil Conservation Service methodology, run off area : 5-5.5, run off irrigation: 0.7, Exfiltration upper aquifer to surface water: 4
Range of run off: 9.7 -10.3 Assumption: 10  Error: 1,

Cell: F28
Note: Erosion according Baccini, von Steiger (1992): Assumption: erosion of the cultivated area (32km2) is about 2.6 kgP/ha.y; erosion from pasture
(28km²) is 2kgP/ha.y.
Total erosion: 14tP/y +/- 4tP/y

Cell: G28
Note: see F28

Cell: J28
Note: Assumption: erosion : 0.1-0.5 tC/ha.y , Eroded area 20 km², Average value: 600tC/y +/- 400 tC/y

Cell: D29
Note: Infiltration area: 16.8 sqkm, Assumption total amount of P-EVT infiltrates.

Cell: F29
Note: Assumption P is adsorbed to soil/clay during water infiltration.

Cell: H29
Note: Assumption P is adsorbed to soil/clay during water infiltration.

Cell: D30
Note: 20% of sewage is lost due to damaged sewerage systems, [personal communication EAAT, 1993], [Calixto, Valcarcel, 1994]

Cell: F30
Note: Sewage losses in urban areas according to the transfer coefficient from water flux. 20% of P input to household 20.3 tP/y
in rural areas the total P consumption goes to soil: 3.5 tP/y.
Total P- flux into soil: 23.8 +/- 4tP/y

Cell: G30
Note: see F30

Cell: J30
Note: Sewage losses in urban areas according to the transfer coefficient from water flux. 20% of P input to household 273 tC/y
in rural areas the total C consumption goes to soil: 83.5 tC/y. (excreta: 28.5tC/y, rural waste:55 tC/y)
Total C- flux into soil: 356 tC/a. Estimated error 15%
**Cell: K30**  
Note: Assumption error 15%

**Cell: F31**  
Note: Waste is about 10% of consumed food in the urban area. 6t/y + waste from market place 0.4t/y. [Gorraiz et al, 1988]

**Cell: G31**  
Note: Assumed error 10%

**Cell: J31**  
Note: Waste is 10% of consumed food in the urban area. 1035TC/y + waste from market place +90TC/y [Gorraiz et al, 1988]

**Cell: K31**  
Note: Assumed error 10%

**Cell: D35**  
Note: Dry season: 12.4 E6 m3/y rainy season 16.4 E6 m3/y. [Rios, Tovar, 1994]  
Assumption: 5 months rain and 7 months dry season: 14 E6 m3/y +/- 2.8 E6 m3/y

**Cell: F35**  
Note: Ortho- P conc. 2.8 mg/l, ortho P is 50% +/- 10% of total P-conc. [Boller, 1994; Boller personal communication 1995], Total P conc.: 4.7 - 7mgP/l,  
Assumed conc. 5.9 mgP/l

**Cell: H35**  
Note: Ortho- P conc. 2.8 mg/l [Rios, Tovar, 1994], ortho P is 40% -60% of total P-conc. [Boller, 1994; Boller personal communication 1995], Total P conc.: 4.7 - 7mgP/l,  
Assumed conc. 5.9 mgP/l

**Cell: L35**  
Note: Average COD in surface water: 228 mg/l [Rios Tovar, 1994], Conversion factor COD: TOC = 1:3 [Boller, 1994]. Error: 15%

**Cell: D36**  
Note: EV total = Ev area + Ev Irrigation  
Ev area, Ev = 451 mm/a, area = 74 km2 [Calixto, Valcarcel, 1994]
EV Irrigation: 90% of irrigation: 3 -4m³/year, Assumption 3.5 m³/year
Assumption: Root crops and cereals are irrigated up to 80% of their theoretical needs, and about 80% of the area is irrigated. For pasture it was assumed, that about 15% of the area is irrigated to 80% of the theoretical need.
Transpiration Human neglectable: 0.02 [Baccini et al, 1993]

Cell: F37
Note: Assumption P conc. as in H22

Cell: H37
Note: Assumption P conc. as in H22

Cell: J38
Note: 94% of food consumed is respirated [Baccini et al, 1993]

Cell: K38
Note: Error 5%

Cell: E39
Note: Assumption: Error 20%
2 Mathematical Model for Subsystem Water

The subsystem water can be described with 6 processes and 22 fluxes. Figure A1 shows the system for the water model showing the variables as used for the mathematical modeling. The equations used to describe the water, phosphorous and carbon fluxes are given in different sections.

Variables

- $\mathbf{M}^{(1)}, \ldots, \mathbf{M}^{(5)}$: 5 stock change of balance volume (landfill excluded)
- $I_1, I_{2a}, I_{2b}, I_{3a}, I_{3b}, I_5$: 6 input fluxes
- $A_{jn}$: 10 internal fluxes
- $O_{2a}, O_{2b}, O_{2c}, O_3, O_4, O_5$: 6 output fluxes
Annex A: Subsystem Water

Parameters

- \( P_1, \ldots, P_6 \)  
  6 input fluxes
- \( P_7 \)  
  \( k_{in}^{(2)} \), internal transfer-coefficients
- \( P_8 \)  
  \( k_{in}^{(3)} \), internal transfer-coefficients
- \( P_9, \ldots, P_{14} \)  
  \( k_{in}^{(5)} \), ..., \( k_{in}^{(10)} \), internal transfer-coefficients
- \( P_{15}, \ldots, P_{18} \)  
  \( k_{op}^{(2)} \), ..., \( k_{op}^{(5)} \), output transfer-coefficients
- \( P_{19} \)  
  second output transfer-coefficient

Model specific equations (Model assumptions)

Balance equations

\[
F_1 = \frac{1}{\rho} + A_{s1} - A_{t5} - A_{t6} = F_{\phi} + P_{14} * P_1 + P_5 * P_7 + P_{10} * P_1
\]

\[
\cdot
\]

\[
F_6 = A_{s6} + A_{s6} + A_{s6} + A_{s6} + A_{s6} = P_{10} * P_1 + P_{11} * P_2 + P_{12} * P_2 + P_8 * P_4 + P_{13} * P_5
\]

Given rates for balance volume

\[
F_7 = \dot{M}^{(1)} - 0
\]

\[
F_8 = \dot{M}^{(2)} - 0
\]

\[
F_9 = \dot{M}^{(3)} - 0
\]

\[
F_{10} = \dot{M}^{(5)} - 0
\]

Defined Inputs

\[
F_{11} = l^{(2)}_p - l_1 = F_{\phi} - P_1
\]

\[
\cdot
\]

\[
\cdot
\]

\[
F_{16} = l^{(6)}_p - l_6 = F_{\phi} - P_6
\]
Annex A: Subsystem Water

Input - Output equations

\[ F_{17} = A_{12} - k_{12} \cdot I_{tot}^{(1)} = F_{in}^{(2)} - P_7 \cdot I_{tot}^{(1)} \]

\[ F_{18} = A_{24} - k_{24} \cdot I_{p}^{(2)} = F_{in}^{(3)} - P_8 \cdot F_{p}^{(2)} \]

\[ F_{19} = A_{32} - k_{32} \cdot I_{tot}^{(3)} = F_{in}^{(5)} - P_9 \cdot I_{tot}^{(3)} \]

\[ F_{24} = A_{36} - k_{36} \cdot I_{tot}^{(3)} = F_{in}^{(10)} - P_{14} \cdot I_{tot}^{(3)} \]

\[ F_{25} = O_2 - k_{op}^{(2)} \cdot I_{tot}^{(4)} = F_{op}^{(2)} - P_{15} \cdot I_{tot}^{(4)} \]

\[ F_{26} = O_3 - k_{op}^{(3)} \cdot I_{tot}^{(2)} = F_{op}^{(3)} - P_{19} \cdot I_{n}^{(2)} = F_{op}^{(3)} - P_{16} \cdot F_{p}^{(2)} - P_{19} \cdot F_{in} \]

\[ F_{27} = O_4 - k_{op}^{(3)} \cdot I_{tot}^{(2)} = F_{op}^{(4)} - P_{17} \cdot I_{tot}^{(2)} \]

\[ F_{28} = O_5 - k_{op}^{(5)} \cdot I_{tot}^{(5)} = F_{op}^{(5)} - P_{18} \cdot I_{tot}^{(5)} \]
Annex A: Subsystem Water

Mathematical Model for Subsystem Water/Phosphorous

Variables

- $M^{(1)}_,... ,,M^{(5)}$: 5 stock change of balance volume (landfill excluded)
- $I_1, I_{2a}, I_{2b}, I_{3a}, I_{3b}, I_5$: 6 input fluxes
- $A_{i_1}$: 10 internal fluxes
- $O_{2a}, O_{2b}, O_{3c}, O_{3d}, O_{3e}, O_{5}$: 6 output fluxes

Parameters

- $P_1,...,P_6$: 6 input fluxes
- $P_7$: $k^{(2)}_{in}$ internal transfer-coefficients
- $P_8$: $k^{(3)}_{in}$ internal transfer-coefficients
- $P_9,...,P_{14}$: $k^{(3)}_{in},..., k^{(10)}_{in}$ internal transfer-coefficients
- $P_{15},...,P_{18}$: $k^{(3)}_{op},..., k^{(6)}_{op}$ output transfer-coefficients

Model specific equations (Model assumptions)

Balance equations

\[
F_1 = f^{(1)} + A_{31} - A_{15} - A_{41} = F^{(1)}_{v} + P_{14} \times P_1 + P_5 \times P_1 + P_{10} \times P_1
\]

\[
F_2 = A_{16} + A_{26} + A_{36} + A_{46} + A_{56} = P_{10} \times P_1 + P_{11} \times P_2 + P_{12} \times P_2 + P_8 \times P_4 + P_{13} \times P_5
\]

Given rates for balance volume

\[
F_7 = \dot{M}^{(1)} - 0
\]

\[
F_8 = \dot{M}^{(3)} - 0
\]

\[
F_9 = \dot{M}^{(4)} - 0
\]

\[
F_{10} = \dot{M}^{(5)} - 0
\]
Defined Inputs

\[ F_{11} = I_p^{(1)} - I_1 = F_p^{(1)} - P_1 \]

\[ \quad \]

\[ \quad \]

\[ F_{16} = I_p^{(6)} - I_6 = F_p^{(6)} - P_6 \]

Input - Output equations

\[ F_{17} = A_{12} - K_{12} \cdot I_{tot}^{(1)} = F_{in}^{(2)} - P_7 \cdot I_{tot}^{(1)} \]

\[ F_{18} = A_{24} - K_{24} \cdot I_p^{(2)} = F_{in}^{(3)} - P_8 \cdot F_p^{(2)} \]

\[ F_{19} = A_{32} - K_{32} \cdot I_{tot}^{(3)} = F_{in}^{(5)} - P_9 \cdot I_{tot}^{(3)} \]

\[ \quad \]

\[ \quad \]

\[ F_{24} = A_{36} - K_{36} \cdot I_{tot}^{(3)} = F_{in}^{(10)} - P_{14} \cdot I_{tot}^{(3)} \]

\[ F_{25} = O_3 - K_{op}^{(3)} \cdot I_{tot}^{(2)} = F_{op}^{(3)} - P_{15} \cdot I_{tot}^{(2)} \]

\[ F_{26} = O_4 - K_{op}^{(4)} \cdot I_{tot}^{(2)} = F_{op}^{(4)} - P_{16} \cdot I_{tot}^{(2)} \]

\[ F_{27} = O_5 - K_{op}^{(5)} \cdot I_{tot}^{(3)} = F_{op}^{(5)} - P_{17} \cdot I_{tot}^{(3)} \]

\[ F_{28} = O_6 - K_{op}^{(6)} \cdot I_{tot}^{(2)} = F_{op}^{(6)} - P_{18} \cdot I_{tot}^{(2)} \]
Mathematical Model for Subsystem Water/Carbon

Variables
- $\bar{M}^{(1)}, \ldots, \bar{M}^{(6)}$: 5 stock change of balance volume (landfill excluded)
- $I_1, I_{2a}, I_{2b}, I_3, I_{3a}, I_{3b}, I_5$: 6 input fluxes
- $A_{jk}$: 10 internal fluxes
- $O_{2a}, O_{2b}, O_{2c}, O_3, O_4, O_5$: 6 output fluxes

Parameters
- $P_1, \ldots, P_6$: 6 input fluxes
- $P_7$: $k^{(2)}_m$, internal transfer-coefficients
- $P_8$: $k^{(3)}_m$, internal transfer-coefficients
- $P_9, \ldots, P_{14}$: $k^{(5)}_m$, $\ldots$, $k^{(10)}_m$, internal transfer-coefficients
- $P_{15}, \ldots, P_{18}$: $k^{(3)}_o$, $\ldots$, $k^{(6)}_o$, output transfer-coefficients

Model specific equations (Model assumptions)
Balance equations
- $F_1 = I_p^{(1)} + A_{51} - A_{15} - A_{16} = F_p^{(1)} + P_{14} \cdot P_1 + P_5 \cdot P_1 + P_{10} \cdot P_1$
- $\ldots$
- $F_6 = A_{16} + A_{26} + A_{36} + A_{46} + A_{56} = P_{10} \cdot P_1 + P_{11} \cdot P_2 + P_{12} \cdot P_2 + P_8 \cdot P_4 + P_{13} \cdot P_5$

Given rates for balance volume
- $F_7 = \bar{M}^{(1)} - 0$
- $F_8 = \bar{M}^{(3)} - 0$
- $F_9 = \bar{M}^{(4)} - 0$
- $F_{10} = \bar{M}^{(5)} - 0$
Annex A: Subsystem Water

Defined Inputs

\[ F_{11} = F_{ip}^{(1)} - I_1 = F_{ip}^{(1)} - P_1 \]

\[ \ldots \]

\[ F_{16} = F_{ip}^{(6)} - I_6 = F_{ip}^{(6)} - P_6 \]

Input - Output equations

\[ F_{17} = A_{12} - k_{12} \times I_{tot}^{(2)} = F_{in}^{(2)} - P_7 \times I_{tot}^{(1)} \]

\[ F_{18} = A_{24} - k_{24} \times I_{p}^{(2)} = F_{in}^{(3)} - P_5 \times F_{ip}^{(2)} \]

\[ F_{19} = A_{32} - k_{32} \times I_{tot}^{(3)} = F_{in}^{(6)} - P_5 \times I_{tot}^{(3)} \]

\[ \ldots \]

\[ F_{24} = A_{36} - k_{36} \times I_{tot}^{(3)} = F_{in}^{(10)} - P_{14} \times I_{tot}^{(3)} \]

\[ F_{25} = O_3 - k_{op}^{(3)} \times I_{tot}^{(2)} = F_{op}^{(3)} - P_{15} \times I_{tot}^{(2)} \]

\[ F_{26} = O_4 - k_{op}^{(4)} \times I_{p}^{(2)} = F_{op}^{(4)} - P_{16} \times F_{ip}^{(2)} \]

\[ F_{27} = O_5 - k_{op}^{(5)} \times [I_{p}^{(5)} - A_{36}] = F_{op}^{(5)} - P_{17} \times [F_{ip}^{(5)} - F_{in}^{(10)}] \]

\[ F_{28} = O_6 - k_{op}^{(6)} \times I_{tot}^{(2)} = F_{op}^{(6)} - P_{18} \times I_{tot}^{(2)} \]
Annex B: Subsystem Food

The annex subsystem food consists of (i) a Table showing the water and phosphorous content of the different food types, (ii) Tables showing the input, output, origin and destiny of the different products surveyed at Market Place and (iii) a Table showing the input and origin of the different products surveyed at Supermarkets and Specialized Shops.
1 Water and Phosphorous-content and Estimated Waste Proportion of Each Food Type
Table B1:
Water- and Phosphorous- content and estimated waste proportion of each food type

Source: Souci et. al., 1990.

<table>
<thead>
<tr>
<th>Fresh Products</th>
<th>Water content</th>
<th>P content (mg/100g)</th>
<th>Waste (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leguminous not dry</td>
<td>78</td>
<td>90</td>
<td>56</td>
</tr>
<tr>
<td>Cereals and derivates</td>
<td>26</td>
<td>150</td>
<td>40</td>
</tr>
<tr>
<td>Root crops, tubers and plantain</td>
<td>76</td>
<td>45</td>
<td>24</td>
</tr>
<tr>
<td>Green and yellow vegetables</td>
<td>90</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Other vegetables</td>
<td>90</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Fruit</td>
<td>85</td>
<td>20</td>
<td>37</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Processed Products</th>
<th>Water content</th>
<th>P content (mg/100g)</th>
<th>Waste (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereals</td>
<td>12.5</td>
<td>189</td>
<td>1</td>
</tr>
<tr>
<td>Leguminous</td>
<td>11.5</td>
<td>417</td>
<td>1</td>
</tr>
<tr>
<td>Oils and fats</td>
<td>15</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Milk</td>
<td>88</td>
<td>92</td>
<td>1</td>
</tr>
<tr>
<td>Sugar and derivates</td>
<td>10</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>Other</td>
<td>31</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Eggs</td>
<td>74</td>
<td>200</td>
<td>12</td>
</tr>
<tr>
<td>Meat, fisch</td>
<td>75</td>
<td>200</td>
<td>5</td>
</tr>
</tbody>
</table>

Carbon content is estimated to be about 45% of dry matter
Note: Consists of arveja, frijol and haba

Note: Average waste according to Martínez et. al. is 56%, Range of waste according to Souci et. al.: Min: 55% Max: 75%, Average 60%, Assumption: 56%

Note: The whole maize contains more water than only the grains. The total water content is estimated to be twice as large as the water content of the grains.

Note: Whole grain of the maize has a content of 256 mg/100g. More than half of the maize is no grain. Thus, it was estimated that the phosphorous content is 150 mg/100g.

Note: As potato makes up nearly 70% of the total of the tubers, it was estimated, that the average p-content is 45mg/100g

Note: Waste for potato 20%, for platanos 33%. As potato is about 70% of consumption, the total proportion of waste was assumed to be 24%.

Note: Average of several vegetables
Note: Average of different fruit

Note: 86% grains, (200mg/100g), 14% flour (120 mg/100g), average: 189mg/100g

Note: Assumption: 50% of the products, including chocolate and maize flour, have a water content of about 12%. The 50% of the products, including salt and related products, have a water content of about 50%. The average is: 31%
2 Origin and Destiny of Fresh Products Entering and Sorting the Market Place
## Table B2: Market Place

Average of the three measurements in 1993.

Measurement dates: August 25-27; October 30 to November 1; November 10-12

<table>
<thead>
<tr>
<th>Origin</th>
<th>t/year</th>
<th>percent</th>
<th>Destiny</th>
<th>percent</th>
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<tbody>
<tr>
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<td>Tunja</td>
<td>Others</td>
<td>Total</td>
<td></td>
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<tr>
<td>9</td>
<td>Vegetables (Leguminous not dry)</td>
<td>2791</td>
<td>170</td>
<td>613</td>
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<tr>
<td>10</td>
<td>Cereals and derivates</td>
<td>1607</td>
<td>8</td>
<td>161</td>
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<tr>
<td>11</td>
<td>Root crops, tubers and plantain</td>
<td>59445</td>
<td>4815</td>
<td>5259</td>
</tr>
<tr>
<td>12</td>
<td>Green and yellow vegetables</td>
<td>3219</td>
<td>92</td>
<td>1759</td>
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<tr>
<td>13</td>
<td>Other vegetables</td>
<td>9776</td>
<td>144</td>
<td>1298</td>
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<tr>
<td>14</td>
<td>Fruit</td>
<td>2772</td>
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<td>4002</td>
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<td>15</td>
<td>Total</td>
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<td>5230</td>
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</table>

### Total consumption in Tunja in TS and P

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<tr>
<th>Origin</th>
<th>Water content</th>
<th>t(TS)/year</th>
<th>P content (mg/100g)</th>
<th>P t/year</th>
<th>Waste (%)</th>
<th>Waste t/year</th>
<th>Waste t(TS)/year</th>
<th>P in Waste</th>
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</thead>
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<td>20</td>
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<td>395</td>
<td>44</td>
<td>90</td>
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<td>21</td>
<td>Cereals and derivates</td>
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<td>26</td>
<td>1075</td>
<td>120</td>
<td>150</td>
<td>2</td>
<td>11</td>
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<tr>
<td>22</td>
<td>Root crops, tubers and plantain</td>
<td>27164</td>
<td>76</td>
<td>6524</td>
<td>730</td>
<td>45</td>
<td>12</td>
<td>59</td>
</tr>
<tr>
<td>23</td>
<td>Green and yellow vegetables</td>
<td>2944</td>
<td>90</td>
<td>294</td>
<td>33</td>
<td>30</td>
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<td>4</td>
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<td>24</td>
<td>Other vegetables</td>
<td>8416</td>
<td>90</td>
<td>842</td>
<td>94</td>
<td>30</td>
<td>3</td>
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<td>25</td>
<td>Fruit</td>
<td>5962</td>
<td>85</td>
<td>894</td>
<td>100</td>
<td>20</td>
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<tr>
<td>26</td>
<td>Total</td>
<td>47752</td>
<td>10024</td>
<td>1121</td>
<td>21</td>
<td>100</td>
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</table>
Cell: C21
Note: Maize

Cell: E21
Note: The whole maize contains more water than only the grains. The total water content is estimated to be twice as large as the water content of the grains.

Cell: H21
Note: Whole grain of the maize has a content of 256 mg/100g. More than half of the maize is no grain. Thus, it was estimated that the phosphorous content is 150 mg/100g.

Cell: H22
Note: As potato makes up nearly 70% of the total of the tubers, it was estimated, that the average P-content is 45mg/100g.

Cell: K22
Note: Waste for potato 20%, for plantanos 33%. As potato is about 70% of consumption, the total proportion of waste was assumed to be 24%.

Cell: K23
Note: Average of several vegetables

Cell: K24
Note: Average of several vegetables

Cell: K25
Note: Average of different fruit
3 Origin and Amount of Products Entering Supermarkets and Specialized Shops
# Table B3: Supermarket and Specialized Shops

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<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
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<th>I</th>
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<td>36</td>
<td>Oils and fats</td>
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<td>15</td>
<td>663</td>
<td>10</td>
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<td>1138</td>
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<td>Sugar and derivates</td>
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<td>1976</td>
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<td>5</td>
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<td>42</td>
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</table>
Inh. 120'000 kg/lnh.y;

FAO, Note:

D40 Cell:
1994 al., et Martinez to according Estimations

L39 Cell:
31% Average: 50%. About is content water the where products related and salt includes products

D37 Cell:
Note: FAO, 79 kg/lnh.y, Assumption 120'000 Inh.

L34 Cell:
189 mg/100g average: mg/lOOg, (120 mg/100g), flour

L38 Cell:
Note: Estimations according to Martinez et. al., 1994

E39 Cell:
Note: Assumption: one half of the products includes chocolate, maizena where the water content is about 12%. The other half of the products includes salt and related products where the water content is about 50%. Average: 31%

L39 Cell:
Note: Estimations according to Martinez et. al., 1994

D40 Cell:
Note: FAO, 6.1 kg/lnh.y; Assumption 120'000 Inh.
Annex C: Subsystem Durables

The annex of the subsystem durables consists of (i) the questionnaire for the sociological survey, (ii) a Table of the output transfer-coefficients for the different groups of durables, (iii) a Table showing the theoretical lifetime of durables and the lifetime of durables in industrialized and in developing countries, and (iv) an overview over the different income-consumption/stock models tested.
1 Survey Questionnaire
ENCUESTA MUNICIPAL SOBRE BIENES DE CONSUMO

Fecha:  
IDENTIFICACION:
Dirección ____________________________  
Barrio ________________________________  Estrato ________

I Datos generales
1. Aspectos demográficos

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<th>Edad</th>
<th>Actividad Laboral</th>
<th>Relación Laboral</th>
<th>Aporte al Ingreso familiar</th>
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2. Gastos del Hogar:
¿Aproximadamente cuánto gastan mensualmente en las siguientes necesidades?

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<th>Alimentos</th>
<th>Vivienda</th>
<th>Educación</th>
<th>Vestuario</th>
<th>Recreación</th>
<th>Salud</th>
<th>Servicios públicos</th>
<th>Otro Cuales</th>
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</table>
II. Bienes de Uso Diario

3. ¿Usted donde almuerza?
   Restaurante • Casa • Trabajo •

4. Lugares donde se compran los alimentos
   Cuadro 4A:

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<td>Supermercado</td>
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<td>Carnicería</td>
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III. INFORMACION SOBRE BIENES DURADEROS

5. Muebles

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<td>Comedor</td>
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<td>Camas semidobles</td>
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<td>Camas sencillas</td>
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</tr>
<tr>
<td></td>
<td>5-10</td>
<td>Vendió</td>
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</tr>
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<td>10-15</td>
<td></td>
<td>Guarda</td>
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### ELECTRODOMESTICOS

6. Estufa

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### Cuadro 6B: Anterior Estufa

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### 7. Calentador

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#### Cuadro 7B: Anterior Calentador

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### 8. Equipo de Sonido, Grabadora, Radio

#### Cuadro 8A

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### Cuadro 8B: Anterior Equipo de Sonido, Grabadora, Radio

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<td></td>
<td></td>
</tr>
<tr>
<td>Radio 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio 3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 9. Televisor (TV):

#### Cuadro 9A:

<table>
<thead>
<tr>
<th>TV No.</th>
<th>Color</th>
<th>Pulgadas</th>
<th>Años de tenencia (años)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B / N</td>
<td>&lt; 14</td>
<td>14</td>
</tr>
<tr>
<td>TV 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TV 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TV 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TV 4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Cuadro 9B:

<table>
<thead>
<tr>
<th>Nuevo</th>
<th>Usado</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>TV 1</td>
<td></td>
</tr>
<tr>
<td>TV 2</td>
<td></td>
</tr>
<tr>
<td>TV 3</td>
<td></td>
</tr>
<tr>
<td>TV 4</td>
<td></td>
</tr>
</tbody>
</table>

#### Cuadro 9C: Anterior Televisor

<table>
<thead>
<tr>
<th>Cant.</th>
<th>Duración TV anterior (años)</th>
<th>Destino del TV</th>
<th>A quién</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;1</td>
<td>1-5</td>
<td>5-10</td>
</tr>
<tr>
<td>TV No.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
10. Nevera y Congelador

Cuadro 10A:

<table>
<thead>
<tr>
<th>Pies</th>
<th>Años de tenencia (años)</th>
<th>Nuevo</th>
<th>Usado</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;1</td>
<td>1-5</td>
<td>5-10</td>
</tr>
<tr>
<td>Nevera 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nevera 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Congelador 1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cuadro 10B: Anterior Nevera/Congelador

<table>
<thead>
<tr>
<th>Cant.</th>
<th>Duración (años)</th>
<th>Destino</th>
<th>A quién</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;1</td>
<td>1-5</td>
<td>5-10</td>
</tr>
<tr>
<td></td>
<td>Botó</td>
<td>Regaló</td>
<td>Vendió</td>
</tr>
<tr>
<td>Nevera 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cong. 1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

11. Lavadora

Cuadro 11A:

<table>
<thead>
<tr>
<th>Libras</th>
<th>Años de tenencia (años)</th>
<th>Nuevo</th>
<th>Usado</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 12 15 18</td>
<td>&lt;1</td>
<td>1-5</td>
<td>5-10</td>
</tr>
<tr>
<td>Lavadora 1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cuadro 11B: Anterior Lavadoras

<table>
<thead>
<tr>
<th>Cant.</th>
<th>Duración (años)</th>
<th>Destino</th>
<th>A quién</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;1</td>
<td>1-5</td>
<td>5-10</td>
</tr>
<tr>
<td></td>
<td>Botó</td>
<td>Regaló</td>
<td>Vendió</td>
</tr>
<tr>
<td>Lava. 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cong. 1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
12. Medios de Transporte de uso personal y/o trabajo

- ¿Qué medios de transporte y/o trabajo tiene su familia?
  Taxi • Colectivo • Bus • Camión • Volqueta •
  Camión • Motocicleta • Bicicleta •

- ¿Cuántos tiene de cada uno?
  Taxi_____ Colectivo_______ Bus____ Camión____ Volqueta_____
  Camión____ Volqueta_____
  Carro______ Motocicleta______ Bicicleta______
Cuadro 12A:

<table>
<thead>
<tr>
<th>Medio de Transp</th>
<th>Marca y Modelo</th>
<th>Años de tenencia</th>
<th>Nuevo</th>
<th>Usado</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Marca</td>
<td>Modelo</td>
<td>&lt;1</td>
<td>1-5</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cuadro 12B: Anterior Medio de Transporte

<table>
<thead>
<tr>
<th>Medio de Transp.</th>
<th>Duración</th>
<th>Destino</th>
<th>A quién</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;1 1-5</td>
<td>Botó</td>
<td>Botó</td>
</tr>
<tr>
<td></td>
<td>5-10</td>
<td>Regaló</td>
<td>Regaló</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>Vendió</td>
<td>Vendió</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>Guarda</td>
<td>Guarda</td>
</tr>
<tr>
<td></td>
<td>20 o&gt;</td>
<td>Otro</td>
<td>Otro</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

13. Con el fin de realizar un estudio de basuras en el Municipio, necesitamos que nos facilite su basura. Representaría para usted algún inconveniente si pasáramos durante los siguientes 4 meses 8 veces a recogerla?

Si • No •

¿Qué día de la semana y a qué hora pasan por la basura en su casa?
_____________________________________________________

15. Observaciones?
_____________________________________________________

_____________________________________________________

Nombre del encuestador________________Facultad____________
Guía de observación:

- Hay negocio en la misma casa? (Microempresa?), Tienda?

- Estado de vivienda: Bueno, malo, regular (Material de construcción)

- ¿Cuántos pisos tiene la casa?

- ¿Cuánto tiempo duró la entrevista?

- ¿Qué dificultades tuvo al realizar la encuesta?
Table C1:
Output transfer-coefficients for durables in Tunja.

Output transfer-coefficient (in percent) of the groups of durables for the different each social strata in Tunja.

<table>
<thead>
<tr>
<th></th>
<th>present to relatives or friends</th>
<th>present to others</th>
<th>sold to relatives or friends</th>
<th>sold to others</th>
<th>Waste</th>
<th>Recycling</th>
<th>kept in HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furniture</td>
<td>Strata 2</td>
<td>33</td>
<td>7.5</td>
<td>36</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Strata 3</td>
<td>30</td>
<td>6</td>
<td>24</td>
<td>9.7</td>
<td>3.8</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Strata 4</td>
<td>19</td>
<td>15</td>
<td>37</td>
<td>8.9</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Strata 5</td>
<td>27</td>
<td>1.5</td>
<td>42</td>
<td>13</td>
<td>4.8</td>
<td>4.2</td>
</tr>
<tr>
<td>Elec. Appl.</td>
<td>Strata 2</td>
<td>6.5</td>
<td>0</td>
<td>22</td>
<td>7.1</td>
<td>7.5</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Strata 3</td>
<td>16</td>
<td>3.3</td>
<td>32</td>
<td>8.7</td>
<td>6</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>Strata 4</td>
<td>22</td>
<td>3.6</td>
<td>32</td>
<td>5.1</td>
<td>5.7</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>Strata 5</td>
<td>25</td>
<td>2.5</td>
<td>22</td>
<td>11</td>
<td>5.4</td>
<td>1</td>
</tr>
<tr>
<td>Vehicles</td>
<td>Strata 2</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Strata 3</td>
<td>3</td>
<td>0</td>
<td>70</td>
<td>18</td>
<td>0.04</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>Strata 4</td>
<td>0</td>
<td>0</td>
<td>54</td>
<td>44</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Strata 5</td>
<td>0</td>
<td>0</td>
<td>56</td>
<td>39</td>
<td>0</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Source: Survey 1993
<table>
<thead>
<tr>
<th>Durable</th>
<th>Theoretical lifetime (year)</th>
<th>Lifetime in industrialized countries, e.g. USA (year)</th>
<th>Lifetime in developing countries (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washing maschine</td>
<td>5</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>Stereos</td>
<td>35</td>
<td>1.1</td>
<td>50</td>
</tr>
<tr>
<td>Bicycle</td>
<td>25</td>
<td>2</td>
<td>75</td>
</tr>
<tr>
<td>Car</td>
<td>11</td>
<td>2.2</td>
<td>40</td>
</tr>
</tbody>
</table>

*Source: Binswanger, 1982*
4. Income and Consumption/Stock Growth Models

In the following, four modelling approaches are used to analyze the relationship between income and consumption/stock of durables. The four selected approaches are (i) a linear model which analyzes the relationship between income and stock, (ii) a logistic growth model which analyzes the relationship between income and consumption, (iii) a polynomial model which analyzes the relationship between income and stock, and (iv) a discrete choice model which was only applied for vehicles.

All models show that income has a significant influence on consumption/stock of durables at a significance level of 95%. However, the explanatory power of income is relatively low. This could be due to the following: (i) The sample was chosen in order to characterize the metabolism of the region. Thus, the larger part of the sample corresponds to the middle income social strata. Even though, for stratum 5, the sample size taken corresponded to a higher share than its population share, it seems that the variability within households in stratum 5 is very high. Thus, the selected sample does not include enough observations to characterize the relationship between income and consumption/stock of higher-income households. (ii) Weight of durables and their composition are indispensable in characterizing the metabolism of the region. However, these indicators might not be adequate to measure the relationship between income and consumption/stock. For example, it could be the case that as income increases, households buy more furniture but the weight of the furniture they buy is lower. This could alter the relationship between income and consumption/stock because households with low and high income might have the same weight of stock. (iii) Variables such as prices of durables were not included in the survey. These variables are important determinants of the demand for durables.

The logistic growth model was chosen for developing the scenarios for the following reasons (i) according to Deaton and Muellbauer (1980), it is appropriate for modeling the relationship between income and consumption; (ii) it assumes saturation of consumption and stock with increasing income. The linear model is quite accurate for modeling income-stock relationships of low income households, because in Tunja those households still are in the linear growth phase. However, a linear model does not model saturation of the stock growth which has to be expected for higher-income households; (iii) the polynomial model mimics saturation of stock growth up to a certain income level, where the model shows nearly exponential growth. The saturation level is lower than the one obtained with the logistic growth model. So, in order to estimate a maximum scenario, the logistic growth model was preferred over the polynomial model.

The Data

In Figures 1a and 1b the data problem is exemplified for the income-stock relationship of electrical appliances. Figure 1a shows that the bulk of the data is between the monthly income of 100,000 to 250,000 pesos/household (US$ 200-500/cap.year) which corresponds to the average income of strata 3 and 4 which
Annex C: Subsystem Durables

have a population share of nearly 90%. The few observations with income higher than 600,000 pesos/month, which is twice the average income, show that there is a high variability in the data for income above 600,000 pesos/month. If stock weight is averaged over different income ranges it can be seen that stock increases in the form of a logistic growth curve with increasing income. The same can be shown for consumption.

In Figure 1b only households with income equal or less than 600,000 pesos/month were included. There is a clear trend to increase stock as income increases. There is a large variance among households of the same income range.

In Figure 1b only households with income equal or less than 600,000 pesos/month were included. There is a clear trend to increase stock as income increases. There is a large variance among households of the same income range.

Figure 1:
Relationship between income and stock of electrical appliances in households of Tunja.

1. Linear Model

The linear model was used to estimate the relationship between income and stock for the group of durables furniture and electrical appliances. Here the results for electrical appliances will be shown. Given the assumption that there is saturation of the stock with increasing income, two approaches were used to estimate the linear function. The first approach used the whole sample. The second approach included only households with income equal or below two times the average income (Figure 1b). It is assumed that household size has an influence on the consumption/stock of durables. Therefore, household size was included in the regression. In addition, household income was replaced by social strata in order to analyze the relationship between the social strata and stock. The results for the estimations of the model using income and social strata are shown separately.

1a) Income

The main results are:

- Income is a significant explanatory variable (Table C1; $t=6.9$, 6.5). The low $r^2$ of 0.11 indicates that the model does not completely explain the variance of the stock of electrical appliances. However, according to Greene, 1990, with cross sectional data even an $r^2$ as low as 0.2 might be noteworthy.
Annex C: Subsystem Durables

- If upper income households\(^1\) are excluded from the data set, \(r^2\) increases to 0.13. This result indicates that for the lower income households the relationship between income and stock might be linear. In addition, the coefficient for the sample without the upper income households is double the one of the whole sample. Thus, stock growth is larger if upper income households are excluded from the sample. This indicates that upper income households might be in the saturation stage.

- Household size is also a significant explanatory variable (Table C2; \(t=1.9, 2.2\)).

Table C1:
OLS of stock of electrical appliances vs. income in urban households of Tunja.

**Equation:** Stock (el. appl.) = \(C1 + C2 \times inc\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coefficient</th>
<th>Std. Error</th>
<th>(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size: 321 Income</td>
<td>0.22</td>
<td>0.03</td>
<td>6.9</td>
</tr>
<tr>
<td>(F=48, r^2=0.13) C</td>
<td>103</td>
<td>8.8</td>
<td>12</td>
</tr>
<tr>
<td>Sample size: 346 Income</td>
<td>0.1</td>
<td>0.06</td>
<td>6.5</td>
</tr>
<tr>
<td>(F=43, r^2=0.11) C</td>
<td>130</td>
<td>6.5</td>
<td>20</td>
</tr>
</tbody>
</table>

Table C2:
OLS of stock of electrical appliances vs. income and persons per household in urban households of Tunja.

**Equation:** Stock (el. appl.) = \(C1 + C2 \times inc + C3 \times PHH\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coefficient</th>
<th>Std. Error</th>
<th>(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size: 321 Income</td>
<td>0.21</td>
<td>0.03</td>
<td>8</td>
</tr>
<tr>
<td>(F=26, r^2=0.14) PHH</td>
<td>5</td>
<td>2.7</td>
<td>1.9</td>
</tr>
<tr>
<td>C</td>
<td>80</td>
<td>15</td>
<td>5.5</td>
</tr>
<tr>
<td>Sample size: 346 Income</td>
<td>0.1</td>
<td>0.016</td>
<td>6.3</td>
</tr>
<tr>
<td>(F=24, r^2=0.12) PHH</td>
<td>5.9</td>
<td>2.7</td>
<td>2.2</td>
</tr>
<tr>
<td>C</td>
<td>103</td>
<td>14</td>
<td>7.5</td>
</tr>
</tbody>
</table>

\(^1\) households with income greater than twice average income
1.2 Social Strata

If strata are used instead of income in the regression, it is found that:

- Stratum is a significant explanatory variable (Table C3; t=9). The model explains better the variance in stock of electrical appliances ($r^2 = 0.2$) than if income is taken as an explanatory variable. Possible explanations could be that (i) there are only four social strata and thus the variability of the data (same income, different stocks) is averaged; and (ii) there is a tendency that households have a consumption pattern similar to the social stratum where they live in, i.e. if a household lives in a higher stratum of the city than it would correspond to its income, it is probable that the consumption pattern of this household is more similar to that of its neighbors than to that of households of the same income level living in a lower stratum area of the city.

- If the upper income households are excluded from the regressions, the results do not change significantly. The coefficients also remain similar. Thus, if strata are selected instead of income the higher income households do not influence the results significantly.

- Household size is a significant explanatory variable (Table C4; t=3).

Table C3:
OLS of electrical appliances vs. stratum in urban households of Tunja.

**Equation:** $\text{Stock (el. appl.)} = C1 + C2 \times \text{Stratum}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coefficient</th>
<th>Std. Error</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size: 321 Stratum</td>
<td>55</td>
<td>6.2</td>
<td>8.9</td>
</tr>
<tr>
<td>F:78, $r^2 :0.2$</td>
<td>C</td>
<td>-19</td>
<td>20</td>
</tr>
<tr>
<td>Sample size: 346 Stratum</td>
<td>51</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>F:82, $r^2 :0.19$</td>
<td>C</td>
<td>-5</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table C4:
OLS of electrical appliances vs. stratum and household size in urban households of Tunja.

**Equation:** $\text{Stock (el. appl.)} = C1 + C2 \times \text{Stratum} + C3 \times \text{PHH}$

$\text{PHH: persons per household}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coefficient</th>
<th>Std. Error</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size: 321 Strata</td>
<td>56</td>
<td>6.2</td>
<td>9.1</td>
</tr>
<tr>
<td>F=45, $r^2 =0.22$</td>
<td>PHH</td>
<td>7.6</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>-57</td>
<td>24</td>
</tr>
<tr>
<td>Sample size: 346 Strata</td>
<td>51</td>
<td>5.6</td>
<td>9.3</td>
</tr>
<tr>
<td>F=47, $r^2 =0.22$</td>
<td>PHH</td>
<td>8.2</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>-44</td>
<td>22</td>
</tr>
</tbody>
</table>
2. Logistic Growth Model

In this model it is assumed that there is a saturation point in consumption, which means the point at which consumption no longer increases, even when income does. This assumption is based on studies carried out in Switzerland, where people with lower income do not necessarily have smaller amounts of durables. It is further assumed that at a certain income no increase in the consumption of durables takes place, i.e. the old goods are replaced by new ones.

A model which is widely used in biology as well as in economics to describe such a phenomenon is the logistic growth model. It goes back to Verhulst in 1837. A short description of it is found in Deaton & Muellbauer (1980) and Baccini & Bader (1996). The equations of the model are shown below.

\[ M(t) = R(t, M(t)) \]
\[ R(t, M(t)) = aM(t) - \beta(M(t))^2; \quad a, \beta > 0 \]
\[ M(0) = M_0 \]

where:
- \( t \) : income
- \( M(t) \) : consumption in kg as a function of income
- \( a(M(t)) \) : growth equation
- \( \beta(M(t))^2 \) : negative feedback due to saturation or competition

The solution leads to equation (4.6)

\[ M(t) = M_0 \cdot \frac{1}{\mu - (\mu - 1) \cdot e^{-\alpha \tau}}; \quad \mu = \frac{\beta M_0}{\alpha} \]

The parameters of the model are \( \alpha, \beta \) and \( M_0 \). The turning point of this function indicates at which levels of income the curve turns from growth to saturation. The turning point is defined as:

\[ t = 1/\alpha \cdot \ln((1 - \mu) / \mu) \]

a) Parameter Estimation

The parameters which fit best with the empirical data were estimated by using a nonlinear least squares regression. The method used was the Marquart algorithm. Average values of income of the different social strata were selected to estimate the model. Two approaches were chosen:

A1: First, the best estimation values for \( M_0, \alpha \) and \( \mu \) were calculated using the empirical data set. The results of this approach are shown in Figures C2 a, b, and c.

A2: Second, in addition to the empirical data set, a saturation value was defined. It was chosen to be the Swiss average consumption per capita. In the model this value corresponds to \( M_0 / \mu \). Therefore, only two parameters had to be estimated. The results are shown in Figures C2 d, e, and f.
Figure C2:
Graphs showing the model results of the parameter estimations of the approaches A1 (left) and A2 (right) for the different durables.

The main differences between the two approaches are (i) the income at which saturation is reached, (ii) the α-values indicating the steepness of the slope of the growth part of the model and (iii) the income of the turning point.

The graphs on the left side (a, b, and c) show a similar saturation income (between US$ 700 and 800/cap.year) for the different goods. The saturation incomes of the graphs on the right side are different for each goods group. While the saturation value is reached at an income of about US$ 2,000/cap.year for furniture, this seems to be the case for US$ 2,500/cap.year for vehicles and at an even higher income for electrical appliances.
The $\alpha$-values indicate the "steepness" of the growth part of the model. The $\alpha$-values for the estimation A1 are similar and about 10 times larger than the $\alpha$-values for the estimation A2. Thus, the consumption of strata with lower incomes will grow faster in A1 than in A2. The consumption of strata with higher incomes will almost stagnate in the case of A1, but will still grow in the case of A2.

Table C6:
Income at which the curves turn from growth to saturation (turning point).

<table>
<thead>
<tr>
<th></th>
<th>Turning point for A1 US$/cap.year</th>
<th>Turning point for A2 US$/cap.year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furniture</td>
<td>320</td>
<td>500</td>
</tr>
<tr>
<td>Elec. Appl.</td>
<td>370</td>
<td>1,060</td>
</tr>
<tr>
<td>Vehicles</td>
<td>430</td>
<td>890</td>
</tr>
</tbody>
</table>

The turning point for A1 lies for all goods groups at an annual income between US$ 300 and 450 per capita. For furniture and vehicles, the turning point of A2 lies at double the income of A1. For electrical appliances, the turning point of A2 lies at three times the income of A1. Thus, in A2, as shown in graphs C2 d to f, input growth continues up to a higher income than in A1.
3. Polynomial model

The third approach chosen to analyze the data was to define a polynomial function. The results obtained are (Table C7):

- Both terms, the quadratic and the cubed income term, are significant.
- Up to an income of US$ 500/cap.year the model shows results similar to those in the logistic growth model A1. The turning point and thus the saturation income is slightly lower at an income of about US$ 270/cap.year. However, with incomes higher than US$ 500/cap.year the model shows nearly exponential growth of stock. Thus, the model is not accurate for higher-income households.

Table C4:
OLS of electrical appliances vs income, income\(^2\), and income\(^3\) in urban households of Tunja.

**Equation:** \(\text{Stock} = \alpha_1 + \alpha_2 \text{Inc} + \alpha_3 \text{Inc}^2 + \alpha_4 \text{Inc}^3\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coefficient</th>
<th>Std. Error</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Income</td>
<td>0.74</td>
<td>0.36</td>
<td>2.1</td>
</tr>
<tr>
<td>Income(^2)</td>
<td>-0.0015</td>
<td>0.0013</td>
<td>-1.16</td>
</tr>
<tr>
<td>Income(^3)</td>
<td>1.11E-06</td>
<td>1.28E-06</td>
<td>0.9</td>
</tr>
<tr>
<td>C</td>
<td>56</td>
<td>29</td>
<td>1.93</td>
</tr>
</tbody>
</table>

Sample size: 321

\(F=18, r^2=0.14\)

4. Discrete Choice Model for Vehicles

According to Deaton and Muellbauer (1980), for many durables, such as cars, the stock of those goods is not a continous variable, as it might be for electrical appliances, but the situation of a discrete choice, i.e. it is the choice between ownership and nonownership.

One of the models that can be used to describe that relationship is given in the following equation:

\[
g(x) = \text{prob}(S = 1; x) = \int_{-\infty}^{x} f(\varepsilon; \mu, \sigma^2) d\varepsilon = \Lambda(x; \mu, \sigma^2)
\]

where \(\Lambda(x; \mu, \sigma^2)\) : cumulative distribution function of the lognormal distribution

For microeconomic data on individual households, such models can be estimated directly by the principle of maximum likelihood. One observes that as
average income increases, or the price of the durable falls, the proportion of owners will follow an increasing S-shaped or sigmoid curve (see also logistic growth). Thus, in any income group, some proportion will have sufficiently low thresholds to be owners, and this proportion will increase with increasing income groups. Eventually saturation is reached and ownership becomes unresponsive to changes in income and price.

The results of these estimations for the ownership of a car in Tunja are given in Table C5. The model estimates the probability that given a certain income the households will not own a car. The probability of owning a car is given as $1 - P_i$ (see equation below). The T-statistic shows that income is a significant explanatory variable for the selected model. The coefficient doubles if only the low income households are used to define the model.

Table C5:
Logit model for stock of vehicles in urban households in Tunja.

Table C5:
Logit model for stock of vehicles in urban households in Tunja.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coefficient</th>
<th>Std. Error</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size: 321</td>
<td>Income</td>
<td>0.0034</td>
<td>0.000914</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>-1.96</td>
<td>0.28</td>
</tr>
<tr>
<td>Sample size: 346</td>
<td>Income</td>
<td>0.0016</td>
<td>0.0005</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>-1.47</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Equation: $P_i = \frac{1}{1 + e^{-\alpha - \beta x_i}}$
Annex D: Subsystem Paper/Cardboard "to Communicate"

Paper and cardboard are solids with a lifetime smaller than one year. They are used mostly for the activities "to communicate" (e.g. printed matter) and "to transport" (packaging). In this Chapter the following question is of interest:

• What is the balance of paper and cardboard in Tunja?

The annex is divided into methods and results.

1. Methods

1.1 System Analysis

The system consists of 7 processes and 13 goods (Figure D1). Only the system border and the selected processes will be discussed.

System border

For the subsystem paper/cardboard, the system border is the urban part of the municipality of Tunja.

Figure D1: Subsystem paper/cardboard.
Selected Processes

The subsystem paper/cardboard consists of one supply process, three consumption processes and three waste management processes.

Supply:

The process Supply consists of the process paper supply, which is composed of big and small supply shops.

Consumption

The process Consumption consists of Households, Services and Commerce. Households consume paper and cardboard mainly in the form of printed matter and packaging materials. Services includes banks, educational institutions and hospitals and consumes printed matter. Commerce consists of companies which consume and distribute mostly cardboard.

Waste Management

The process Waste Management consists of the processes Acopio, Incineration and Landfill. Acopios are regional cooperatives which buy recyclable solids and which sell these to industries. The process Incineration is used only by Services for burning their confidential papers. Paper and cardboard which are neither recycled nor burned are disposed of in Landfill.

1.2 Collection and Measurement of Data

To quantify the subsystem paper/cardboard the following measurements were made (i) input into the supply shops, (ii) consumption of Households, Services and Commerce, (iii) stock in Households, (iv) recycled material in Acopios and (v) amount of paper/cardboard in household solid waste at Landfill. The data was collected and measured by two undergraduate students of the UNIBOYACA for their diploma thesis. Below the surveys made are described separately for the different processes.
Annex D: Subsystem Paper/Cardboard

**Paper-Supply.** The supply shops were divided into big and small suppliers according to the parameters listed in Table D1. The survey sample was chosen to be 100% for the big suppliers and about 25% for small suppliers.

Table D1:
Criteria to differentiate big and small suppliers in Tunja and sample size chosen.

<table>
<thead>
<tr>
<th></th>
<th>Big Suppliers</th>
<th>Small Suppliers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Area (m²)</strong></td>
<td>150-450</td>
<td>&lt;150</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>city center</td>
<td>other districts</td>
</tr>
<tr>
<td><strong>Number of workers</strong></td>
<td>&gt;3</td>
<td>1-2</td>
</tr>
<tr>
<td><strong>Store-room</strong></td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td><strong>Total in Tunja</strong></td>
<td>12</td>
<td>49</td>
</tr>
<tr>
<td><strong>Survey sample</strong></td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>

**Services and Commerce.** Two surveys were carried out to determine the amount of paper consumed in Services and Commerce. Services were divided into banks, governmental institutions, municipal services, private services, hospitals and educational centers which additionally were classified into 3 subgroups (big, medium, small) according to their number of employees. The survey sample chosen is shown in Table D2.

Commerce: The companies were divided into big, medium and small companies according to their turnover statistics. Preliminary studies showed that in spite of the large number of small companies, their paper/cardboard flux was less than one tenth the flux of other companies. Thus, these companies were not further studied. The survey sample chosen is shown in Table D3.

The following data were obtained in the survey: (i) the amount of paper/cardboard consumed, (ii) the origin of the consumed paper/cardboard (iii) the waste volume produced per year and (iv) the disposal of waste paper/cardboard.

Table D2:
Sample size for Services

<table>
<thead>
<tr>
<th>Institution</th>
<th>Total in Tunja</th>
<th>Survey sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banks</td>
<td>24</td>
<td>10</td>
</tr>
<tr>
<td>Governmental Institutions</td>
<td>101</td>
<td>12</td>
</tr>
<tr>
<td>Municipal services</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Private services</td>
<td>91</td>
<td>4</td>
</tr>
<tr>
<td>Hospitals</td>
<td>17</td>
<td>3</td>
</tr>
<tr>
<td>Educational Centers</td>
<td>107</td>
<td>9</td>
</tr>
</tbody>
</table>
Table D3:
Sample size for Commerce.

<table>
<thead>
<tr>
<th></th>
<th>Big</th>
<th>Medium</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total in Tunja</td>
<td>22</td>
<td>53</td>
<td>6,000</td>
</tr>
<tr>
<td>Survey sample</td>
<td>22</td>
<td>5</td>
<td>$3^1$</td>
</tr>
</tbody>
</table>

1: Sample of the preliminary study

**Households.** The current consumption and stock were measured in a household survey, where 10 households per stratum were surveyed.

**Acopio.** The surveys in the acopios were carried out twice. All the acopios were surveyed.
Annex D: Subsystem Paper/Cardboard

2 Results

The data obtained in the surveys was not sufficient to quantify and validate the subsystem paper/cardboard. In the following first results for paper are shown.

2.1 Mass Fluxes

The paper balance in kg/cap.year of Tunja is shown in Figure D2.

Figure D2:
Paper balance in the municipality of Tunja (kg/cap.year).

Tunja imports about 265 kg paper per capita and year. Paper-Supply accounts for about 76% of the imported paper, Services for the rest. Services consume about 80% of the total imported paper, with Household accounting for 17% and Commerce for only 3%. The consumption of Households in Tunja is in the same order of magnitude than the consumption in Swiss Households (Obrist and Baccini 1990).

The stock growth in Households is about 9 kg/cap.year, which is equal to the total stock growth of durables. The stock growth of paper/cardboard in Switzerland (including Services) at 2 kg/cap.y is about 5 times smaller than the stock growth of paper/cardboard in the Households of Tunja. Thus, the data for paper consumption and stock growth does not seem plausible.
For Services and Commerce a steady state was assumed, i.e. the amount of paper consumed corresponds to the amount of paper which is disposed of or burned.

The largest waste flux is the flux from Services to Incineration at 48%. The total flux to Landfill accounts for 37%, the flux to Acopio for 15%. The balance of the process Acopio shows that the input into this process is about 10 times larger than the output surveyed. The cause for this discrepancy could be (i) other recycling processes existing in Tunja were not taken into account (ii) the survey technique applied at the Acopios was not accurate enough or (iii) the input/output estimations and measurements in Households have a large error.

2.2 Conclusions

- It was not possible to determine and validate the paper/cardboard balance. The major error sources are: balance of Household and balance of Acopio.
- For paper, first results show that Services determine the paper balance in Tunja. Their way of disposal has a large influence on the amount of recycled paper.
- To improve the paper/cardboard balance and use it for early recognition it is necessary to (i) verify the balance of Household and (ii) complement the system with processes related to the recycling activities of the part of informal sector which do not interact with Acopio.
Annex E: Subsystem Energy "to Transport"

The subsystem energy analyzes the use of different energy sources for the activities "to transport" and "to reside and work". The following question is of interest:

- What is the energy balance of the municipality?

The annex is divided into methods and results.

1. Methods

1.1 System Analysis

The system consists of 6 processes and 10 goods (Figure E1). Only the system border and the selected processes will be discussed.

System border

For the subsystem energy, the system border is the urban part of the municipality of Tunja.

Figure E1: Subsystem energy.
Selected Processes

The subsystem energy consists of four supply processes and two consumption processes.

Supply

The process Supply consists of the processes Electricity Supply, Coal Supply, Gasoline Supply and Propane Supply, which supply the municipality with the corresponding products. Electric energy is generated by hydro- and thermal power in a relation 3 to 1.

Consumption

The process Consumption consists of Industry/Services and Households. To meet their energy needs, the brick industry uses hard coal and the other industries use electric energy. Services use mostly electricity. Households use gasoline for the activities "to transport" and electricity and gas for the activity "to reside".

1.2 Collection and Measurement of Data

To quantify the subsystem energy, the supply and some consumption processes were surveyed. The amount of energy imported by the supply companies (except coal) was surveyed from July to December 1993 (Table E1). The coal consumption was measured at the consumption processes. The supply of gasoline was cross-checked by estimating the amount of gasoline consumed according to Duenas (1988). The data was collected and measured by four undergraduate students of the UNIBOYACA as a part of their diploma theses.

Table E1:
Data source of the different energy carriers used in Tunja.

<table>
<thead>
<tr>
<th>Energy carrier</th>
<th>Data source</th>
<th>Data</th>
<th>Error Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>Empresa Electrificadora de Boyaca</td>
<td>Supply data from July to December and Nr. of subscriptions</td>
<td>——</td>
</tr>
<tr>
<td>Hard coal</td>
<td>Brick industries</td>
<td>Average coal consumption/month</td>
<td>20%</td>
</tr>
<tr>
<td>Brown coal</td>
<td>Restaurants</td>
<td>Average coal consumption/month</td>
<td>20%</td>
</tr>
<tr>
<td>Propane gas</td>
<td>Supply companies</td>
<td>Supply data from July to December</td>
<td>20%</td>
</tr>
<tr>
<td>Gasoline</td>
<td>Supply companies</td>
<td>Average supply/month</td>
<td>20%</td>
</tr>
<tr>
<td>Gasoline (cross-check)</td>
<td>DATT, Duenas, 1988</td>
<td>Nr of vehicles registered in Tunja, average consumption/vehicle</td>
<td>20%</td>
</tr>
</tbody>
</table>
2. Results

The data obtained in the surveys was sufficient to quantify but not to validate the subsystem energy. In the following first results are shown.

2.1 Energy Fluxes

Figure E2 shows the energy balance of Tunja. All the energy is imported. Households consume about 90%, Industry/Services only about 10% of the total energy. The low consumption of Industry reflects the low degree of industrial activity within the municipality. Gasoline, which is used for the activity "to transport" constitutes about 70% of the total energy consumed, with coal, electric energy and gas accounting for about 10% each. About 50% of the gasoline is used for private and 50% for public transportation [Martinez et al., 1994].

![Energy Balance Diagram]

Figure E2: Energy balance of Tunja in GJ/cap.y

The total energy consumption in Tunja is about half the average energy consumption in Colombia. While for Households the energy consumption is about equal, for Industry/Services the consumption in Tunja is only one tenth that in Colombia (Table E2). Oil products are the main energy source for Households, in Tunja as well as in Colombia. Coal is in both cases the main energy source for Industry.
Table 5.1: Energy consumption in Tunja and in Colombia.

<table>
<thead>
<tr>
<th></th>
<th>Colombia (1990), GJ/cap.y</th>
<th>Tunja, (1993), GJ/cap.y</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Industry/Services</td>
<td>Household</td>
</tr>
<tr>
<td>Oil products</td>
<td>3.2</td>
<td>9.3</td>
</tr>
<tr>
<td>Coal</td>
<td>17</td>
<td>0.9</td>
</tr>
<tr>
<td>Gas</td>
<td>5.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Electricity</td>
<td>1.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Total</td>
<td>27</td>
<td>12</td>
</tr>
</tbody>
</table>

Source: Martínez et al, 1994
International Energy Agency, 1993

Development of energy consumption in Colombia

The energy consumption in Colombia has augmented from 20 GJ/cap.y to about 40 GJ/cap.y during the last 15 years (Figure E3). Coal consumption has increased by about 70% and constitutes 50% of the total energy consumed. The consumption of oil products has increased by about 35%. The proportion of oil consumption on the total energy consumption decreased from 40% in 1975 to about 30% in 1990. Electricity and gas consumption for residential use has doubled during the last 15 years.

The per capita energy consumption in Colombia is still about one order of magnitude smaller than in Switzerland. The current pattern of energy consumption in Colombia compares to the energy consumption is Switzerland during the years 1950/1960 (Bundesamt für Statistik, 1995).
2.2 Validation

The energy balance of Tunja could be validated by (i) comparing supply data with consumption data of the municipality or (ii) by estimating the air pollution from the consumption data for the different energy sources to air quality measurements. To calculate air pollution, data concerning to fuel mix, coal type, the type of combustion processes and "air flows" are needed. This type of data was not available and could not be determined due to time, manpower and equipment constraints.

2.3 Conclusions

- It was possible to determine the energy balance. However, it could not be validated and used for early recognition due to insufficient data.
- First data show that in Tunja the largest energy flux is originated by Households and is due to the activity "to transport" (75%).
- To use the energy balance for early recognition of environmental impacts the data sets should be improved by data on (i) fuel mix, (ii) type of coal used, (iii) "air flows" and (iv) spot measurements of air quality.
Annex F: Mathematical Model for Solids

The subsystem solids can be described with 7 processes and 14 fluxes. Figure F1 shows the system for the model for solids showing the variables as used for the mathematical modeling.

\[ M^{(1)}, \ldots, M^{(7)} \] 7 stock change of balance volume
\[ F_{ip}^{(1)}, \ldots, F_{ip}^{(3)} \] 3 input fluxes
\[ F_{in}^{(1)}, \ldots, F_{in}^{(7)} \] 7 internal fluxes
\[ F_{op}^{(1)}, \ldots, F_{op}^{(4)} \] 4 output fluxes
Parameters

- $P_1, P_2$: 2 input fluxes into processes 2 and 3
- $P_3$: 1 total input flux $I_1^{(3)}$ into process 1
- $P_4, \ldots, P_{10}$: 7 internal transfer-coefficients
- $P_{11}, \ldots, P_{14}$: 4 output transfer-coefficients

Model equations

Balance equations

\[
\begin{align*}
F_1 &= I_p^{(3)} + A_{41} - A_{14} - A_{16} = F_p^{(3)} + P_5 \cdot I_{\text{tot}} - P_4 \cdot P_3 - P_6 \cdot P_3 \\
\vdots \\
F_7 &= A_{37} - 0_{7} = P_{10} \cdot P_2 - P_{12} \cdot I_{\text{tot}} 
\end{align*}
\]

Given rates for balance volume

\[
\begin{align*}
F_8 &= \dot{M}^{(2)} - 0 \\
F_9 &= \dot{M}^{(3)} - 0 \\
F_{10} &= \dot{M}^{(4)} - 0 \\
F_{11} &= \dot{M}^{(5)} - 0 \\
F_{12} &= \dot{M}^{(7)} - 0
\end{align*}
\]
Annex F: Mathematical Model for Subsystem Solids

Defined Inputs

\[ F_{13} = I_p^{(2)} - I_2 = F_p^{(2)} - P_1 \]
\[ F_{14} = I_p^{(3)} - I_3 = F_p^{(3)} - P_2 \]
\[ F_{15} = I_{tot}^{(5)} - \lambda_1 - A_{41} = F_p^{(3)} - P_5 * l_{tot}^{(4)} \]

Input - Output equations

\[ F_{16} = A_{14} - k_{14} * l_{tot}^{(5)} = F_{in}^{(3)} - P_4 * P_3 \]
\[ F_{17} = A_{16} - k_{16} * l_{tot}^{(5)} = F_{in}^{(3)} - P_6 * P_2 \]
\[ F_{18} = A_{26} - k_{26} * l_{tot}^{(2)} = F_{in}^{(6)} - P_8 * P_1 \]
\[ F_{19} = A_{36} - k_{36} * l_{tot}^{(3)} = F_{in}^{(6)} - P_9 * P_2 \]
\[ F_{20} = A_{37} - k_{37} * l_{tot}^{(3)} = F_{in}^{(7)} - P_{10} * P_2 \]
\[ F_{21} = A_{41} - k_{41} * l_{tot}^{(4)} = F_{in}^{(2)} - P_5 * l_{tot}^{(4)} \]