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Addressing water resources concerns in forest management models. A case study in Portugal

Wesley Hilebrand

Mestrado em Investigação Operacional

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Dissertação orientada por:

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"Everything should be as simple as it is, but not simpler".

Albert Einstein

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Acronyms

FRC: Forest Research Center, at School of Agriculture from the Technical University of Lisbon.

GP: Goal Programming.

MCDA: Multi-Criteria Decision Approach.

MOP: Multi-Objective Programming.

NA: Non-Attributed.

NPV: Net Present Value.

OR: Operations Research.

SEV: Soil Expectation Value.

Addressing water resources concerns in forest management models. A case study in Portugal

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Summary

Water is one of the most important resources in forests. Forest management has a direct impact on water quality and its availability. Thus, forest management planning should be carefully accomplished. This study addressed forest management models incorporating water resources indicators. A strategic forest planning was carried out, considering *Eucalyptus globulus* Labill. species in a forest situated in Central Portugal.

The hypothesis of the present study is that the runoff reduction reduces the financial indicator. Pareto efficient curve and metrics to link a reference point to the nearer solution were presented. For that, a general linear goal programming structure was proposed, from which five models were derived: two financial-based models; two models to minimize extreme runoff events; and one model to minimize the total runoff. Equations for annual runoff estimations were fitted.

Results confirmed that the runoff reduction affects SEV. It was further verified that: SEV was decreased by the inclusion of constraint on non-decreasing timber flows; the runoff was higher when more timber was harvested; harvesting postponement and a smaller harvested area was noticed when runoffs were minimized. Substantial reduction of runoff cost only 1.44 Euro m^{-3}, but its minimization raised it to 5.40 Euros m^{-3}. The metrics indicated that solution should be chosen close to the ideal point at a lower cost, if the decision maker assigns the same importance either to financial indicator or to runoff. The same results were obtained among models that minimize extreme runoff events.

Key-words: linear programming, goal programming, forest management models, runoff, *Eucalyptus globulus* Labill.

Inclusão de variáveis hídricas nos modelos de gestão florestal. Caso de estudo em Portugal

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Resumo

As florestas podem fornecer recursos valiosos para os seres vivos, tais como: madeira, habitat, oportunidade de recreio, beleza visual, frutas, flores, cascas, ramos, folhas, sequestro de carbono e fauna. Contudo, um recurso natural pode ser considerado o mais relevante para a humanidade: a água. A sobrevivência dos seres vivos depende da qualidade e disponibilidade da água, os quais podem ser directamente afectados pela gestão florestal. Desta forma, o plano de gestão florestal e as operações inerentes devem ser cuidadosamente implementados. Este estudo tratou da optimização da gestão florestal, tendo em conta a protecção dos recursos hídricos.

Em Portugal, 19% da área florestal é ocupada pela espécie *Eucalyptus globulus* Labill., totalizando uma área de 647.000 ha. Esta é uma espécie relevante para produção de pasta de papel e papel em Portugal, em que 90% e 77% são destinados a exportação, respectivamente; o que a torna numa espécie interessante para casos de estudo.

A água da chuva que chega à rede hidrográfica é resultante do escoamento, o qual pode transportar sedimentos e prejudicar a qualidade da água. Há estudos que indicam um aumento de escoamento em períodos imediatamente seguintes ao corte de eucaliptos. Adicionalmente, outros estudos indicam que o volume de madeira em pé no eucaliptal está negativamente correlacionado com o escoamento.

Na literatura, encontram-se propostas de investigação sobre optimização de volume de madeira e escoamento, especialmente através de programação por metas. No momento presente, verificam-se poucos trabalhos a tratar deste assunto, provavelmente devido a dados inexistentes e dificuldades na modelação do sistema floresta-água, tendo em conta efeitos temporais e espaciais. Apesar de haver alguns estudos a tratar deste tema, estes foram aplicados a locais em condições diferentes daquelas verificadas em Portugal.

Este estudo tem como objectivo optimizar o valor esperado do solo e recursos hídricos, em uma floresta de eucaliptos situada no centro de Portugal. Para tal, um modelo geral de programação por metas é proposto, do qual cinco modelos são extraídos.

A principal hipótese do estudo é que uma redução de escoamento afecte o valor esperado do solo. O fundamento desta hipótese é que, se uma redução de escoamento for possível, isso poderá exigir um menor volume de madeira cortado, o que por sua vez poderá reduzir o valor esperado do solo. Uma solução diferente entre os modelos que minimizam o escoamento anual máximo e aumento máximo de escoamento é esperada. Acredita-se que a inclusão de restrições para os fluxos não-decrescentes de madeira reduza o valor esperado do solo. São esperados um maior volume de escoamento, caso um maior volume de madeira seja cortado, bem como uma menor área cortada, quando o escoamento total é minimizado.

Os dados da área de estudo foram obtidos de um sistema de gestão de base de dados fornecido pelo Centro de Estudos Florestais (CEF), Instituto Superior de Agronomia da Universidade Técnica de Lisboa. A espécie tratada foi *Eucalyptus globulus* numa floresta com 11.873 ha de dimensão, a qual foi dividida em 1.000 povoamentos puros e regulares.

A madeira cortada foi o produto de venda considerado, enquanto o corte raso foi o método de corte aplicado. Os custos estiveram relacionados com as actividades florestais consideradas: plantação, corte, monda, limpeza de matos, fertilização, remoção das toiças. O horizonte de planeamento foi de 21 anos, em que a análise foi feita anualmente. O estudo incluiu 49.872 prescrições, cada uma representou um conjunto de actividades florestais implementadas ao longo dos anos. As prescrições foram feitas pelo CEF. Até 3 rotações foram consideradas, enquanto a idade possível de corte pertenceu ao intervalo [9, 13] anos.

Dois modelos empíricos para determinar o escoamento foram ajustados: um para o alto-fuste e outro para as talhadias. O método dos mínimos quadrados foi aplicado. A variável dependente foi o escoamento anual (mm), enquanto as variáveis independentes consideradas foram: precipitação anual (mm) e idade das árvores (em anos).

Um modelo geral de programação linear por metas foi proposto, o qual incluiu na função objectivo o valor esperado do solo, o escoamento total, o escoamento anual máximo e o aumento anual máximo de escoamento. Como restrições apresentaram-se aquelas relativas a: afectação total da área dos povoamentos às prescrições, fluxos anuais de madeira não-decrescentes, fluxos anuais de lucro não-decrescentes, escoamento anual máximo, aumento anual máximo de escoamento, escoamento total e de não-negatividade das variáveis. As variáveis de contagem apresentadas no modelo estiveram associadas a: volumes de madeira cortados anualmente, lucros anuais, escoamentos anuais.

Cinco modelos foram obtidos do modelo geral acima referido. Cada um representa uma estratégia de gestão florestal e seus resultados não devem ser directamente comparados. O modelo OR1 visou maximizar o valor esperado do solo. OR2 fez o mesmo que o anterior, mas restrições sobre fluxos de madeira não-decrescentes foram adicionadas. OR3 tratou da minimização do escoamento total. OR4 minimiza o escoamento anual máximo, enquanto o modelo OR5 tratou da minimização do aumento anual máximo de escoamento.

A construção de um programa para obter formulações foi necessária. Este importa dados, formula o problema e exporta-o em formato texto. Os programas informáticos utilizados neste estudo foram: ArcGIS para editar o mapa da área de estudo; CPLEX para resolver os problemas de investigação operacional; Microsoft Access 2007 para guardar os dados e cruzá-los de forma a obter os coeficientes; Microsoft Excel 2007 para ajustar os

modelos de escoamento e organizar soluções; e Visual Basic.NET 2008 para construção do programa de formulação referido no início do parágrafo.

Os resultados apresentaram valores óptimos dos modelos, valores anuais para volume de madeira cortada, lucro, escoamento e idade da floresta ponderada pela área. A área cortada foi apresentada por ano de corte, rotação e modelo. A curva de soluções não-dominadas entre o valor esperado do solo e escoamento total foi apresentada, bem como os valores óptimos mais próximos do ponto de referência (ponto ideal), segundo as métricas consideradas. Uma análise pós-óptima foi realizada através da relaxação das restrições de volume de madeira cortada e lucro, separadamente.

A hipótese do estudo foi confirmada. A curva de soluções não-dominadas indicou que o escoamento total pode ser reduzido sem significativas reduções do valor esperado do solo. No entanto, a minimização do escoamento total provocou uma redução substancial deste indicador financeiro. O custo passou de 1,44 Euros m^{-3} para 5,40 Euros m^{-3}. As métricas consideradas indicaram que soluções próximas ao ponto ideal devem ser escolhidas ao menor custo, caso o agente de decisão atribua a mesma importância quer ao valor esperado do solo quer ao escoamento total.

Algumas limitações podem ser identificadas no estudo. O valor esperado de solo incluiu volumes de madeira sobrestimados. Não se teve em conta os tipos de solo, efeitos espaciais e temporais para estimação do escoamento. O número de dados para estimação deste foi reduzido.

Como esperado, a introdução das restrições de fluxos de madeira não-decrescentes reduziu o valor esperado do solo em 7%. O escoamento total foi maior quanto se cortou mais madeira, mas isso não ocorreu com baixas precipitações e no último ano do horizonte de planeamento. Os resultados dos modelos que incorporam preocupações hídricas sugeriram um adiamento de cortes, enquanto o modelo que minimiza o escoamento total cortou a menor área. Contudo, os modelos que minimizam o escoamento anual máximo e aumento anual máximo de escoamento produziram os mesmos resultados, o que não era

esperado. A análise pós-óptima indicou um menor volume total de escoamento, quanto mais relaxadas estivessem as restrições de fluxos não-decrescentes de madeira ou lucro.

O modelo que minimiza o escoamento total forneceu valores óptimos dos modelos relativos aos eventos extremos de escoamento. Contudo, minimizar o escoamento total não correspondeu a minimizar o valor esperado do solo.

Seria valioso se futuras investigações estruturassem melhor o problema e melhores indicadores de qualidade e quantidade da água fossem incorporados em modelos de gestão florestal. Equações que tivessem em conta tipos de solo, bem como efeitos temporais e espaciais seriam determinantes para uma melhor compreensão do efeito da gestão florestal nos recursos hídricos. Mais estudos que incluíssem modelos que minimizam o escoamento anual máximo e aumento anual máximo de escoamento seriam úteis para confirmar se são modelos que produzem resultados iguais.

Palavras-chave: Programação linear, programação por metas, modelos de gestão florestal, escoamento, *Eucalyptus globulus* Labill.

1. Introduction

Many products and services delivered by forests are valuable for living beings, such as: timber, habitat, opportunities for recreation, water, visual beauty, fruits, flowers, bark, branches, leaves, carbon fixation, wildlife, and flora. However, one of those products is probably the most important for worldwide: water. The survival of living beings depends on water quality and its availability. If forest operations or forest management planning is not carefully carried out, they may be impaired.

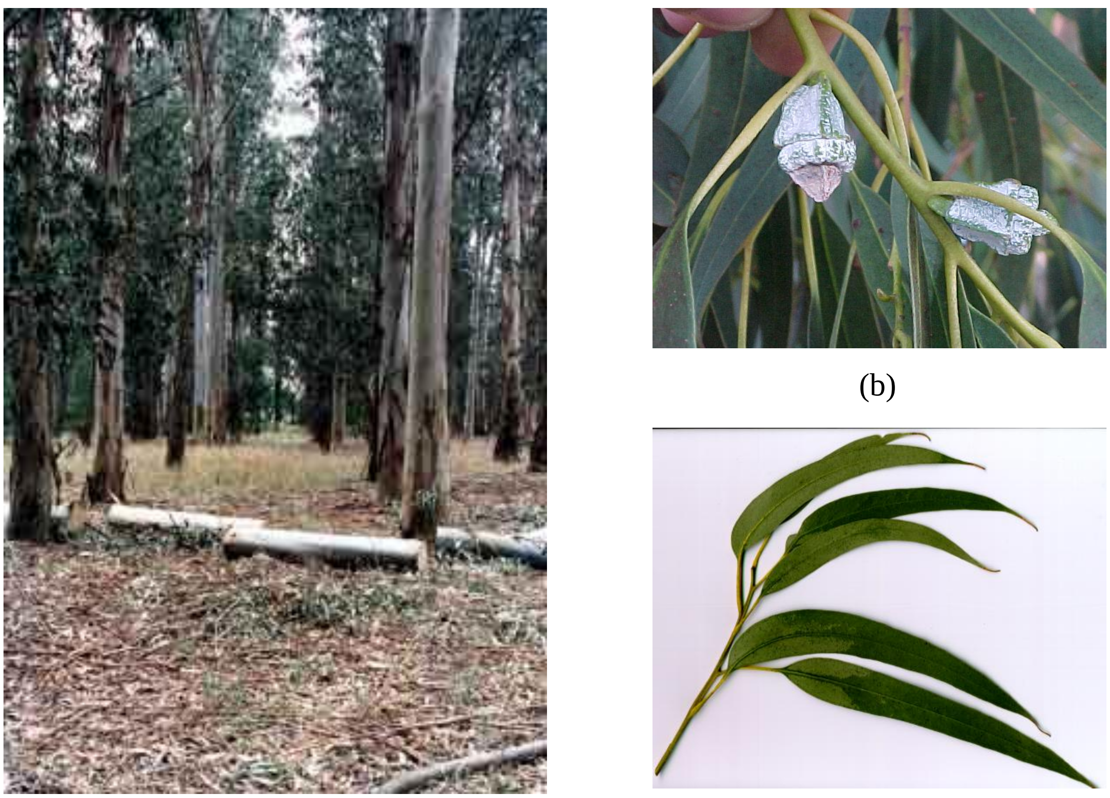
In this thesis, operations research is applied to forestry and water resources. As such, some basic forest and hydrologic concepts are essential to comprehend the study. Next, they are presented, and objectives and hypothesis are introduced after that.

1.1. Concepts

Eucalyptus globulus is a fast-growing tree species: its mean annual increment is no less than 15 m^3 per hectare, and it is harvested in less than 20 years (Cossalter and Pye-Smith (2003), in Jewitt (2005)). It can reach a height of 60 meters and a diameter at breast height - 1.30 meters above the ground - of 2 meters. Various products can be obtained from that, such as: timber, pulp wood, leaves, bark, and flowers.

In forest management, *rotation* is the number of years between the establishment of the stand and the final harvest (Bettinger, et al. 2009, 107). Normally, Eucalypt is harvested from 10 to 15 years old, but it can be earlier in favorable growing conditions (Silvicultores, Ambientes e Recursos Naturais, Lda. 2001, 33). Coppice system involves reproduction by stool of shoots or suckers (Matthews 1989, 190). After trees are harvested, several shoots normally resprout on the stool. When the stand reaches three years of age some of the sprouts are cut off, leaving 1 or 2 sprouts per stool to continue its growth. Three to four rotations are possible to implement from an economic point of view, after that, the productivity significantly declines (David, et al. 1994).

The forest area may be organized by relatively small portions of land, each one representing a homogeneous and contiguous area, which originates the *management units* (Marques, Marques and Borges 1999, 58). Management unit and stand will be used as synonymous in this study. A stand is even-aged if all trees have the same age; if not, it is an uneven-aged stand. Pure stand has at least 75% of the area occupied by one species; when this is not verified and more than one species exists, mixed stand arises. Management alternatives or prescriptions are composed by silvicultural operations implemented over time, which originate costs, revenues or inventory changes.



(a) (b) (c)

Figure 1 – *Eucalyptus globulus*: (a) forest; (b) fruits; and (c) leaves[1]

[1] Pictures were supplied by FRC.

The SEV represents the difference between revenues and costs from a prescription repeated perpetually, discounted to the actual moment (Bettinger, et al. 2009, 40). Reader is recommended to consult Bettinger, et al. (2009) for an introduction of forest management.

By another side, this study deals with hydrologic terms, which are presented next. They are based on Brooks, et al. (1991).

Before rainfall touches the surface, interception may occur. *Canopy interception* is performed by tree leaves, whilst *litter interception* is accomplished by leaves and other materials on the surface. Interception reduces runoff by absorbing part of the rainfall and improving the infiltration capacity of the soil.

When the rainfall rate exceeds the infiltration capacity, the water that flows over the soil surface is called *surface runoff*. *Subsurface flow* is part of the precipitation that infiltrates into the soil, yet arrives at the stream channel over short enough time periods. The term *channel interception* corresponds to the rainfall that falls directly on the stream channel and saturated areas. Surface runoff, subsurface runoff and channel interception represent the *quick flow*. However, *groundwater* is the water that achieves a deep level in the soil and occurs in voids between soil and rock particles in the zone of saturation. That subsurface flow that arrives late at the stream channel and the groundwater correspond to the *delayed flow*. In this thesis, the full quantity of runoff (quick flow + delayed flow) was addressed.

Nonetheless, the evaporation from soils, plant surfaces, and water bodies, together with water losses through plant leaves is called *evapotranspiration*. The runoff may be written as follows (Alves, Pereira e Silva 2007):

$$\text{Runoff} = \text{Rainfall} - \text{Evapotranspiration} \quad (1)$$

Figure 2 introduces the relationships between the definitions presented above. The blue rectangles (dashed border line), and those in green (thicker border line) are in agreement with concepts from Jewitt (2005) – blue and green water. Evaporation, evapotranspiration, delayed and quick flows are the outputs of that flowchart, while rainfall is the input.

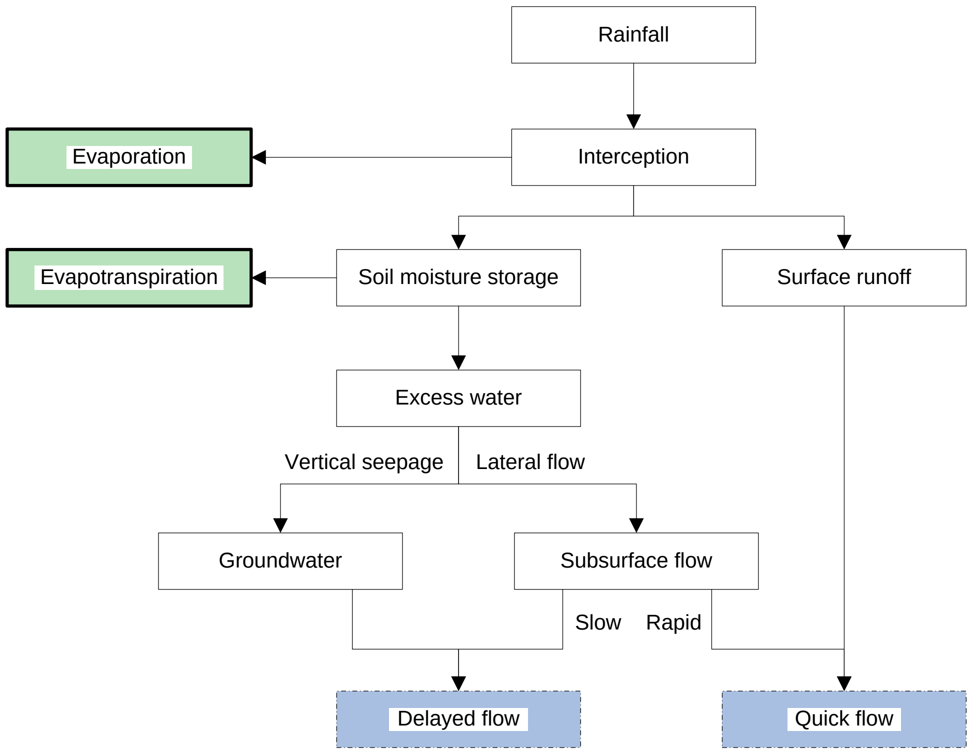


Figure 2 – Runoff relationships, adapted from Brooks, et al. (1991, 340).

1.2. Objective and hypothesis

In this study, the rationale is to harvest timber with a minimum runoff, since the harvest in the studied area may increase erosion and impair water quality. However, it is not presupposed that runoff is negative for the ecosystem. In other areas, it may be more interesting to maximize runoff (water availability) while ensuring a certain level of standing trees (i.e. to avoid excessive erosion).

In Portugal, 19% of forest land is occupied by *Eucalyptus globulus* Labill., totaling an area of 647,000 ha. It is an essential species for pulp wood and paper production in Portugal, whereby around 90% and 77% are exported, respectively (Alves, Pereira e Silva 2007, 20). This becomes an attractive species to study.

Due to interest rates, timber volume in one year produces higher present value than this same volume obtained in the next years (considering the same price and a discount rate greater than zero). By another side, the growth of trees along years originates a tradeoff: obtain less timber volume now with higher discounted price or greater quantity later with smaller discounted price (Bettinger, et al. 2009, 105).

A simplified diagram about the effect of harvest on runoff, and its impact on living beings, investor and society are presented by Figure 3. In this thesis, the harvest was considered a manageable variable. The signal beside to arrows is related to the cause-effect sense (e.g. timber increases with harvest, but the runoff retention capacity of the stand decreases with it). Ultimately, an integrated high level of harvest and rainfall can cause a higher SEV, but can impair the capacity of living being to survive, and can cause substantial material losses.

Some authors propose a runoff and timber optimization study (Samraj, et al. 1988), especially by goal programming (Silva, et al. 2010). At the moment, studies addressing that matter are scarce, probably because of non-existent data and the real difficulties in modeling the forest-water system over time and space. Although some studies focusing timber-water optimization have been performed, they were conducted in different conditions (e.g. climate and soil features) from those in Portugal.

In this sense, the present study aims to optimize financial forest values and water resources in a Portuguese eucalypt forest. Linear programming models were used for this purpose. Models to determine runoffs were fitted. Further, a post-optimal analysis was carried to identify the effect of relaxing major constraints on runoff. This thesis is based on Amaral (2002); however, annual rainfalls, and new mathematical models were considered.

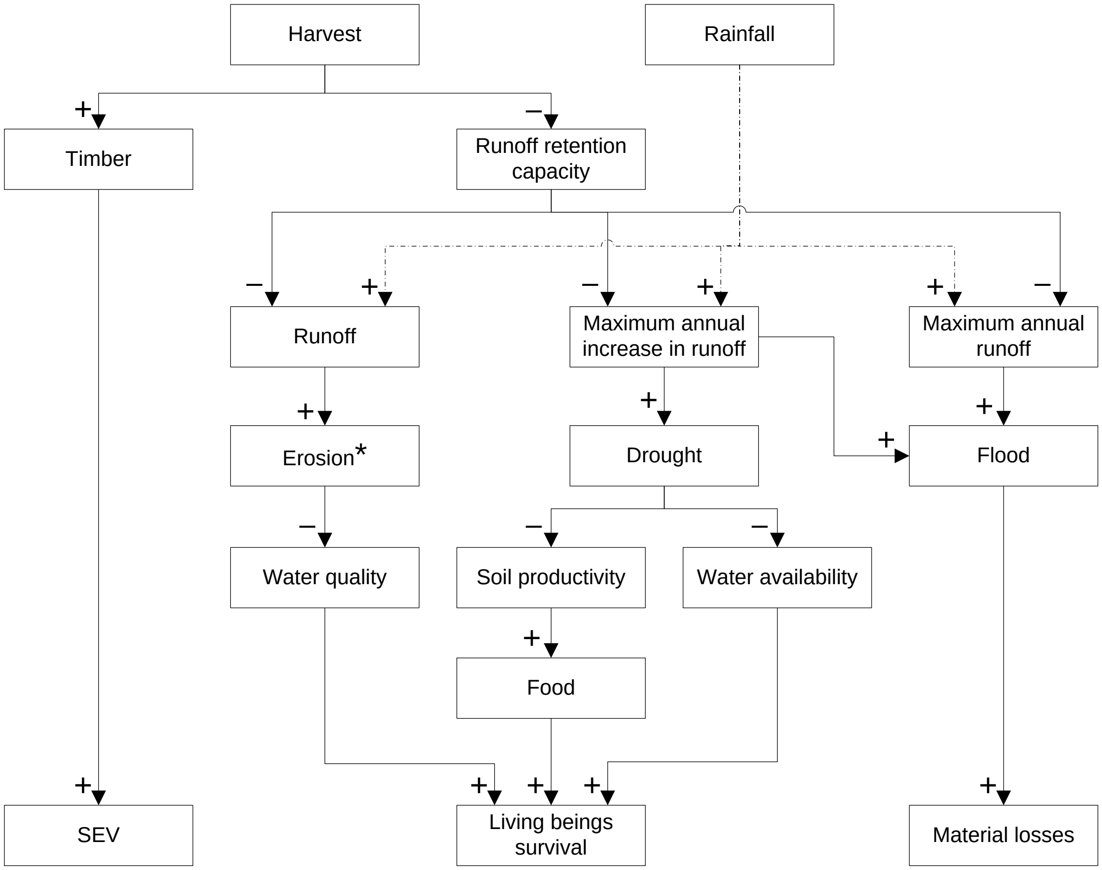


Figure 3 – The effect of harvest on living beings, investors, and society

*Harvest may not be associated to higher erosion, since it depends on soil type, slope, and harvesting methods. See, for example, Neary, et al. (2010).

Some studies (e.g. Sharda, et al. (1998)) indicated that runoff increase occurs in the first years immediately after harvesting eucalypts, and by another side, runoff is negatively correlated to eucalypts age (Samraj, et al. 1988). Accordingly, a higher runoff is believe to occur in this study after harvesting timber.

The major hypothesis in this study is that the runoff reduction decreases the financial indicator. It is also expected that: 1) Minimization of the maximum annual runoff to produce a different solution from that of minimization of the maximum annual increase in runoff; 2) The inclusion of constraints on non-decreasing timber flow to reduce SEV when it is maximized; 3) A larger runoff volume to be generated, if a greater timber volume is harvested; 4) A smaller area to be harvested when total runoff is minimized.

This thesis is organized in the following manner:

1. Introduction: the basic concepts about forestry and hydrology are presented as well as the objectives and hypothesis of the study.
2. Literature review: aims to review critical points of current knowledge in operations research applied to forestry.
3. Material and methods: it presents what was studied and how the work was performed. The following information can be found: study area, income and costs values, forest activities, time horizon, management alternatives, software, SEV, runoff estimation, and formulations.
4. Results: this section comprehends the outcome of the study, e.g. optimal values for SEV, harvested timber and runoffs; non-dominant solutions curve. At the end of this section, a post-optimal analysis is carried out.
5. Discussion: arguments, criticism against the results, and proposals for future research are presented.
6. Conclusions: resume the contribution accomplished by this study.

2. Literature review

Operations research tools have been applied in many forest management problems, including those related to harvest scheduling, forest biodiversity conservation, forest sustainability, forestry industry, risk and uncertainty (Diaz-Balteiro and Romero 2008). Various model types have been addressed, such as: non-linear programming (e.g. Haight, Monserud and Chew (1992)), linear programming (e.g. Buongiorno, et al. (1995)), multi-objective programming (e.g. Weng, Huang and Li (2010)), lexicographic goal programming (e.g. Silva, et al. (2010) and stochastic programming (e.g. Ferreira, Constantino and Borges (2011)).

In the field of linear programming addressing economic and water resources concerns, some studies have been successfully carried out. Baskent and Keles (2009) formulated nine linear models to maximize NPV from harvested timber, water production and carbon sequestration in Turkey. About 1,126 ha of spruce and beech forest were subject to harvesting scheduling. The mean annual precipitation was 719.7 mm. A function for runoff estimation was considered, where the basal area was the explanatory variable. Likewise, Rowse (1998) aimed the maximization of NPV from harvested timber and water production in Canada, by means of 8 different linear models, having into account stumpage fees, water value, harvest smoothing constraints, the size of blocks harvested and the road network construction. A forest with spruce, lodgepole and Douglas fir in an area of 271,736,000 ha was considered.

Amaral (2002) proposed 3 linear programming models to maximize profit having water concerns in Brazil. The forest was composed by Eucalypt trees, with an area of 8,007 ha. The mean annual precipitation was 1,562 mm. A statistical model for runoff was fitted, whereas the standing timber was the explanatory variable. The first linear programming model had as major restriction a non-decreasing timber flow; the second one added a constraint on non-increasing runoff flow; the third formulation had a goal programming structure, whereby a deviation from a runoff threshold is minimized.

Other authors concentrated on water quality rather than in quantity. Eriksson, Löfgren and Öhman (2011) proposed a linear programming model to maximize NPV from timber harvesting. The quantity of nitrogen, phosphorus, methyl mercury and dissolved organic carbon was restricted to a pre-established level. This study took into account the EU Water Framework Directive. Naturally, that threshold should not be too ambitious because this would lead to an infeasible problem. That study was conducted in Sweden, in three sub-catchments. The total area reached 238 ha occupied mostly by Norway spruce and Scots pine.

Other studies focused on non-linear programming models. The minimization of the cost of ponds network construction has been addressed by identifying the optimal number, location and size of ponds, restricting water quality to a minimum level. Zhen, Yu e Lin (2004) applied the scatter search to solve the problem. Travis and Mays (2008) used dynamic programming for optimization, while Perez-Pedini, Limbrunner e Vogel (2005), and Harrell and Ranjithan (2003) made use of the genetic algorithm. See Labadie (2004) for a review of operations research models and methods applied to multi-reservoir systems.

In stochastic programming, the computational complexity may lead to untreatable problems (Labadie 2004). However, some studies successfully addressed that issue in a stand level management. Pukkala and Miina (1997) employed a multi-objective programming to optimize SEV, growing stock value and scenic beauty score in Finland, where Scots pine and Norway spruce were considered. They applied Hooke and Jeeves algorithm and took into account the time preferences, risks and risks preferences. Ferreira, Constantino and Borges (2011) and Garcia-Gonzalo, Pukkala e Borges (2011) made use of Maritime pine stand from Leiria National Forest in Portugal in their studies. The former developed a new stochastic dynamic programming approach, which was applied to a SEV maximization problem, considering wildfire risk, damage, and the cost of fuel treatments. Fuel treatments were possible to be implemented for mitigation of the wildfire risk. The latter applied the Bright and Price approach to identify the prescription that maximizes soil expectation value, taking into account the fire risk and damage, and thinnings. Fuel treatments were possible to be implemented over years to mitigate the fire damage by a cost. The Hooke and Jeeves and other direct search methods were used to find the optimal solution.

Actually, the multi-use perspective has gained more importance in forest management planning. The reason may be associated to the necessity of the decision maker to take into account several factors before the decision making, such as: timber supply, profit, water resources, carbon sequestration, sustainability, recreation; and on the other hand, new mathematical models and methods contributed to its greater use. Diaz-Balteiro and Romero (2008) showed that the use of MCDA has substantially increased in forestry since the last quarter of the past century. Besides that, it may even be considered essential to solve problems where several conflicting and related variables are faced (Silva, et al. 2010). See Mendoza and Martins (2006) and Diaz-Balteiro and Romero (2008) for an extensive review about MCDA applied to forestry.

However, as Baskent and Keles (2009) stressed, MCDA may require information on the decision-maker's preferences in the form of weights, priorities, and targets for each management objective. These are related to *a priori* methods, which can be listed in: minimum distance to a reference point method; method based on utility function; lexicographic method; and goal programming. Another option may be to use *a posteriori* methods to support the decision making. They are classified in: 1) Approximated methods: weighting method; constraints method; non-inferior solutions estimation (NISE); and 2) Exact methods that are based on simplex method and extensions. The *a posteriori* methods are instrumental to design the Pareto efficient curve among conflicting objectives. This would help the decision maker to decide which level of each criteria wants to achieve. Nonetheless, the progressive or interactive methods may be further valuable, since they allow decision maker to get knowledge on the feasible region, and thus converges progressively to the desired solution. Some of the progressive or interactive methods are: Step method (STEM); Zionts e Wallenius; TRIMAP; Interval Criterion Weights; Pareto Race (Clímaco, Antunes e Alves 2003, 122; 126; 141).

The terms MOP and GP may be claimed with different interpretations. Taha (2007) described GP as a mathematical programming where multiple objectives are considered, and presented: 1. The weights method, comprehending “a single objective function that is formed as the weighted sum of the functions representing the goals of the problem”; and 2. The preemptive method, which “starts by prioritizing the goals in order of importance. The model is then optimized, using one goal at a time so that the optimum value of a higher-priority goal is never degraded by a lower-priority goal”. Hillier and Lieberman (2001) defined goal programming similarly to Taha (2007), and named those two methods as non-preemptive and preemptive methods, respectively. However, Diaz-Balteiro and Romero (2008) differentiated GP from MOP in their review, while Romero (2001) referred to MOP as the Weighted Goal Programming method, but considered GP in an integrative way as mentioned before. Thus, attention should be taken to the concepts used in studies wherein several objectives are optimized in a single model.

Silva, et al. (2010) applied lexicographic goal programming to optimize economic and environmental values in a Chilean forest. A tactical forest planning was made for an area of 4,087.2 ha composed by *Pinus radiata*. The economic indicator comprised net present value, while the latter encompassed soil erosion, contamination of water resources and visual impact of harvesting. The Analytic Hierarchy Process was used to determine the weight factor of different criteria, and a protection index was derived from the solution and the weights. The selling products considered in this study were exportable timber, sawtimber, and pulp timber. The type of harvesting machinery as well as road construction was also taken into account.

Weng, Huang and Li (2010) built a multi-criteria decision support system for water resources planning. A basin with an area of about 31,880 ha located in northern China was used as a case study. The average annual precipitation was 548 mm. Their model comprised three indicators in the objective function: gross domestic product, biological oxygen demand and total crop. The first one represents the economic indicator; the second one is a water quality indicator, while the last one is associated to the quantity of food available to population. The system presented in that study is based on scenarios; they were related to water saving, environment protection and water transfer between regions.

At present, forest management decisions are frequently made in group. In this case, decision making may become impossible owing to conflicting goals. Mendoza and Martins (2006) focused the participatory modeling as a plausible alternative to get a satisfactory solution shared by all participants. Furthermore, they pointed out that Soft-OR may be appropriate for problem structuring, transparency and understanding, and may overcome some drawbacks from the conventional OR approaches. See Mendoza and Prabhu (2005) for a real application of participatory modeling.

The approaches more frequently employed are Lexicographic GP ones, the second more commonly used is MOP, and finally, the MINMAX Goal Programming (i.e. Romero (2001); Mendoza and Martins (2006)). The use of Lexicographic GP and MOP has decreased probably because of new methods have been developed (Diaz-Balteiro and Romero 2008). Romero (2001) clarified the connectivity between several GP models and proposed a general optimization structure, which offers the advantage of being easily converted to various model types. However, in a broader context, Kangas and Kangas (2002), in Mendoza and Martins (2006), underlined that methods and results are not necessarily directly comparable.

The objective functions formulated in forest management problems have included mostly a financial indicator: SEV (e.g. Pukkala and Miina (1997)) or net present value (e.g. Rowse (1998); Baskent and Keles (2009)). Even so, other types of indicators can be found in the objective function, as mentioned before in several studies.

Similarly, constraints of various types have been considered in forest management models. Some studies have introduced harvest smoothing constraints (Rowse 1998). A pre-defined value set to the constraints' right hand side has been used to assure that: a minimum timber volume is harvested (Baskent and Keles 2009), the concentration of chemical substances does not surpass a maximum value (Eriksson, Löfgren and Öhman

2011), demand is satisfied (Silva, et al. 2010), a minimum number of trees exists for timber harvesting, or to ensure visual quality and deer habitat (Haight, Monserud and Chew 1992). Constraints to guarantee physical relationships were also considered, e.g. area harvested cannot exceed the available forested area; to ensure that products are complementary (Rowse 1998); and to achieve sustainability, diversity and profitability (Buongiorno, et al. 1995). Accounting variables are used in the mathematical formulation (e.g. Baskent and Keles (2009), Weng, Huang and Li (2010)) to facilitate the understanding of the formulation, by isolating extensive and complicated calculations from the central ideas.

3. Material and methods

3.1. Study area

The geographical and silvicultural information used in this study was obtained from a relational database management system (Microsoft Access 2007) designed by the FRC. The species considered was *Eucalyptus globulus* Labill. in a forest situated in Central Portugal; it was named as Globland (Figure 4).

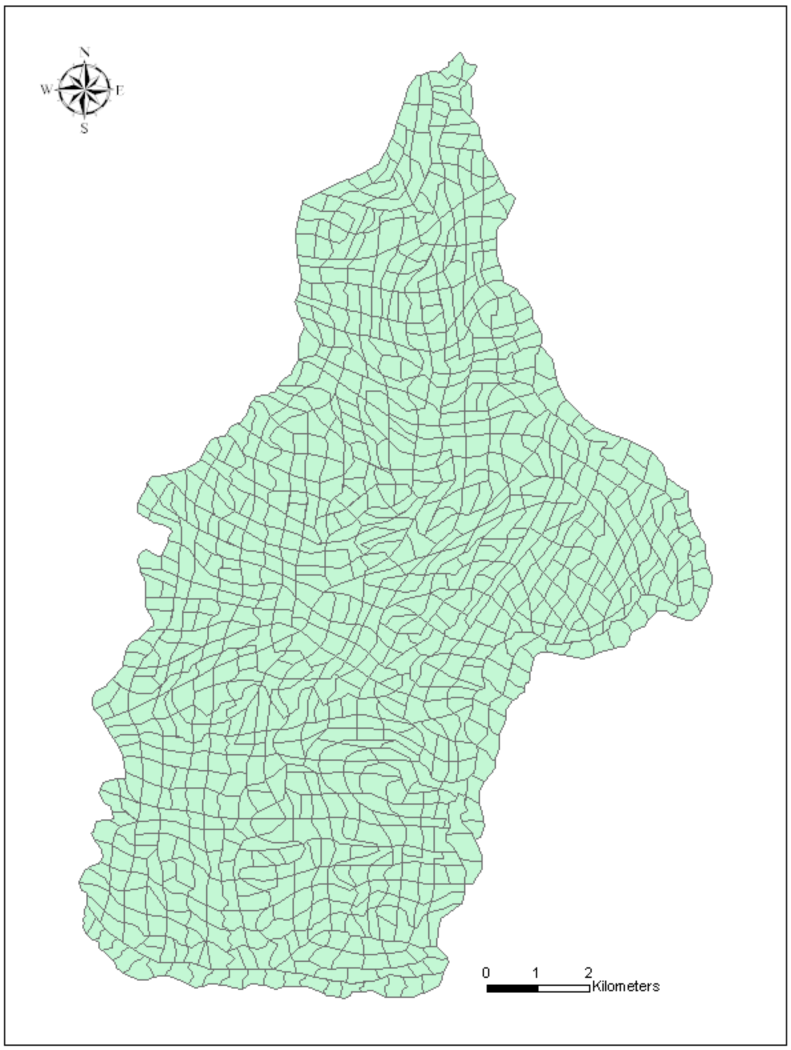


Figure 4 – Globland area

The inventory is related to year 2007, while forest area is over 11,873 ha and was divided into 1000 even-aged and pure stands. Its distribution by age at the beginning of planning horizon is shown in Figure 5. For presentation of the results, the age of the trees was weighted by area.

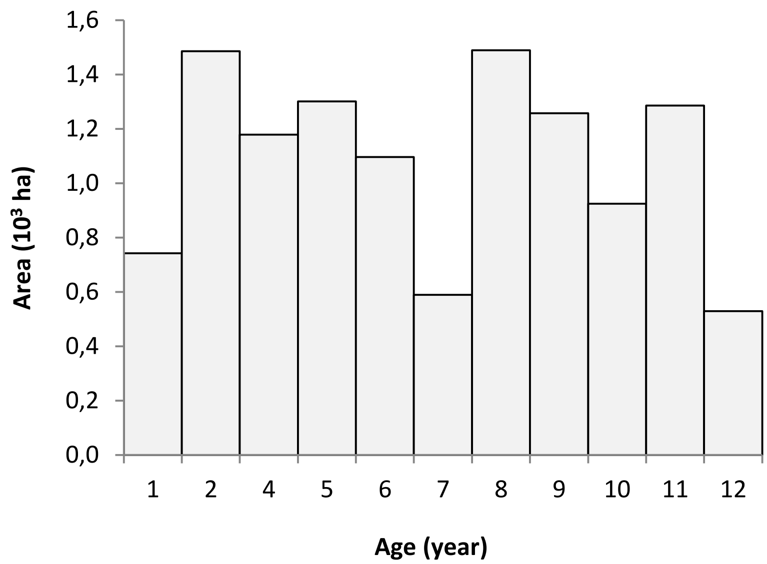


Figure 5 – Area by age at the beginning of planning horizon

The selling product was the harvested timber, and clearcutting was the harvesting method. The stumpage price considered was 32.5 Euros m^{-3}, whilst forest activities and their respective costs are given in Table 1. Selling price and cost values were obtained through personal communication and from the Accompaniment Commission of Forestry Operations of Portugal. A 4% discount rate was applied to compute present values.

Table 1 – Forestry activities and their cost (Euros/ ha^{-1})

Planting	350 / 0.25 $plant^{-1}$
Cut	100
Hand weeding	200
Cleaning	150
Fertilization	24.21
Stool removal	550

The planning horizon consisted of 21 one-year analysis. This study considered 49,872 prescriptions, each one representing a set of forest activities implemented over the years. A typical eucalyptus rotation may include up to 2 or 3 coppice cuts, each coppice cut being followed by a stool thinning that may leave an average number of shoots per stool ranging from 1 to 2. The prescriptions resulted from a combination of cutting ages and number of rotations (Table 2). Planting density was 1,400 trees ha^{-1} and the number of shoots left per stool after shoots selection was 1.6. However, some combinations (prescriptions) were infeasible, and thus they were removed. The design of the prescriptions was performed by FRC.

Table 2 – Descriptive statistics of main indicators of the study

	Minimum	Average	Maximum
Cutting age (years)	9	11	13
Number of rotations (units)	1	2	4[1]
Area of stand (ha)	5	12	27
Altitude of stand (m)	107	169	419
Annual temperature (ºC)	5	11	34
Prescriptions by stand (units)	16	50	64
Annual rainfall (mm)	283	634	1,033

[1]Prescriptions including fourth rotation are about 0.02% of total.

Portugal is defined as a Mediterranean climate, where most of the rainfalls occur during autumn and winter (October-March), while summer is usually very dry (David, et al. 1994). Stands' features and climate information from the study area are given in Table 2. Rainfalls were simulated by FRC for the whole planning horizon and took into account climate change. Data used for runoffs estimation were gathered from FRC, and they are yearly presented in Table 3.

Table 3 – Data to fit the runoff model

Water year	Precipitation (mm)	Watershed 1			Watershed 2		
		Runoff (mm)	Rotation	Age (years old)	Runoff (mm)	Rotation	Age (years old)
1982-83	571	0,1	2ª	11	3,9	3ª	1
1983-84	842	8,4	2ª	12	24,6	3ª	2
1984-85	939	61,3	3ª	1	20,3	3ª	3
1985-86	732	25,3	3ª	2	12,2	3ª	4
1986-87	645	17,1	3ª	3	13,2	3ª	5
1987-88	1038	22,5	3ª	4	8,5	3ª	6
1988-89	672	7,3	3ª	5	9,4	3ª	7
1989-90	1068	123,9	3ª	6	94,8	3ª	8
1990-91	845	32,5	3ª	7	30,8	3ª	9
1991-92	513	3,4	3ª	8	1,3	3ª	10
1992-93	623	1,3	3ª	9	0,5	1ª	1
1993-94	893	15,0	3ª	10	16,9	1ª	2
1994-95	483	3,1	1ª	1	2,0	1ª	3
1997-98	983	57,1	1ª	4	56,2	1ª	6

Water-years start on the 1 October and finish on the 30 September.

The software used in this study is presented in Table 4. In addition, the growth and yield model Glob3PG was used by FRC to estimate stand development for each prescription. This is instrumental to compute the management model coefficients (i.e. annual timber, profit, and runoff).

Table 4 – Software used in the study

Program	Used to...
ArcGIS	Format the forest map.
CPLEX	Solve the problems and export results.
MS Access 2007	Store and query data.
MS Excel 2007	Fit the runoff statistical model and store solutions.
Visual Basic.NET 2008	Build the program to convert data in OR formulations.

The proposed approach automates the quantification of outcomes associated to all management regimes. Likewise, an extended version of the prescription writer SADfLOR (Borges, et al. 2003) was used to simulate all possible management alternatives for all stands in the test forest.

Soil Expectation Value

The determination of SEV encompassed revenues from timber selling and costs (presented on page 16) over years, according to each prescription.

FRC calculated the two components from (2). For each stand were done 2 runs, whereby the author gathered the SEV by summing those two components (see definition of sets I and $J(i)$ on page 21). The first component is the NPV of using prescription j in stand i, and the second one is the highest NPV from all prescriptions in $J(i)$ applied to stand i. This best prescription was considered to start after the final cutting, and repeated to perpetuity (Bettinger, et al. 2009, 42).

$$SEV_{ij} = NPV_{ij} + NPV\ to\ perpetuity_i, \quad \forall\, i \in I, \forall\, j \in J(i) \qquad (2)$$

Runoff

David, et al. (1994) studied the effect of clearcutting *Eucalyptus globulus* on runoff in an area near to that used in this study, and concluded that increases in runoff after harvesting occur up to the second year for coppice rotations. Samraj, et al. (1988) conducted a similar study in India, they indicated that those runoff increases last until the fourth year for plantation rotation.

Two multiple regression models were developed, one for planted stands and another for coppice stands. For that, the ordinary least of squares method was employed. Equation

(3) is a generic equation used to determine runoffs, wherein w is the annual runoff (mm), R is the annual rainfall (mm), A is the age of trees (year), and ε is the error. The first one was the dependent variable while the following two variables were the independent ones. Since the relationship between some variables is not linear (see Figure 17, in Appendix), it was converted to linear using logarithm neperian. In total, 8 equations were adjusted. Consider l = *plant* for plantation rotations; and *cop* for coppice rotations.

$$S_l: w = \beta_0 + \beta_1 R + \beta_2 A + \varepsilon \qquad (3)$$

For runoff model fitting, data were selected in such a way that only pre-calibrated and calibrated periods are compared. Due to non-extensive data, first rotation runoffs were estimated through a pre-treatment of data, by delaying the runoff increase with variations presented by David, et al. (1994).

The fitting of the models was carried out by: Microsoft Excel 2007 » Data analysis Add-in » Regression.

3.2. Forest management models

3.2.1. General structure

A deterministic general model was proposed to optimize financial and water resources, from which particular formulations may be extracted. The variables' type related to the Model I (Johnson and Scheurman (1977), in Baskent and Keles (2009)). Sets, coefficients, variables, parameters, objective functions, constraints and accounting rows are presented next.

Sets

T is the set of periods considered, where $t \in T$;

I is the set of management units; where i ∈ I;

$J(i)$ is the set of prescriptions for each management unit; where $j \in J(i)$.

Coefficients

v_{ij} is the SEV (monetary units) coefficient for the management unit i and prescription j, $v_{ij} \in \mathbb{R}$;

w_{ijt} is the runoff volume (m^3) coefficient assigned to the management unit i and prescription j, undertaken in period t, $w_{ijt} \geq 0$, $\forall\, i \in I,\ j \in J(i)$, $t \in T$; where $w_{ij} = \sum_{t=1}^{|T|} w_{ijt}$;

h_{ijt} is the coefficient for timber (m^3) harvested from the management unit i, prescription j, undertaken in period t, $h_{ijt} \geq 0, \forall\, i \in I,\ j \in J(i),\ t \in T$;

p_{ijt} is the profit (monetary units) coefficient achieved from the management unit i, prescription j, undertaken in period t, $p_{ijt} \in \mathbb{R}, \forall\, i \in I,\ j \in J(i)$, $t \in T$.

Decision variables

x_{ij} is the proportion of the area from the management unit i managed by prescription j, where $0 \leq x_{ij} \leq 1, \forall\, i \in I,\ j \in J(i)$.

Accounting variables

$winc_{max}$ is the maximum increase in runoff (m^3) among two consecutive years, $winc_{max} \geq 0$;

w_{max} is the maximum annual runoff (m^3), $w_{max} \geq 0$;

th_t is the total timber volume harvested in period t, $th_t \geq 0$;

tp_t is the total profit achieved in period t, $tp_t \in \mathbb{R}$;

tw_t is the total runoff occurred in period t, $tw_t \geq 0$.

Parameters

$w_{pre-defined}$ is the total runoff occurred for entire planning horizon and forest, $w_{pre-defined} \geq 0$.

$$Min \;\; (Z_1, Z_2, Z_3, -Z_4) \tag{4}$$

$$subject \;\; to:$$

$$Z_1 = w_{\max} \tag{5}$$

$$Z_2 = winc_{\max} \tag{6}$$

$$Z_3 = \sum_{i=1}^{|I|} \sum_{j=1}^{|J(i)|} w_{ij} x_{ij} \tag{7}$$

$$Z_4 = \sum_{i=1}^{|I|} \sum_{j=1}^{|J(i)|} v_{ij} x_{ij} \tag{8}$$

$$\sum_{j=1}^{|J(i)|} x_{ij} = 1 \qquad \forall i \tag{9}$$

$$\sum_{i=1}^{|I|} \sum_{j=1}^{|J(i)|} h_{ijt} x_{ij} = th_t \qquad \forall t \tag{10}$$

$$th_{t+1} \geq th_t \qquad \forall t \setminus \max\{T\} \tag{11}$$

$$\sum_{i=1}^{|I|} \sum_{j=1}^{|J(i)|} p_{ijt} x_{ij} = tp_t, \qquad \forall t \tag{12}$$

$$tp_{t+1} \geq tp_t \qquad \forall t \setminus \max\{T\} \tag{13}$$

$$\sum_{i=1}^{|I|} \sum_{j=1}^{|J(i)|} w_{ijt} x_{ij} \leq w_{\max}, \qquad \forall t \tag{14}$$

$$\sum_{i=1}^{|I|} \sum_{j=1}^{|J(i)|} w_{ijt} x_{ij} = tw_t, \qquad \forall t \tag{15}$$

$$tw_{t+1} - tw_t \leq winc_{\max} \qquad \forall t \setminus \max\{T\} \tag{16}$$

$$\sum_{i=1}^{|I|} \sum_{j=1}^{|J(i)|} w_{ij} x_{ij} = w_{pre-defined} \tag{17}$$

$$x_{ij} \geq 0 \qquad \forall i, j \tag{18}$$

$$winc_{\max} \geq 0 \tag{19}$$

Objective functions

(4) it represents a set of objective functions possible to be optimized. The order of those elements does not refer that one element has more priority than the following one. In addition, the number of objective functions to optimize can be smaller than that.

(5) it is the maximum annual runoff. This is minimized by (4) and requires the inclusion of (14).

(6) it is the maximum annual increase in runoff. It is minimized by (4), and equations (15) and (16) must be introduced.

(7) it is the total runoff from all management units over the planning horizon, which is minimized by (4).

(8) it is the SEV from all the management units. This is maximized by (4).

Constraints

(9) indicates that the whole area from each management unit must be entirely assigned to at least one prescription.

(11) and (13) reflect the non-decreasing annual flows of harvested timber and profit, respectively, i.e. the value in one year should be greater than or equal to that from the preceding year. Note that variable th_t was derived from (10) and variable tp_t from (12).

(14) compels the annual runoffs discharged from the whole area to be less than or equal to w_{max}. Note that this variable is minimized in (4).

(16) similarly to the previous one, it forces the annual increases of runoff to be less than or equal to $winc_{max}$. This is minimized in (4) and tw_t is calculated by (15).

(17) restricts the total runoff occurred for the whole area and planning period to a pre-defined value. This was used for computation of the Pareto efficient curve and on the post-optimal analysis.

(18) indicates that the proportion of the management units' area assigned to prescription(s) must be non-negative.

(19) limits the maximum annual increase in runoff to be non-negative.

Accounting variables

(10) indicates the total timber harvested in the year t from all management units.

(12) refers to the total profit undertaken in the year t from all management units.

(15) represents the total runoff volume occurred in the year t from all management units.

The value of objective functions and accounting variables depends on the prescription(s) selected to each management unit (i.e. the value of decision variables) in the way that the constraints are respected.

3.2.2. Forest management strategies

Five models (Table 5) were derived from the general structure presented before, wherein each one represents a forest management strategy. The first two models have strictly financial objectives, while the following ones include water concerns. Consider the sets: T = {1, 2…, 21}; I = {1, 2…, 1000}; J(i) = {1, 2…, |J(i)|}, where |J(i)| is the last prescription for the management unit i. The general formulation comprised 1,082 main constraints, 63 accounting variables, and 1,001 non-negativity constraints.

Model OR1 maximizes SEV without any flow constraint. Only the area allocation of each stand is computed for each prescription. OR2 uses the previous model adding timber flow constraints. It allows determining the effect of including those constraints in the model OR1. Model OR3 aims to minimize the total runoff. This is useful for agents who consider runoff as negative disregarding the total SEV value. Nevertheless, non-decreasing flows of timber and profit are ensured. Models OR4 and OR5 are lexicographic goal programming models. The former addresses the minimization of the maximum annual runoff, which has real implications in mitigating the risk of catastrophes. However, this did not provide a non-dominated solution, whereas a second optimization was necessary (SEV maximization). Model OR5 intents the minimization of the maximum increase in runoff from two consecutive years. The main purpose was to compare its results with those from the previous model. Herein, the effort was to reduce the greater runoff increase, even if it required reducing runoff from any year and augmenting runoff from the preceding year. Similarly to what happened to model OR4, a second optimization was needed.

Table 5 – Forest management strategies

Model	Objective function	Forestry constraint	Equation
OR1	Max SEV	NA	(8), (9), (18).
OR2	Max SEV	non-decreasing timber flow.	(8), (9), (10), (11), (18).
OR3	Min total runoff	non-decreasing timber flow; non-decreasing profit flow.	(7), (9), (10), (11), (12), (13), (18).
OR4	Min Lex[2] (w_{max}, -SEV)	non-decreasing timber flow; non-decreasing profit flow; maximum annual runoff.	(5), (8), (9), (10), (11), (12), (13), (14), (18).
OR5	Min Lex ($winc_{max}$, -SEV)	non-decreasing timber flow; non-decreasing profit flow; maximum annual increase in runoff.	(6), (8), (9), (10), (11), (12), (13), (15), (16), (18), (19).

Two models based on OR3 were considered in a post-optimal analysis. The purpose was to identify the impact of relaxing timber and profit constraints (20) on total runoff, one at a time. In both cases, the parameter δ was altered from 0.5 to 1, by 0.1 intervals. SEV was maximized after that, restricting total runoff to the value found previously.

$$\text{Total flow}_{t+1} \geq \delta * \text{Total flow}_{t}, \quad \forall\, t \in \{1,2,\dots,|T|-1\} \qquad (20)$$

[2] It is an achievement function. It consists of an ordered vector, whose each element and position into the vector represent an objective function and its relative importance, respectively (Silva, et al. 2010). After the optimal value is achieved, it is placed as a constraint in the next optimization, in such a way that its value does not deteriorate.

Besides that, OR3 was used to design the Pareto efficient curve between SEV and total runoff. For that, the extreme points of the curve were identified by means of the SEV maximization and the total runoff minimization. The maximization of SEV, restricting total runoff to its minimum value, was further required to obtain a non-dominated solution. Then, the total runoff was set as a constraint (constraint method, see Cohon (1978, 115)), and equation (8) was introduced as the objective function. Equidistant pre-defined values among the extreme points were assigned to the right hand side of equation (17), and then the models were optimized. Extra points were additionally determined in order to design a more complete Pareto efficient curve.

The equation below (21) was used to identify the optimal values (points) nearest to the ideal point (reference point). z_i^1 and z_i^2 are the ideal point and optimal values coordinates. The value of λ_i was set to 1, and 0.1 was assigned to ε_i when it was considered, $i = 1, 2, \ldots, n$. See Steuer (1986, 44) and Clímaco, Antunes e Alves (2003, 113).

$$L_{p,\varepsilon}^{\lambda} = \left[\sum_{i=1}^{n} \lambda_i \left| z_i^1 - z_i^2 \right|^p \right]^{1/p} + \sum_{i=1}^{n} \varepsilon_i \left| z_i^1 - z_i^2 \right|, \qquad (21)$$

$$p \in \{1, 2, \ldots, \infty\}$$

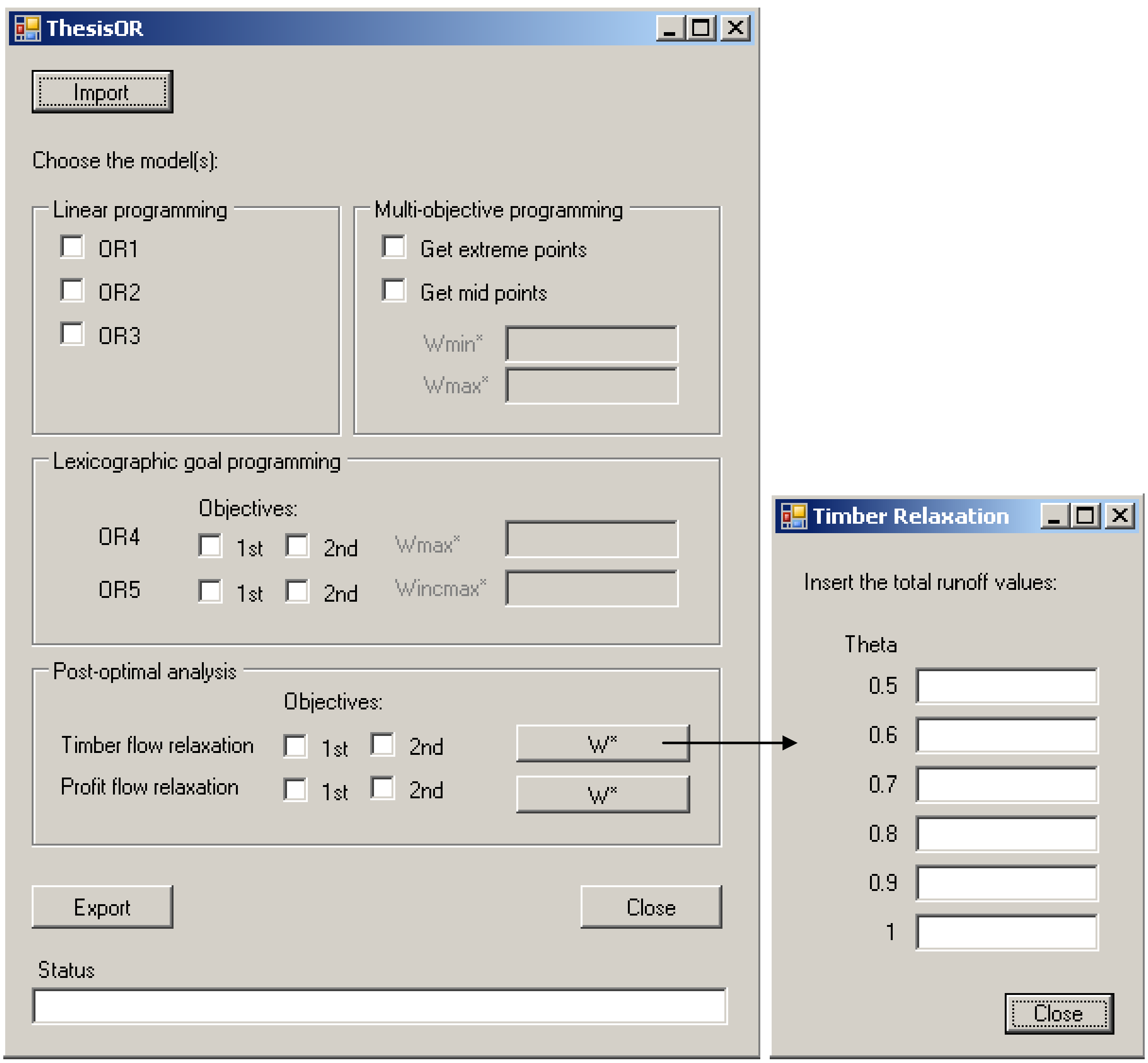
$$\textit{where } \lambda \in \Re^n \textit{ is a non-negative vector of weights.}$$

For that, data normalization was required (22) due to its different scales; *V* is the set of optimal values. The minimum distances were found by computing all distances, ordering them and getting the small one for each metric.

$$\bar{y}_i = \frac{y_i - y_{\min}}{y_{\max} - y_{\min}}, \qquad \forall\, i \in V \qquad (22)$$

3.3. Program for the models' formulation

A program to obtain formulations was developed especially for this thesis, and was denominated as *ThesisOR* (Figure 6). It presents the processing time required to import data and to export formulations (beside to the *Import* and *Export* buttons, respectively) as well as the status, i.e. what the program is processing in the current moment.



(a) (b)

Figure 6 – Program for the problems' formulation: (a) Main form; (b) Auxiliary form

```
\ Objective function
Min
Runoff_Total:  12983.2 x(1,1) + 12983.2 x(1,2) + 12983.2 x(1,3) +…
+ 35762.66 x(2,1) + 35762.66 x(2,2) + 35762.66 x(2,3) +…
…
+ 21888.92 x(1000,1) + 21888.92 x(1000,2) + 21888.92 x(1000,3) + …

Subject to:
\ Each stand must be entirely assigned to prescriptions
R_Stand(1): x(1,1) + x(1,2) + x(1,3) +… = 1
R_Stand(2): x(2,1) + x(2,2) + x(2,3) +… =1
…
R_Stand(1000): x(1000,1) + x(1000,2) + x(1000,3) +…

\ Timber flow in year t+1 must be equal to or greater than that from t
R_Timber(08,09): th(2008) - th(2009) <= 0
R_Timber(09,10): th(2009) - th(2010) <= 0
…
R_Timber(27,28): th(2027) - th(2028) <= 0

\ Profit in year t+1 must be equal to or greater than that from t
R_Profit(08,09): tp(2008) - tp(2009) <= 0
R_Profit(09,10): tp(2009) - tp(2010) <= 0
…
R_Profit(27,28): tp(2027) - tp(2028) <= 0

\ Accounting rows for annual timber flow
AR_Timber(2008): 447.4 x(1,17) + 447.4 x(1,18) + 447.4 x(1,19) + … - th(2008) = 0
AR_Timber(2009): 506.38 x(1,1) + 506.38 x(1,2) + 506.38 x(1,3) +… - th(2009) = 0
…
AR_Timber(2028): 1243.97 x(1,17) + 1830.52 x(2,6) + 1615.39 x(2,12) + 1416.99 x(3,1) +… - th(2028) = 0

\ Accounting rows for annual profit
AR_Profit(2008): 14540.5 x(1,17) + 14540.5 x(1,18) + 14540.5 x(1,19) +… - tp(2008) = 0
AR_Profit(2009): 16457.35 x(1,1) + 16457.35 x(1,2) + 16457.35 x(1,3) + … - tp(2009) = 0
…
AR_Profit(2028): - 1686.68 x(1,14) - 1686.68 x(1,15) - 1686.68 x(1,16) +… - tp(2028) = 0

Bounds
tp(2008)  free
tp(2009)  free
…
tp(2028)  free

End
```

Figure 7 – Output from the program *ThesisOR*

The process to export formulations is explained as follows (Figure 6 (a)): 1. Press the *Import* button. The data from MS Access will be imported; 2. Choose the models to be formulated after the “Imported successfully.” message appears in the status; 3. Then, press the *Export* button to create formulations and to export them; 4. The text files will be available to be imported and solved by CPLEX after the message “Exported successfully.” appears in the status.

The auxiliary form (Figure 6 (b)) was created to support in the second optimization on post-optimal analysis. The optimal runoff values identified in the first optimization should be inserted within adequate fields. This is required to formulate constraints on runoff quantity in such a way that its value does not deteriorate in the second optimization.

Figure 7 shows the output for the model OR3 from the program *ThesisOR*. However, the file included more rows than those showed in that figure, e.g. accounting rows for the area harvested by age, area harvested by rotation, area by age and year; SEV; total harvested timber. The file resulted in 225,634 rows.

After models (presented on page 25) were solved and exported by CPLEX, solutions were linked to MS Excel by the tool *Get external data from text*. When it was necessary, data was updated through *Refresh* on *Connections* tab. The Visual Basic Application for Excel was used to place solutions into tables and figures.

The working process is synthesized by following diagram on next page (Figure 8):

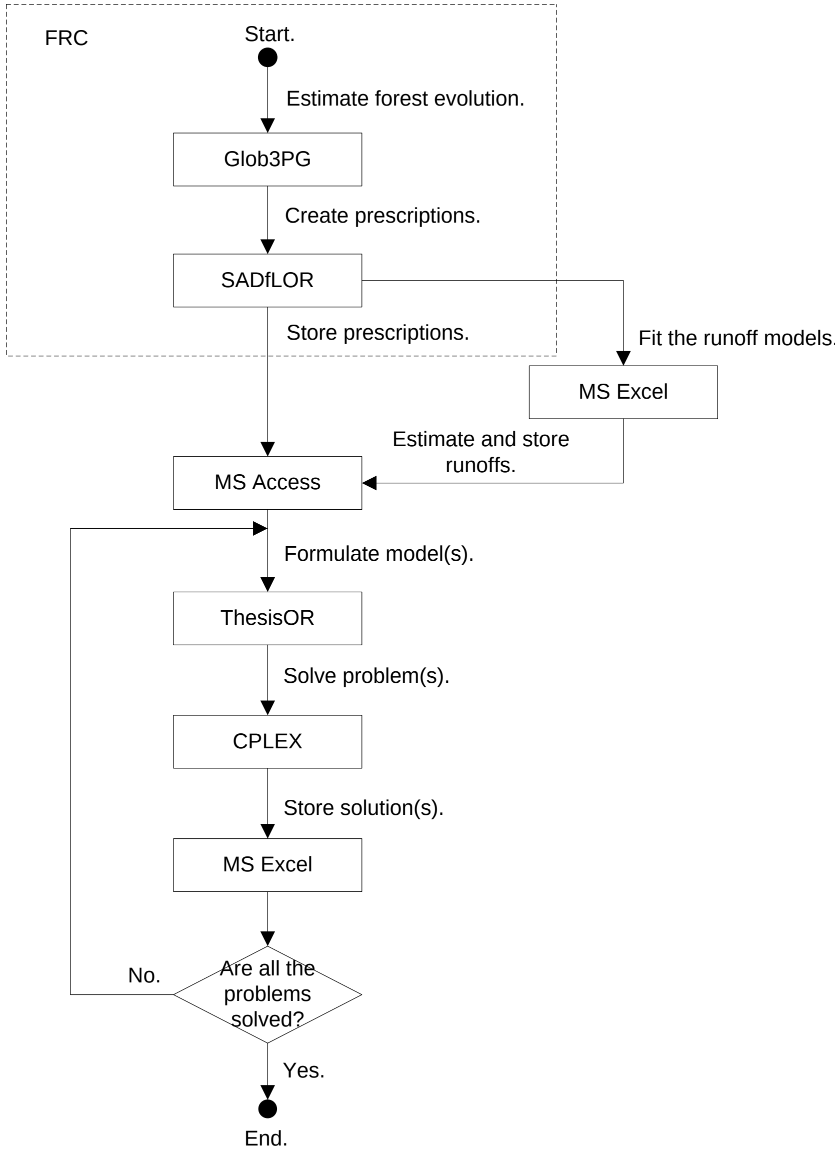


Figure 8 – Working process

4. Results

Foremost, results for the runoff statistical models are presented. After, outcomes from optimizations are shown. At the end of this section, a post-optimal analysis is carried out.

4.1. Runoff statistical models

Table 6 and Table 7 show the models fitted for runoff determination, considering rainfall and trees age as exogenous variables. *Multiple r* is an indicator of goodness-of-fit of the model, while the quality of the model is represented by the *F-Snedcor significance* (asterisk). Two asterisks reflect a higher-quality model than that model with only one asterisk. *Multiple r* and *F-Snedcor significance* are shown in the last column.

Table 6 – Runoff statistical model for plantation rotation

Model	Equation	Multiple r
$S_{plant}(1)$	$w = -43.9539 + 0.1122\ R - 2.7423\ A$	0.64*
$S_{plant}(2)$	$w = e^{(-1.6666 + 0.0066\ R - 0.2043\ A)}$	0.62**
$S_{plant}(3)$	$w = -505.1829 + 82.8171\ \ln(R) - 2.8291\ A$	0.64*
$S_{plant}(4)$	$w = -48.9852 + 0.1142\ R - 7.3389\ \ln(A)$	0.60*
$S_{plant}(5)$	$w = -516.9066 + 84.0477\ \ln(R) - 7.5968\ \ln(A)$	0.60*
$S_{plant}(6)$	$w = e^{(-28.9685 + 4.8929\ \ln(R) - 0.2098\ A))}$	0.63**
$S_{plant}(7)$	$w = e^{(-2.0334 + 0.0067\ R - 0.5655\ \ln(A))}$	0.57**
$S_{plant}(8)$	$w = e^{(-29.9214 + 5.0006\ \ln(R) - 0.5844 \ln(A))}$	0.58**

** 99% confidence level.

* 95% confidence level.

The highest *multiple r* value from Table 6 is from $S_{plant}(1)$ and $S_{plant}(3)$, wherein some *F-Snedcor* p-values are above 1%. In Table 7, the eight models exhibited a high confidence level, but only the exponential models presented the highest *multiple r* values. The models $S_{plant}(7)$ and $S_{cop}(8)$ were elected.

Table 7 – Runoff statistical model for coppice rotations		
Model	Equation	Multiple r
$S_{cop}(1)$	w = -31.1308 + 0.0711 R - 1.4780 A	0.79**
$S_{cop}(2)$	$w = e^{(-3.4600 + 0.0082 R - 0.1677 A)}$	0.86**
$S_{cop}(3)$	w = -298.1854 + 48.5979 ln(R) - 1.5321 A	0.78**
$S_{cop}(4)$	w = -31.7433 + 0.0732 R - 6.9811 ln(A)	0.81**
$S_{cop}(5)$	w = -307.7115 + 50.1983 ln(R) - 7.2214 ln(A)	0.79**
$S_{cop}(6)$	$w = e^{(-34.3286 + 5.6122 \ln(R) - 0.1741 A))}$	0.87**
$S_{cop}(7)$	$w = e^{(-3.6147 + 0.0083 R - 0.6441 \ln(A))}$	0.91**
$S_{cop}(8)$	$w = e^{(-35.0251 + 5.7109 \ln(R) - 0.6718 \ln(A))}$	0.92**

** 99% confidence level.

* 95% confidence level.

The evolution of runoff occurrence over time under the average rainfall is shown in Figure 9. Runoff values were higher for younger stands and decreases as stands become older. The same behavior was registered either for planted or coppice stands, although plantations had higher runoff values. Runoffs obtained by models S_{plant} and S_{cop} can reach 137 mm and 101 mm, respectively, considering the rainfall values used in this study.

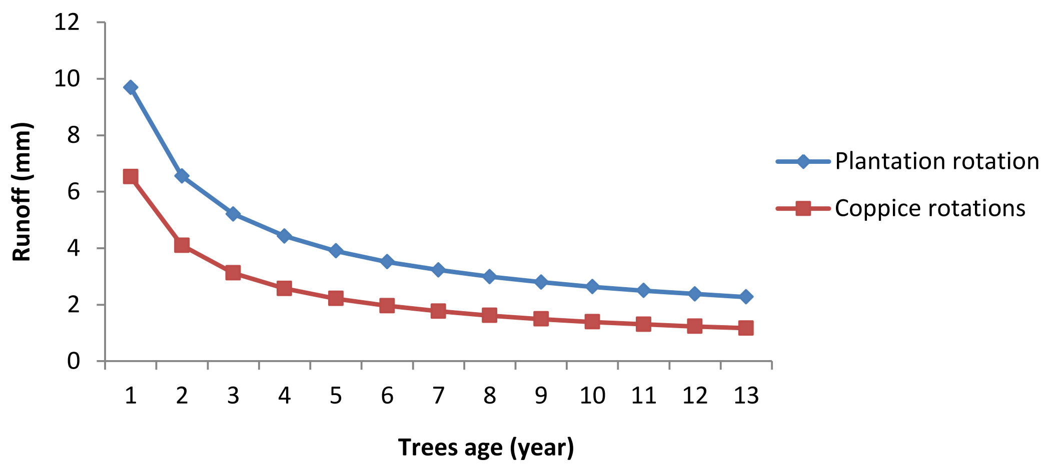


Figure 9 – Runoff along ages of the stand by rotation, with 640 mm of rainfall

4.2. Optimization

The problems were solved with a desktop computer, having 2.13 GHz of Central Processing Unit (CPU) and 1.97 GB of Random Access Memory (RAM). Processing time required to formulate a model was below 23 seconds and no more than 6 seconds were used to solve each one. In sum, about 18 minutes were necessary to import data, formulate all models and solve them; see Table 17 and Table 18 (Appendix).

Results for the five models are shown in Table 8. The SEV, harvested timber and runoffs values were smaller in models incorporating water concerns, albeit SEV of OR4 and OR5 was only 0.3% below the one from OR2. When comparing OR1 and OR2 models, it is evident that the one integrating non-decreasing timber flow constraints (OR2) exhibited smaller values, except for total runoff.

Table 8 – Optimal values

Model	SEV (10^6 Euros)	Harvested timber (10^6 m^3)	Total runoff (10^6 m^3)	Maximum annual runoff (10^6 m^3)	Maximum annual increase in runoff (10^6 m^3)
OR1	**217.53**	2.59	17.87	7.18	5.84
OR2	**201.30**	2.50	17.97	5.91	4.53
OR3	186.61	2.23	**16.82**	4.77	3.36
OR4	**200.67**[2]	2.46	17.17	**4.77**[1]	3.36
OR5	**200.67**[2]	2.46	17.17	4.77	**3.36**[1]

Objective function value is in bold.

[1]First optimization.

[2]Second optimization.

Figure 10 shows the annual timber harvested over the planning horizon. OR1 presented greater annual variability than the other models, with the highest value achieved in year 2028. At this year, all models presented their maximum value. However, the first model produced null harvested timber values for 9 of the total years. The models with constraints on non-decreasing timber flow exhibited regular harvested timber volumes, except for the last year when these values sharply increased.

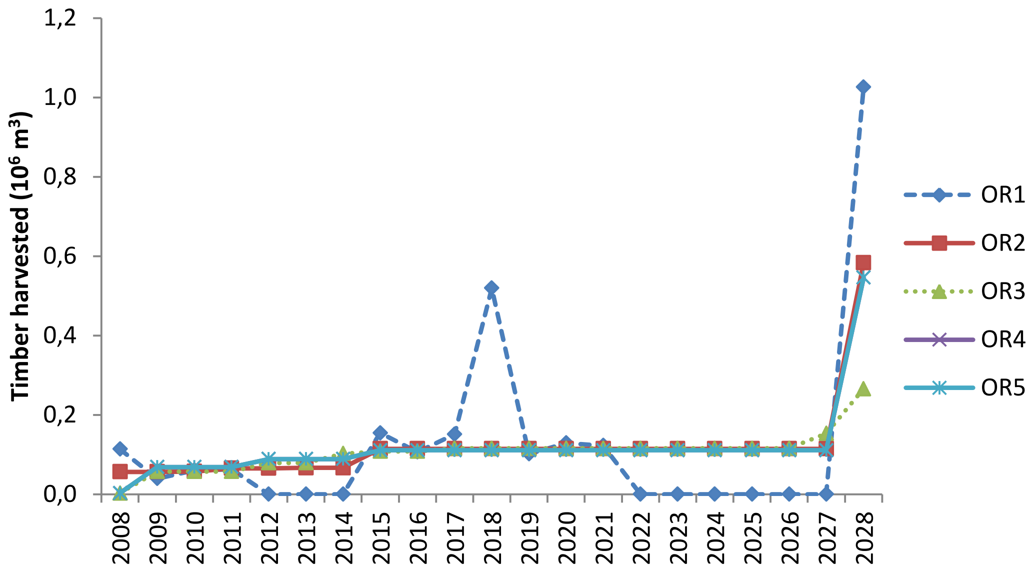


Figure 10 – Evolution of annual harvested timber by model

Figure 11 presents the annual profits, whereby their performance was similar to that from the prior figure. Model OR1 was more unstable than others, and it presented no profit or even loss in those years for which no timber was harvested. For the five models, the maximum annual profit was realized at the year 2028, coinciding with the maximum harvested timber. Although OR2 presented annual profits similar to OR3, OR4, and OR5, they were not non-decreasing.

Figure 12 illustrates annual runoffs, considering rainfall over the years. When rainfall reached its maximum (year 2009), models OR1 and OR2 produced higher runoffs than those models incorporating water concerns. However, at most of the years the differences of runoff values among models were insignificant. Note that runoffs were highly correlated to rainfalls, and for rainfalls below 500mm, runoffs were close to zero.

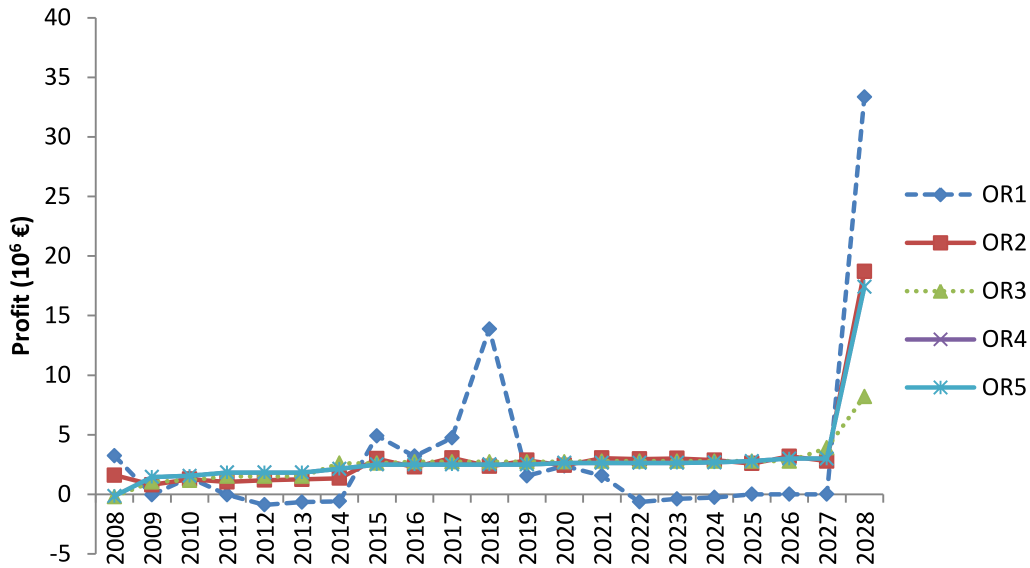


Figure 11 – Evolution of annual profit by model

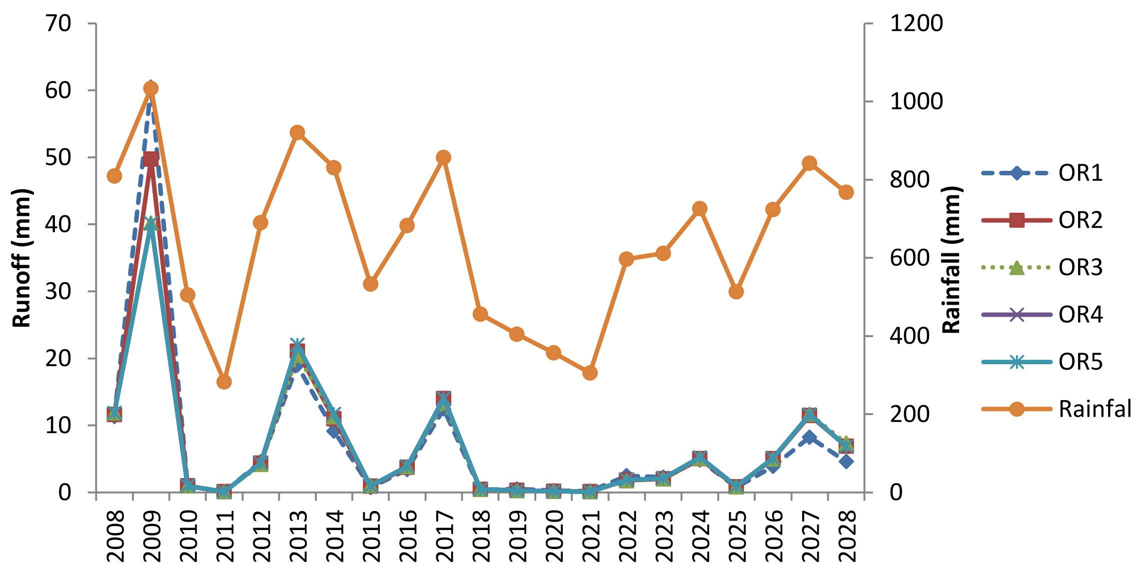


Figure 12 – Evolution of annual runoff by model

Figure 13 introduces the age of the trees along the years. OR1 presented higher age annual variation, and lied in the interval 4-10 years old, while other models' performances were similar to each other varying slightly from 6 to 8 years old. Note that, after the year 2022 the age for OR1 increased continuously, producing smaller runoffs (Figure 12) in the last two years of planning horizon.

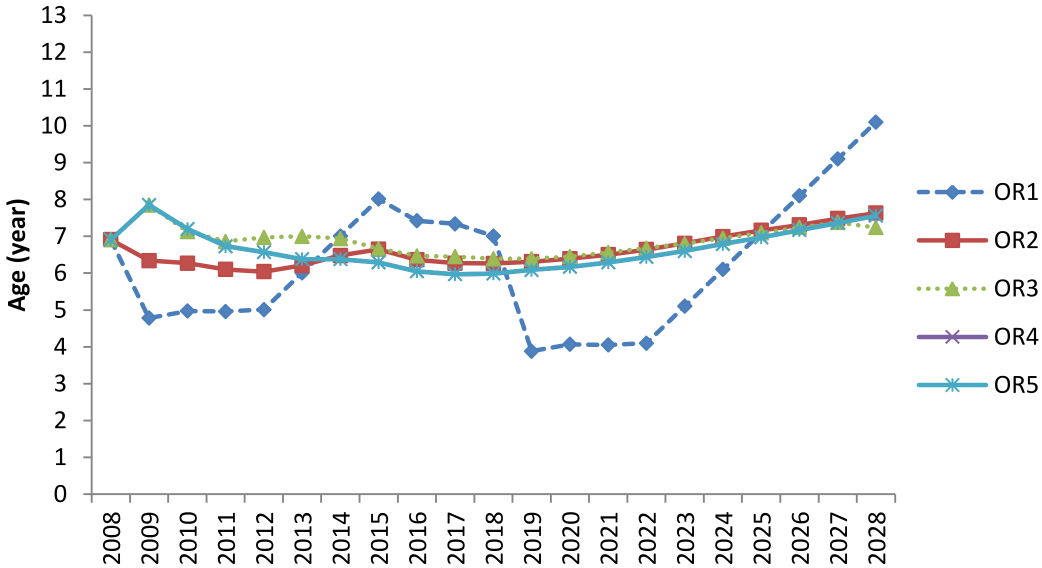


Figure 13 – Evolution of annual age by model

Figure 14 shows the area harvested by trees’ age. Until the age 11, OR1 and OR2 harvested more area for each age than any other model. After that, the situation reversed, the models including water concerns were responsible for harvesting more area. Once again, models OR4 and OR5 produced the same results.

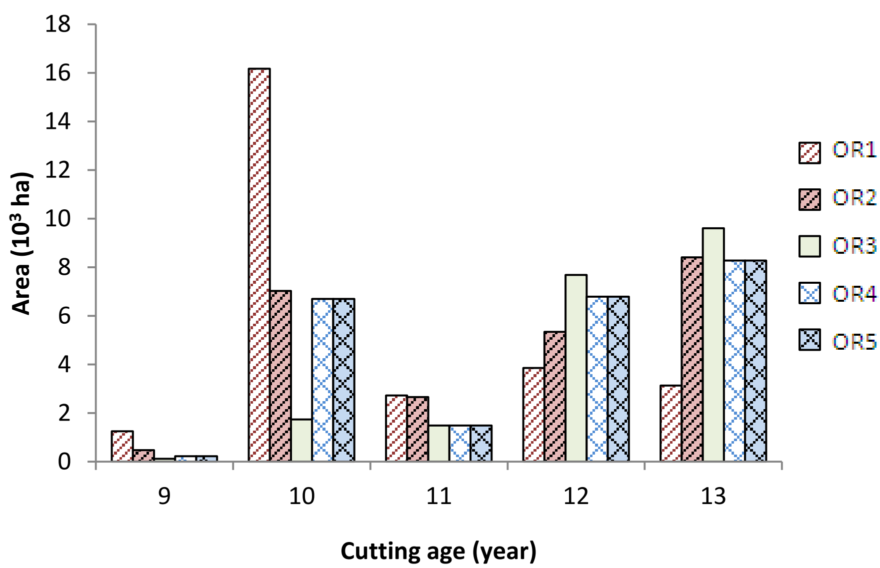


Figure 14 – Area harvested by cutting age, for each model

Figure 15 presents the area harvested for each rotation. For coppice rotations, models considering water indicators harvested less area than other two models. The opposite happened to the plantation rotation. Solution from the five models indicated that it is preferred to harvest more at second rotation ($56x10^3$ ha), while the area harvested in other two rotations were close to each other ($30x10^3$ ha for first rotation and $32x10^3$ ha for third rotation).

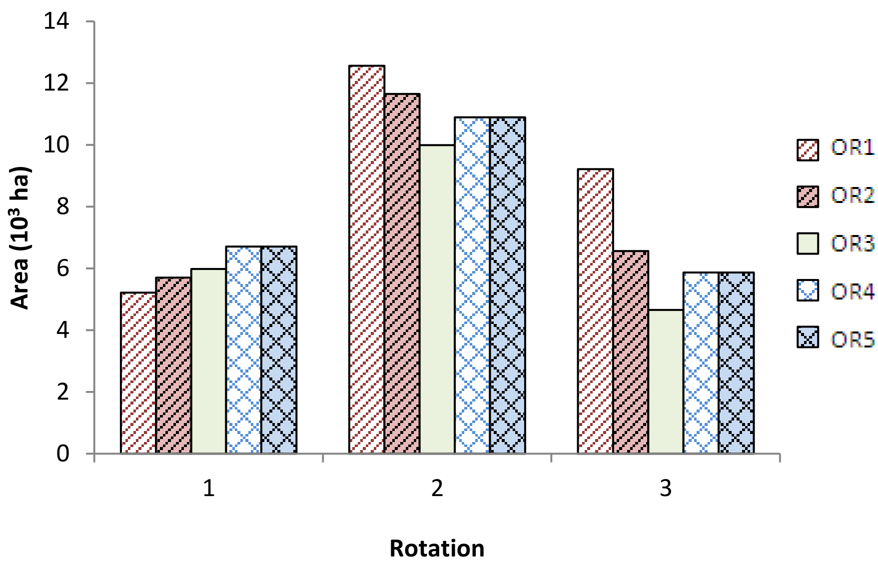


Figure 15 – Area harvested by rotation, for each model

Table 9 shows the total area harvested by each model. Model OR3 harvested the smallest area while OR1 harvested the largest one, comparing to other models. Nonetheless, area harvested by model OR2 was close (only $0.44x10^3$ ha more) to that harvested by OR4 and OR5.

Table 9 – Area harvested by model

Model	Area harvested (10^3 ha)
OR1	27.13
OR2	23.90
OR4	23.46
OR5	23.46
OR3	20.61

Figure 16 presents Pareto efficient curve considering SEV and total runoffs. This curve represents the variation in SEV by varying one unit of total runoff. Along most part of the curve, the effect of decreasing runoff was little relevant in SEV. However, the minimization of total runoff decreased SEV in 2.5% (about $5x10^6$ Euros). The metric L_1 reaches the curve in a diamond form. It is also known as Manhattan distance metric; the L_2 is the well known Euclidean distance; the L_∞ is the greatest value (distance) from the subtraction between the two vectors (points' coordinates), while $L_{\infty,\varepsilon}$ does the same that the previous one, adding an ε value to avoid getting multiple optimal values. Note that the outcomes from those metrics fell only in the points 4 and 5 (from left to right), where the point L_1 overlapped that from L_2, and the same occurred between L_∞ and $L_{\infty,\varepsilon}$ points.

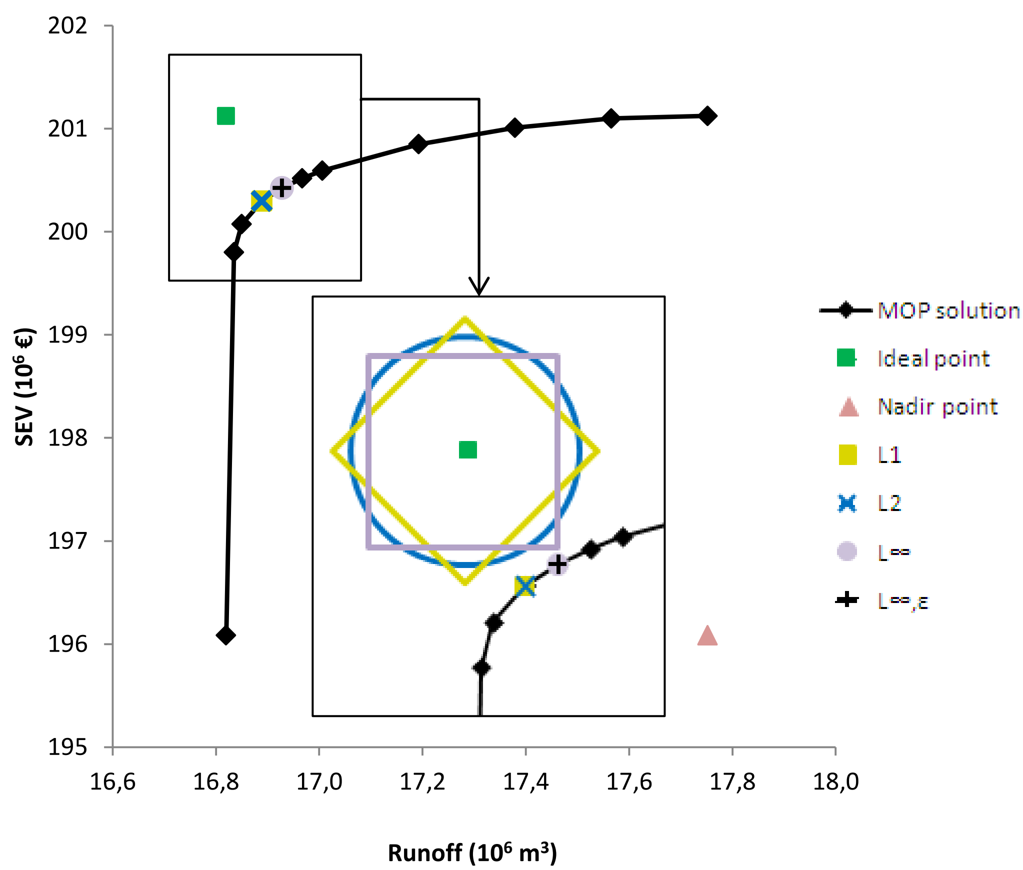


Figure 16 – Pareto efficient curve

4.3. Post-optimal analysis

Next, Table 10 and Table 11 present the results from the post-optimal analysis. In both tables, the value of SEV increases with smaller theta value, even with smaller harvested timber. However, Table 11 shows a break in that tendency when theta was 0.5. The results indicate a smaller total runoff as more relaxed any of those types of constraints is. The maximum annual runoff and the maximum annual increase in runoff remained unchanged.

Table 10 – Timber flow relaxation

δ	SEV (10^6 Euros)	Harvested timber (10^6 m^3)	Total runoff (10^6 m^3)	Maximum annual runoff (10^6 m^3)	Maximum annual increase in runoff (10^6 m^3)
1	**198.94**[2]	2.49	**16.68**[1]	4.77	3.36
0.9	**202.42**[2]	2.47	**16.36**[1]	4.77	3.36
0.8	**204.96**[2]	2.47	**16.12**[1]	4.77	3.36
0.7	**205.95**[2]	2.43	**15.95**[1]	4.77	3.36
0.6	**206.89**[2]	2.39	**15.79**[1]	4.77	3.36
0.5	**207.66**[2]	2.36	**15.64**[1]	4.77	3.36

Objective function value is in bold.

[1]First optimization.

[2]Second optimization.

The results suggest that relaxation of constraints on non-decreasing timber flow has a higher impact on either total runoff or SEV. The timber-related relaxation reduced 6% of total runoff, and increased 4% in SEV, while those related to profit presented a reduction of 4% on total runoff, and an increasing of 2% in SEV.

Table 11 – Profit flow relaxation

δ	SEV (10^6 Euros)	Harvested timber (10^6 m^3)	Total runoff (10^6 m^3)	Maximum annual runoff (10^6 m^3)	Maximum annual increase in runoff (10^6 m^3)
1	**199.79**[2]	2.49	**16.66**[1]	4.77	3.36
0.9	**202.20**[2]	2.47	**16.42**[1]	4.77	3.36
0.8	**204.96**[2]	2.47	**16.23**[1]	4.77	3.36
0.7	**205.61**[2]	2.45	**16.13**[1]	4.77	3.36
0.6	**205.68**[2]	2.40	**16.04**[1]	4.77	3.36
0.5	**203.76**[2]	2.27	**15.96**[1]	4.77	3.36

Objective function value is in bold.

[1]First optimization.

[2]Second optimization.

5. Discussion

The objective of this study was to determine if the runoff reduction decreases SEV. Figure 9 showed that a runoff reduction can be achieved by harvesting tress later; contrarily, harvesting trees earlier increases runoff. The hypothesis of this study is confirmed by Figure 16, which shows that SEV changed along total runoff values; this is in agreement with results from Amaral (2002). Albeit Eriksson, Löfgren and Öhman (2011) addressed water quality in forest management models in a different way from this study, they also indicated that forest economic values were affected by including constraints about water concentration of nitrogen, phosphorus, methyl mercury and dissolved organic carbon.

Results indicated that a decrease of 5.2% of total runoff decreases 0.7% in SEV, and it costs only 1.44 Euro m^{-3}; however, for a 5.3% total runoff reduction, SEV reduces 2.5% and the cost rises to 5.40 Euros m^{-3}. Similar results can be found in Silva, et al. (2010). In equation (21), the value attributed to $\lambda_i, i = 1, 2, \ldots, n$, was set for decision makers that assign the same importance either to SEV or to total runoff. In general, the outcomes from metrics suggest that a value to the right of L_∞ or $L_{\infty,\varepsilon}$ (point 5) should be chosen if the decision maker gives more preference to SEV than to total runoff. Contrarily, a value from the left side of L_1 or L_2 (point 4) should be selected. L_1 did not fall on the second nearest point (the precedent one) by 1.0% of its distance, similarly (but for the following point), the values for L_2, L_∞ or $L_{\infty,\varepsilon}$ were 0.3, 14.0 and 13.3%, respectively. However, multiple SEV values were found in the minimum runoff point. A smaller SEV was obtained by only a runoff minimization, while a higher SEV was achieved from its maximization constraining the total runoff to its minimum value.

Solution from OR4 was the same as that from OR5, which was not expected. This could be ascribed to the second optimization (maximization of SEV), i.e. OR5 could have minimized the maximum annual increase in runoff by reducing the maximum annual runoff and increasing runoff from the preceding year, while OR4 could have minimized the maximum annual runoff, and the second optimization could have increased runoff from the previous year due to harvesting. However, solutions indicate that this did not occur.

Results (Table 8) from models OR1 and OR2 confirmed the expectation that constraints of non-decreasing timber flow reduce SEV. This study exhibited a SEV reduction of about 7%. Although not directly comparable, a Net Present Value reduction of 24% was presented by Baskent and Keles (2009) and 1-17% by Haight, Monserud and Chew (1992), depending on initial stand state.

In post-optimal analysis, when one constraint type was relaxed, another was removed from the formulation. This was required since one constraint type is somewhat correlated to another, and by doing this, the effect of relaxing each one is more fairly determined. In addition, harvested timber and total runoff values indicated when one is higher another one is also higher, resulting in a linear correlation coefficient as large as 0.92 from Table 10, and of 0.76 from Table 11. However, Table 8 shows that total runoff from model OR2 was greater than that from OR1, but the latter harvested more timber. This may be ascribed to the higher timber volume harvested when little rain occurred (compare Figure 10 and Figure 12, in year 2018) and when a large quantity of timber was harvested by OR1 with a higher age at the end of planning horizon (see Figure 10, Figure 12, and Figure 13, at the year 2028). The effect of harvest on runoff is noticed only in years following the cut.

The models including water resources concerns (OR3, OR4 and OR5) exhibited an increasing area harvested along cutting ages (Figure 14). This suggested a harvest postponement. Further, the smallest harvested area was obtained by OR3 (Table 9) as expected. The minimization of the total runoff implied to minimize the extreme runoff events (Table 8); the opposite did not occur. However, minimizing total runoff did not imply minimizing SEV, since more than one SEV was found at the minimum total runoff point (Figure 16). Minimizing the maximum annual runoff implied the minimization of the maximum annual increase in runoff, and vice-versa (Table 8).

Model OR1 produced null harvested timber values in nine years, which suggests that some years are more preferable to harvest than others. In addition, annual profit (Figure 11) seemed highly correlated to the annual harvested timber (Figure 10), which is explained by the high proportion of incomes into profit. Although the model OR2 does not incorporate non-decreasing profit constraints, it presented a profit flow similar to those that included those constraints (Figure 11). The comparison among OR1 and OR2 suggested that this is due to the constraints on non-decreasing timber flows. Timber flow constraints allow a suitable operational, tactical and strategic planning by mills and industries, by compelling solutions to respect the capacity of the mill and/or prohibit milling from varying widely (Rowse 1998).

The harvested area summed by model in Figure 14 was the same as for Figure 15. However, a difference of about $0.1x10^3$ ha was identified in the model OR1 owing to the area harvested in fourth rotation. This was not introduced in Figure 15 due to its irrelevance.

The exogenous variables from runoff statistical models suggested that, given a rainfall quantity, the difference between runoffs is explained by the age of the trees. OR1 presented the minimum age at the year 2009 (Figure 13) causing the maximum runoff (Figure 12), while its highest age contributed to the lowest runoff at the years 2027 and 2028. Although floods are liable to occur whether forests are present or not during unusually heavy storms (Jewitt 2005), the differences in annual runoff among the models presented in this study can be more clearly identified at higher rainfalls. However, the results seem more adequate when they indicate that below 500 mm of rainfall, negligible differences in annual runoff are noticed between models, even the age from one model is substantially different to that from others, due to the evapotranspiration level (David, et al. 1994).

Model $S_{cop}(8)$ presented the greatest statistical performance, and thus it was chosen. Despite $S_{plant}(7)$ did not present a high *multiple r* value, it was chosen since it works better with the previous model elected, in addition it was statistically significant for a high confidence level (*F-Snedcor significance*). Basic hydrological requirements were also satisfied. The coefficient associated to the age of the stand (A) is negative, and that related to the rainfall (R) has a positive sign, in all eight models, for both rotation classes. It means that runoff increases with higher rainfall and decreases with higher age of the stand, which is in agreement with other studies (i.e. David, et al. (1994); Samraj, et al. (1988)). Figure 17 (Appendix) shows the exponential behavior between rainfall and runoff, where no outliers can be visually identified, suggesting that there is not a substantial effect of harvest on runoff. The method considered to adjust the runoff statistical model decreased the number of observations for estimation, but provided superior results probably because of the direct comparison made between pre-calibrated and calibrated periods at same atmospheric conditions (e.g. precipitation rate, solar radiation). Nonetheless, worse statistical results were achieved for the first rotation models, which may be ascribed to the pre-processing operations.

It is not recommended to compare results between models, but rather to compare forest management strategies. Each model has its own objective function and constraints. In most cases, the multi-criteria model is chosen without explicitly justifying the reason for the election (Romero 2001). The epsilon-constraint method was employed to design Pareto efficient curve due to the inefficiency of weighting method (Labadie 2004), but Clímaco, Antunes e Alves (2003, 127) advocate that the epsilon-constraint method may also be inefficient by formulating uninteresting problems or those impossible to solve. All problems formulated in this study were possible to solve; however, the former drawback was not surpassed. By the other side, minimizing deviations in a goal programming structure may not lead to non-dominated solutions (Clímaco, Antunes e Alves 2003, 126). Note that the structure used for first optimization of models OR4 and OR5 is a MINMAX programming as presented by Steuer (1986, 299).

The general model fulfilled the requirements of the current study. It was straightforward employed and may be applied to other ecosystems. For that, runoffs, timber volumes and profits should be re-estimated to determine the model coefficients. The general structure aimed at optimizing forest financial and water values, but may be adapted to include other forest values, such as: carbon sequestration, visual impact, additional products supplied by forests, and other water quantity and quality indicators. This is an even-aged management (Eriksson, Löfgren and Öhman 2011). Note that an upper bound is unnecessary for decision variables x_{ij}, since equation (9) forces those variables to be less than or equal to 1. If $winc_{max}$ was free, its minimization could maximize the runoff annual decrease. Runoff accounting variables were also presented by Baskent and Keles (2009). Initially, non-increasing runoff constraints were introduced in the model OR1, but it became unfeasible, owing to the high variability of rainfall. This variable was considered since it proved to be essential for a more accurate estimation of runoff. However, Amaral (2002) introduced those constraints successfully. She did not include a variable related to rainfall in the statistical model, and obtained a good fit.

Some studies (e.g. Rowse (1998)) denominated the post-optimal analysis as a sensitivity analysis, but this term refers to the determination of the limits within a parameter may change without altering the solution. For greater rigor in the OR field, that was named as post-optimal analysis since it deals with determining the new optimum solution resulting from making targeted changes in the input data (Taha 2007).

Some limitations can be identified in this study. SEV included overestimated timber values. For runoff estimation, spatial and temporal rainfall effects were not taken into account. This would greatly affect the results (Hamilton 2008). Soil features from the study area were also neglected. Moreover, data size for runoff estimation was not extensive. Continuous variables were employed in the mathematical models, which do not have spatial considerations, i.e. solution may indicate to harvest 40% of stand 26, but there is no information about which area or trees should be harvested.

If spatial effects would have been considered, runoffs could have been smaller (Rowse 1998). It is deemed that OR4 and OR5 would not produce the same results, and OR3 would not harvest timber if no timber and profit constraints were introduced, and the set of prescriptions was larger (former case) and it was allowed no harvest over the years (latter case). In this study, these may have reduced significantly the feasible region. The values of extreme runoff events in the post-optimal analysis' tables (Table 10 and Table 11) may be optimal values, since they were optimal values in Table 8. However, SEV reduction caused by the inclusion of timber constraints could be higher if NPV was employed. SEV considers profits after the planning horizon (perpetuity), and these reduce that variation by introducing a greater denominator.

This thesis may support investors in making a conscientious decision about the SEV and total runoff, by means of metrics' points on the non-dominated solutions curve. In addition, the harvest postponement occurred when the runoffs were minimized may be a *rule-of-thumb* for decision makers that prefer to minimize runoff. This study also demonstrated that minimizing the maximum annual runoff may be equivalent to minimizing the maximum annual increase in runoff, whereby both models' optimal values may be found by minimizing only the total runoff. If non-decreasing timber constraints cause undesirable runoffs and those constraints type is required, their relaxation would be preferred. In this sense, post-optimal analysis presented in this study is helpful.

It would be of particular interest that further studies focus on a better structured problem, wherein water quality and quantity were cleverly incorporated in forest management models. For that, equations for erosion and runoff models taking into account spatial and temporal considerations, and soil type would be worthy. Also, more studies addressing the minimization of either the maximum annual runoff or the maximum annual increase in runoff would be valuable to confirm their equivalence.

6. Conclusion

Some relationships between runoff, SEV and harvested timber were studied in Central Portugal, in a *Eucalyptus globulus* forest, by means of operations research models. Two financial-based models, two models for extreme runoff events optimization, and one model for total runoff minimization were derived from a general structure proposed. Equations for runoffs estimation were developed.

Results indicated that runoff reduction decreases SEV, confirming the hypothesis of this study. Further, the inclusion of timber flow constraints reduced SEV by 7%. Model for minimization of the maximum annual runoff produced the same results as that for minimization of the maximum annual increase in runoff. Total runoff may be substantially reduced without affecting much the SEV, costing only 1.44 Euro m^{-3}, but it raised to 5.40 Euros m^{-3} when the total runoff was minimized. The solution should be selected close to the ideal point at a lower cost, if the decision maker assigns the same importance either to SEV or to total runoff. In fact, total runoffs were higher when more timber was harvested, but this did not occur when timber was harvested during low rainfalls or on the planning horizon´s last year. The water-related models indicated harvest postponement, and the minimization of total runoff harvested the smallest area.

However, results should be interpreted with caution. SEV included overestimated timber volumes. Soil types, spatial and temporal rainfall effects were rejected in runoff estimation. Data for runoff estimation was not extensive.

Future studies should focus on forest management models, including soil type, and spatial and temporal effects on runoff. The development of more sophisticated indicators considering water quality and quantity would be worthy. Studies addressing the optimization of the maximum annual runoff and the maximum annual increase in runoff in other ecosystems is imperative, in order to confirm if these models produce the same solution.

Appendix

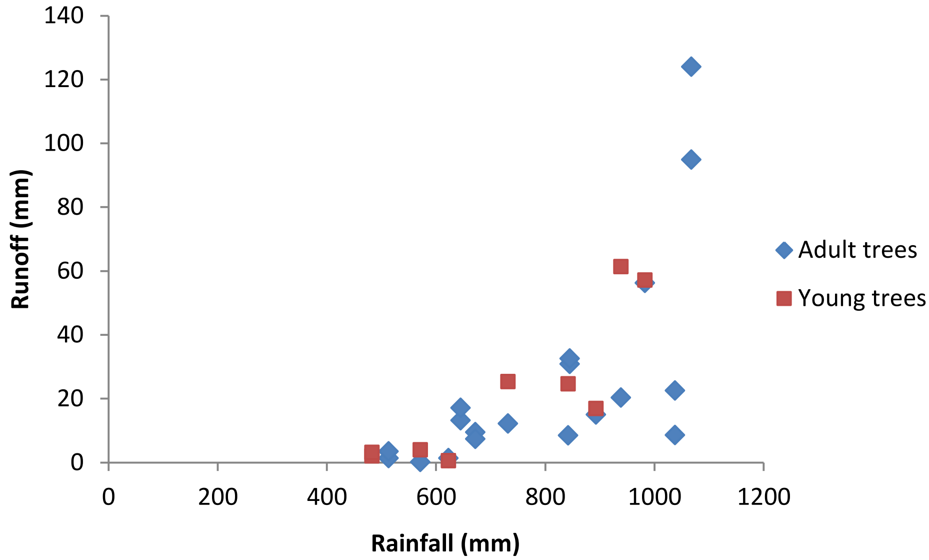


Figure 17 – Runoff for adult and young trees, along rainfall values

Adult trees: age > 2 years old, for coppice rotations; age > 4 years old, for plantation rotation.

Young trees: age <= 2 years old, for coppice rotations; age <= 4 years old, for plantation rotation.

Table 12 – Area (ha) by age over years, for model OR1

Age (year)	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
1	742	3383	961	1204	1130	0	0	0	1485	1090	1332	4672	961	1204	1130	0	0	0	0	0	0
2	1485	742	3383	961	1204	1130	0	0	0	1485	1090	1332	4672	961	1204	1130	0	0	0	0	0
3	0	1485	742	3383	961	1204	1130	0	0	0	1485	1090	1332	4672	961	1204	1130	0	0	0	0
4	899	0	1485	742	3383	961	1204	1130	0	0	0	1485	1090	1332	4672	961	1204	1130	0	0	0
5	983	899	0	1485	742	3383	961	1204	1130	0	0	0	1485	1090	1332	4672	961	1204	1130	0	0
6	1087	983	899	0	1485	742	3383	961	1204	1130	0	0	0	1485	1090	1332	4672	961	1204	1130	0
7	1130	1087	983	899	0	1485	742	3383	961	1204	1130	0	0	0	1485	1090	1332	4672	961	1204	1130
8	1204	1130	1087	983	899	0	1485	742	3383	961	1204	1130	0	0	0	1485	1090	1332	4672	961	1204
9	961	1204	1130	1087	983	899	0	1485	742	3383	961	1204	1130	0	0	0	1485	1090	1332	4672	961
10	1110	961	1204	1130	1087	983	899	0	1485	742	3383	961	1204	1130	0	0	0	1485	1090	1332	4672
11	1277	0	0	0	0	1087	983	899	0	1022	268	0	0	0	0	0	0	0	1485	1090	1332
12	936	0	0	0	0	0	1087	983	858	0	1022	0	0	0	0	0	0	0	0	1485	1090
13	60	0	0	0	0	0	0	1087	627	858	0	0	0	0	0	0	0	0	0	0	1485

Table 13 – Area (ha) by age over years, for model OR2

Age (year)	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
1	742	1660	1126	1200	1067	872	760	778	1224	1220	990	1130	935	920	851	780	752	761	773	760	778
2	1485	742	1660	1126	1200	1067	872	760	778	1224	1220	990	1130	935	920	851	780	752	761	773	760
3	0	1485	742	1660	1126	1200	1067	872	760	778	1224	1220	990	1130	935	920	851	780	752	761	773
4	899	0	1485	742	1660	1126	1200	1067	872	760	778	1224	1220	990	1130	935	920	851	780	752	761
5	983	899	0	1485	742	1660	1126	1200	1067	872	760	778	1224	1220	990	1130	935	920	851	780	752
6	1087	983	899	0	1485	742	1660	1126	1200	1067	872	760	778	1224	1220	990	1130	935	920	851	780
7	1130	1087	983	899	0	1485	742	1660	1126	1200	1067	872	760	778	1224	1220	990	1130	935	920	851
8	1204	1130	1087	983	899	0	1485	742	1660	1126	1200	1067	872	760	778	1224	1220	990	1130	935	920
9	961	1204	1130	1087	983	899	0	1485	742	1660	1126	1200	1067	872	760	778	1224	1220	990	1130	935
10	1110	961	1204	1130	1087	983	899	0	1485	742	1660	1126	1200	1067	872	760	778	1224	1220	990	1130
11	1277	719	561	817	860	762	627	858	0	504	471	531	695	752	761	773	760	778	1224	1220	990
12	936	758	466	306	683	860	760	627	720	0	504	471	531	695	752	761	773	760	778	1224	1220
13	60	246	530	438	81	217	675	699	239	720	0	504	471	531	681	752	761	773	760	778	1224

Table 14 – Area (ha) by age over years, for model OR3

Age (year)	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
1	742	60	1668	1195	815	916	967	1175	1102	934	995	1010	965	886	895	878	770	825	786	786	1041
2	1485	742	60	1668	1195	815	916	967	1175	1102	934	995	1010	965	886	895	878	770	825	786	786
3	0	1485	742	60	1668	1195	815	916	967	1175	1102	934	995	1010	965	886	895	878	770	825	786
4	899	0	1485	742	60	1668	1195	815	916	967	1175	1102	934	995	1010	965	886	895	878	770	825
5	983	899	0	1485	742	60	1668	1195	815	916	967	1175	1102	934	995	1010	965	886	895	878	770
6	1087	983	899	0	1485	742	60	1668	1195	815	916	967	1175	1102	934	995	1010	965	886	895	878
7	1130	1087	983	899	0	1485	742	60	1668	1195	815	916	967	1175	1102	934	995	1010	965	886	895
8	1204	1130	1087	983	899	0	1485	742	60	1668	1195	815	916	967	1175	1102	934	995	1010	965	886
9	961	1204	1130	1087	983	899	0	1485	742	60	1668	1195	815	916	967	1175	1102	934	995	1010	965
10	1110	961	1204	1130	1087	983	899	0	1485	742	60	1668	1195	815	916	967	1175	1102	934	995	1010
11	1277	1110	756	1204	1130	1061	983	899	0	1485	714	60	1223	891	726	661	967	1083	1102	934	995
12	936	1277	1009	617	1204	1083	1061	983	899	0	1333	517	60	1158	762	644	661	869	1083	1102	934
13	60	936	852	805	607	967	1083	969	850	815	0	520	517	60	541	762	636	661	744	1041	1102

Table 15 – Area (ha) by age over years, for model OR4

Age (year)	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
1	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001	941	868	802	812	727	740	735
2	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001	941	868	802	812	727	740
3	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001	941	868	802	812	727
4	899	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001	941	868	802	812
5	983	899	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001	941	868	802
6	1087	983	899	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001	941	868
7	1130	1087	983	899	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001	941
8	1204	1130	1087	983	899	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001
9	961	1204	1130	1087	983	899	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025
10	1110	961	1204	1130	1087	983	899	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927
11	1277	1110	772	994	968	764	662	858	0	783	430	0	787	555	544	727	740	735	1177	1153	966
12	936	1277	944	659	962	959	764	662	685	0	783	134	0	787	555	544	727	740	735	1177	1153
13	60	936	969	814	562	666	959	762	420	654	0	212	134	0	407	555	544	727	740	735	1177

Table 16 – Area (ha) by age over years, for model OR5

Age (year)	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
1	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001	941	868	802	812	727	740	735
2	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001	941	868	802	812	727	740
3	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001	941	868	802	812	727
4	899	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001	941	868	802	812
5	983	899	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001	941	868	802
6	1087	983	899	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001	941	868
7	1130	1087	983	899	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001	941
8	1204	1130	1087	983	899	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025	1001
9	961	1204	1130	1087	983	899	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927	1025
10	1110	961	1204	1130	1087	983	899	0	1485	742	60	1599	1422	1105	1188	987	1003	1177	1153	966	927
11	1277	1110	772	994	968	764	662	858	0	783	430	0	787	555	544	727	740	735	1177	1153	966
12	936	1277	944	659	962	959	764	662	685	0	783	134	0	787	555	544	727	740	735	1177	1153
13	60	936	969	814	562	666	959	762	420	654	0	212	134	0	407	555	544	727	740	735	1177

CPLEX read time was below 2 seconds for each formulation.

Table 17 – Processing time for formulations

	Time (second)	Number of formulations	Average time (second)
Data importation	133	NA	NA
OR1	18	1	18
OR2	16	1	16
OR3	17	1	17
OR4 - 1st objective	16	1	16
OR4 - 2nd objective	16	1	16
OR5 - 1st objective	16	1	16
OR5 - 2nd objective	16	1	16
Pareto efficient curve			
Get extreme points	32	2	16
Get mid points	67	4	17
Get SEVmax, given Wmin	16	1	16
Get extra points			
Point 2	19	1	19
Point 3	18	1	18
Point 4	18	1	18
Point 5	19	1	19
Point 6	19	1	19
Timber flow relaxation - 1st objective	106	6	18
Timber flow relaxation - 2nd objective	129	6	22
Profit flow relaxation - 1st objective	104	6	17
Profit flow relaxation - 2nd objective	128	6	21
Total	*941*	*38*	*NA*
Average	*NA*	*NA*	*18*

Table 18 – Processing time for optimizations

	Time (second)	Number of iterations
OR1	1	0 (0)
OR2	2	2847 (0)
OR3	1	2508 (0)
OR4 - 1st objective	5	3284 (0)
OR4 - 2nd objective	5	2433 (0)
OR5 - 1st objective	5	3413 (0)
OR5 - 2nd objective	6	2480 (0)
Pareto efficient curve		
Min W	1	2508 (0)
Point 1 (Max SEV, given Wmin)	3	3420 (0)
Point 2	3	2853 (0)
Point 3	3	2359 (0)
Point 4	3	2113 (0)
Point 5	3	2294 (0)
Point 6	3	2339 (0)
Point 7	3	2759 (0)
Point 8	4	3288 (0)
Point 9	4	3370 (0)
Point 10	4	3456 (0)
Point 11 (Wmax)	5	3060 (0)
Timber flow relaxation - 1st objective		
$\delta = 0.5$	1	1218 (0)
$\delta = 0.6$	1	1225 (0)
$\delta = 0.7$	1	1269 (0)
$\delta = 0.8$	1	1295 (0)
$\delta = 0.9$	1	1331 (0)
$\delta = 1$	1	1361 (0)
Timber flow relaxation - 2nd objective		
$\delta = 0.5$	1	1743 (0)
$\delta = 0.6$	1	1771 (0)
$\delta = 0.7$	1	1789 (0)
$\delta = 0.8$	1	1856 (0)
$\delta = 0.9$	1	1957 (0)
$\delta = 1$	1	1923 (0)

(Continuation)

	Time (second)	Number of iterations
Profit flow relaxation - 1st objective		
δ = 0.5	1	1341 (0)
δ = 0.6	1	1417 (0)
δ = 0.7	1	1348 (0)
δ = 0.8	1	1405 (0)
δ = 0.9	1	1455 (0)
δ = 1	1	1488 (0)
Profit flow relaxation - 2nd objective		
δ = 0.5	2	1938 (0)
δ = 0.6	2	1798 (0)
δ = 0.7	2	1754 (0)
δ = 0.8	2	2072 (0)
δ = 0.9	2	2227 (0)
δ = 1	2	2186 (0)
Total	*92*	*89951*
Average	*2*	*2092*

Formulations and solutions in digital format follow this thesis.

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Curriculum vitae

Wesley Hilebrand was born in Maringá (Paraná), Brazil, on November 28th 1985. He concluded the basic education in Brazil. In year 2001, he moved to Lisbon (Portugal) where he accomplished the secondary education (2005), and a bachelor in Business (2009). He started his master in Operations Research in 2009. In this year, the Portuguese nationality was attributed to him.

Further, Wesley concluded technical courses in Accounting (2005) and Hardware (2003). He was considered an "A" student in the bachelor, according to European Credit Transfer System. In 2007, he accepted the invitation to improve the database management system from the Portuguese Journal of Management Studies. Furthermore, an academic exchange was carried out by him at the University of São Paulo, in Brazil. He won a concourse about the best article to be published in the journal "O Jornal Económico". In the same year, he was considered the best goalkeeper in a non-professional football league in Lisbon.

Currently, Wesley works at the Forest Research Center (School of Agriculture from the Technical University of Lisbon) since 2010, as research fellow.