THE INTERCEPTION PROCESS IN TROPICAL RAIN FORESTS: A LITERATURE REVIEW AND CRITIQUE (*).

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SUMMARY

A review of the literature on measurements of rain water interception processes by forests is made. Information on Africa, Central and South America, and Asia is given. A general analysis is made and the need to further the measurements under field conditions is stressed.

BACKGROUND

In temperate latitudes, interception as a component of the total evaporative loss from forests has been intensively studied (see, for example, Helvey & Patrick, 1965; Helvey, 1967; Lawson, 1967; Blake, 1975; Calder, 1976, 1978) and its importance well established. Field studies of the interception process have given results which, in many cases, have been expressed as empirical regression equations of the form $I = aP_G + b$ where I is the depth of water intercepted and lost by evaporation, P_G is the gross rainfall incident upon the forest canopy, and a, b are regression coefficients; see, for example, Penman (1963). Many authors, however, Blake (1975) being one, expressed the relation in the alternative form $(I/P_G) = b/P_G + a$ expressing the fact that the percentage interception loss tends to be hyperbolically related to gross rainfall. In contrast to this empirical approach, Rutter **et al**.(1971), Gash & Morton have constructed physically-based computer models using as inputs rainfall and the meteorological variables controlling evaporation to compute a running water balance of a forest canopy with known structure, thereby producing estimates of interception losses. More recently, Sellers & Lockwood (1981) have developed a multilayer crop model for the simulation of interception loss and crop transpiration which, they consider, represents a considerable improvement in terms of physical realism over the Rutter model; Sellers and Lockwood also suggest that the Rutter model substantially underestimates the interception from

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a pine forest during and following storms of low intensity. Shuttleworth and Gash (1982, in press) have suggested that this difference between the Rutter and Sellers & Lockwood models is likely to have arisen from differences in the formulation of the aerodynamic transfer mechanism.

Models like those of Rutter and Sellers & Lockwood, have pratical disadvantages in that they require hourly meteorological data, which are seldom available, and a complex computer program, which is time consuming to construct and operate. Alternative methods of assessing interception losses which are less demanding of computational effort have been developed by Gash (1979); Gash's model retains some of the simplicity of the regression approach described above, whilst including much of the fundamental physical reasoning implicit in the Rutter model.

Over the past decade, process studies such as those of Stewart (1977) have resulted in greatly increased understanding of the dependence of interception loss on climate and canopy structure (eg Gash **et al.**, 1980) such that quantitative predictions of the effects of forests on water resources have been possible (Calder & Newson, 1979). Whilst studies of the interception process in temperate forests are fairly plentiful and well-documented, information about the interception characteristics of tropical forest is much more fragmentary despite the fact that such forests constitute a major natural resource of those countries in which they lie (Klinge et al., 1981; Lal, 1981). The purpose of this paper is to draw together some of the fragments and to fit them together to see what picture, if any, emerges; it begins by assembling the evidence on a regional basis. Units of quantities given in the paper are heterogeneous but are as given in the papers quoted.

AFRICA

Nye (1961) reported the results of a study in moist tropical forests near Kade, Ghana. The forest was mature secondary growth with a wide range of species; at its base was a fairly open shrub layer underlying a dense lower storey between 15 and 50 feet, with a scattered upper storey extending to 130 feet. Occasional massive-crowned emergents extended even higher. Basal area at breast height was 145 ft²/acre.

Annual rainfall in the region is 65 inches a year, with a long-rains season from March to July, and a short-rains season from September to December. In Nye's study, the throughfall penetrating the canopy was measured in 6 (later 8) 8-inch copper gauges; three other gauges of the same type were sited in clearings, to give an estimate of gross rainfall. Initially, gauges were read weekly, but later daily.

In the year 1958-59, the measured gross precipitation, P_G, was 72.7 inches falling in 167 days, with throughfall, T, of 61.5 inches. Initially, stemflow was also measured for a two-month period, but since less than one per cent of gross rainfall was found to flow down trunks its measurement was discontinued. Nye's estimate of interception loss, I, over the year was therefore 16%; this figure is subject to some error, however, because the collector vessels used for measuring throughfall were small and it is known that throughfall is highly variable both spatially and in time. No information was given about the size of the clearings in which were sited the three gauges giving estimates of above-canopy precipitation, nor of their variability in catch.

Hopkins (1960) gives results from a study in the Mpanga Forest Reserve, Uganda, at an altitude of 1160 m where mean annual rainfall is 1130 mm. Besides giving a compre - hensive botanical description of the forest, Hopkins mentions that it possessed both an understorey and an incomplete upper storey with lianas above 30 m. A 120 ft tower extended into the canopy, and three 7.6 cm glass-funnel gauges were sited above the canopy, extending from three of the four corners of the tower at 4 heights (30ft, 60ft, 90 and 120 ft); a second set of four gauges - also glass-funnel type - were mounted at ground level.

Hopkins did not measure stemflow, although he remarks that the botanical structure of the herb-layer understorey would result in channelling along plant stems. He recorded gauge catches during six intervals of the main wet season, concluding that about 35% of the rain falling on the forest is intercepted before it reaches the ground; almost all of this interception took place between ground-level and 9.2 m height, occurring because of the herb layer.

One point about which Hopkins makes no comment is that the uppermost (120 ft) gauges on the tower appeared to catch 11.2 per cent more than the "official" ground-level raingauge at Mpanga, some 300 m to the east; no mention is given, either, of the variability amongst the three gauges sited at each level of the tower.

In a later study on the other side of the continent, Hopkins (1965) set out ten ground-level glass-funnel gauges of 7.6 cm diameter beneath a stand of the Olokomeji Forest Reserve, Nigeria. Measurements were recorded for the period October 1965 to February 1969 and catch by these ten gauges was compared with catch by a gauge at the Olokomeji Forest Station. No actual measurements are given, but Hopkins states that throughfall was recorded as 97%. Again, no measurements of stemflow were made, although presumably this component must have been very small. Hopkins comments on the variability in catch over short distances by his ten ground-level gauges, supporting this statement by some questionable statistical significance (<u>t</u>) tests in which each gauge is compared with every other. In some instances, also, his gauges were found to be full so that throughfall, although high, may have been underestimated. Taking account of this possible underestimation and the absence of stemflow measurement, a figure of 97% for throughfall must be open to some doubt.

Although their results may have doubtful relevance to work on the African continent, Vaughan & Wiehe (1947) studied the interception characteristics of the Upland climax forest of Macabé, in the interior of Mauritius; here the mean annual rainfall is about 3175 mm, "frequently varying by ± 750 mm". Vaughan & Wiehe used one raingauge at an "exposed" site in a clearing outside the forest; about half a mile away, and within the forest, three 4-inch raingauges were installed at random on the forest floor, about 10 yards spart. For the year 1939, catch by the exposed gauge was 3094 mm, whilst catch in the forest gauges was 2375, 1745 and 2336 mm. Direct rainfall on the forest floor, the authors state, was found to be almost two-thirds of the total experienced by the exposed station. They also make the interesting comment that "relatively more rain reaches the forest floor during the warm months of heavy downpours than in the cooler months when the rain is less heavy and the wind velocity lighter".

With only three forest-floor gauges of small diameter, the precision of Vaughan & Wiehe's estimate of throughfall must be low; neither was stemflow measured.

A more recent study is that of Jackson (1971, 1975) working in the West Usambara mountains of northern Tanzania. The forest, described as an Intermediate Evergreen Forest Community, lies between 1300 and 1800 m altitude, and is of the most luxuriant type in East Africa; the 32-year mean annual rainfall is 1338 mm. Jackson describes the botanical composition of the forest, which is very rich in species. Throughfall was measured using 20 standard 5-inch gauges randomly located on an 80 ft x 80 ft square grid; stemflow was measured by spiral gutters of fabric and bitumen, attached to 20 trees. Gross rainfall was measured by means of 5 raingauges sited in a clearing some 70 m square, the edge of which was 45 m from the canopy network. Jackson studied the interception losses for different storm sizes, and for both short and longer periods. Stemflow was small, of the order of 1% of gross rainfall, and catches by his throughfall gauges very variable. Over a period April to September 1969, measured interception loss, for a total gross precipitation of 839 mm, was only 4.2%; however, Jackson argues that interception losses for large storms are poorly defined, and, using a statistical analysis, derives a "corrected" figure of about 16%.

The interception estimates of Pereira (1952), following work by Wimbush (1947), are amongst the most comprehensive, but are to some extent atypical in that they refer to tropical forests at an altitude of about 8,700 ft. Pereira worked with a 20-year old plantation of Montieroy Cypress (**C. macrocarpa**) and with nearly natural bamboo forests (**Arundinaris alpina**). A total of 41 separate gauges was distributed in a 1-acre plot of each cover, measuring "rainfall penetration, drip from the canopy, and runoff down the stems"; throughfall and stemflow, although evidently both measured in total, were not discussed separately. For the six-year period 1946-51, and including the exceptionally dry year 1949, Pereira's results were as in Table 1.

Both in terms of length of record and intensity of sampling, therefore, Pereira's results dominate; however, they cannot be considered typical of low-altitude and naturally-occurring

TABLE 1

Year:	1946	1947	1948	1949	1950	1951
P_G (inches):	41.01	60.60	45.43	25.52	41.52	60.18
% Interception by cypress:	17.2	19.4	22.7	32.0	28.6	29.0
% Interception by bamboo:	13.4	14.5	21.5	25.8	21.5	27.2

forests, whilst measurement of stemflow for a stand of bamboo would have been fraught with difficulty.

CENTRAL AND SOUTH AMERICA

No systematic attempt has been made to explore the Spanish and Portuguese journals for material appropriate to this paper; however, it is known that the UNDP/WMO Project BRA/72/010 "Hydrology and Climatology of the Brazilian Amazon River Basin", which uses personnel from the Brazilian agency SUDAM and in which many other agencies co-operate (Da Silva Neto *et al.*,1979) collects no observation of forest interception losses (Basso, personal communication). This omission is remarkable, since "São objetivos adicionais do estudo, as previsões do tempo e de enchentes e melhoramento no planejamento do uso da terra". Fragmentary information on interception by forests in Central and South America is then the following.

Hopkins (1960) quotes results from Freise (1936) who worked in forests in Brazil which were termed "subtropischen" but which were "probably not very different in structure from Tropical Rain Forests" (Richards, 1952). Two localities, just over 500 km apart, were studied, and in each locality observation posts were set up in a forest clearing, near the forest edge, and well within the forest. At each forest post there were two rainfall gauges, one 1.5 m above ground-level and the other attached to the top of the trunk of the highest tree from which the branches had been removed. These rainfall gauges were recorded daily for 27 years in one locality and for 21 years in the other. Mean annual rainfall recorded at 1.5 m above ground-level varied from 29.8% to 34.8% of that recorded in the crowns. When most of a month's rain fell as thunder showers, 26.7% of the crown rainfall reached the 1.5 m gauge, whereas when most of month's rain fell as long continued fine rain, 35.5% reached the ground.

No information has been found on the comparison of catches by gauges within the forest, with catches by gauges in the forest clearings. Freise's results also appear considerably anomalous, however, by virtue of the very large interception losses that they imply, and by virtue of the fact that interception losses appear to be less, not greater, during period of long continued fine rain.

Heuveldorp (1979) has presented some results for the Amazon Ecosystem MAB Pilot Project at San Carlos de Rio Negro, near the border between Venezuela and Brazil. As part of a larger study, funded by the German Research Foundation DFG and the American National Science Foundation, total rainfall is collected at an unstated number of canopy level gauges; throughfall is collected in four 6-metre long cut-open PVC tubes, which provide a total collecting area of 3.5 m^2. Throughfall is also collected in two sets of 20 tins of unspecified dimension, one set of which is systematically distributed on a podsol site, the other on laterite. The site (119 m altitude) is located near the confluence of Casiquiare and Rio Negro in Territorio Federal Amazonas, and is typical of the black water areas draining towards the Amazon. The forest is described as "natural weakly-seasonal, predominantly evergreen, equatorial-tropical lowland forest".

Heuveldorp presents results in diagrammatic form for the period July 1975 to September 1977; as a guide to the rainfall regime, the annual total for 1976 (read from the graph) was about 3900 mm. Throughfall and drip from leaves in both stands averaged 87% of total incoming precipitation: "a surprisingly large proportion, especially as stemflow, has not been inclued. The amount of stemflow, however, is relatively small, hardly exceeding the error of observation and about equal to the evaporation of inter - ception water at the soil surface".

It is not clear whether the PVC collectors, or the tins, or both, were used in the measurement of throughfall. The width of the PVC collector (3.5/24) seems to have been about 14 cm, with the collector semicircular in cross section; if this was the case, splash could have resulted in an underestimation of throughfall.

Kline & Jordan (1968), as part of a study of tritium movement in soil of a tropical rainforest, investigated a site in the El Verde forest on the Luquillo Mountains of Eastern Puerto Rico. They give no details of the nature of the forest composition, but recorded throughfall at the forest floor by means of two raingauges. Canopy rainfall was measured by one standard tipping-bucket raingauge. Over a 210-day period,1840mm of rain were recorded at canopy level, 370 mm at the forest floor; interception was therefore 25%. No measurement of stemflow is mentioned.

Also in the El Verde forest, Sollins & Drewry (1970) studied the water balance of some individual tree canopies. A catch funnel was mounted on a 92 ft tower, well above the canopy, to collect rainfall, water being routed to an 8-inch tipping.bucket at the base of the trees. Throughfall was also measured by two unmodified gauges (also presumably 8-inch) collecting the catch from 16 collectors placed in a circle. Stemflow was recorded by means of a 1 inch rubber hose attached around the tree.

A twelve-month study of one tree of the species **Manilkara bidentata** (Ausubo) showed that of the incoming rainfall, about 50% penetrated the canopy as throughfall **Dacryodes excelsa** (Tabonuco) and **Croton poecilanthus** (Sabiñon), studied during the relatively wet summer months, showed much less tendency to intercept rainfall (70% throughfall,1% stemflow) depending, however, on the intensity and duration of the rain.For the Manilkara, there was also much variation in monthly interception totals, which range from 30% to 80% of gross precipitation.

Sollins & Drewry also quote results obtained by Clegg (1963) who, in a 130-inch annual rainfall region of montane forest (El Yunque) recorded an interception percentage of 54% (varying from 42 to 77%).

Clements & Colon (1975) reported further results from the El Verde forest. In a 20 x 20 m plot, six troughs (8 inches wide, 24 feet long, 10% slope) of galvanized metal collected throughfall; gross rainfall was measured by a 1 m^2 stainless steel collector mounted on a 72 ft tower. All trees with dbh of 3 inches or more (45 trees altogether) were fitted with stemflow collars.

Clements & Colon calculated the regression of throughfall and stemflow on gross rainfall for 137 storm events over a 12-month period. Throughfall varied from 67% for a storm of 0.1 inch to 92.5% for a 1 inch storm; stemflow as a percentage of rainfall, varied from 1.4% for a 0.5 inch rainfall to 5.1% for a 1 inch storm. The goodness of fit of the linear regressions quoted by Clements & Colon cannot be assessed,and their diagrams show only the lines without any accompanying scatter of 137 events. Depth of canopy storage was estimated as 1.2 mm (0.03 inches).

On the Central American mainland, Read (1977) carried out a microclimatic study near the site of the dam on the Bayano Riber, 70 km east of the Pacific entrance of the Panama Canal. The forest has been uncut up to 1973, but in the dry season January-April 1974 there was extensive clear cutting, followed in 1974 and 1975 by secondary growth of large-leafed and soft wood trees. Gross rainfall was measured by one standard gauge above the canopy, and throughfall was measured some 500 m away by means of a heavy sheet metal trough, 10 m long and 10 cm wide; stemflow, it appears, was not measured. For the year May 1973-April 1974, rainfall at the top of the canopy was 2031 mm, with total throughfall 1187 mm (interception was 844 mm, 42%). For the following year, gross rainfall was 2016 mm with throughfall 1047 mm (interception 969 mm, 48%).

ASIA

In West Pakistan, Raeder-Roitzsch & Masrur (1969) described a study in a 0.4 acre stand of medium-aged (40-50 years) Chir pine (**Pinus roxburghii**). The stand was at an elevation of 5500 ft on a northwest facing 25^0 slope; average height of the trees was 60 ft, and mean dbh 15 inches. Mean rainfall at the site was about 50 inches.

Five raingauges (5-inch diameter standard) were rotated at random amongst 25 points lying on an 8 ft grid underneath the canopy. Gross rainfall was measured by two 5-inch gauges in a large clearing near the forest site; stemflow was measured on three randomly-selected trees by means of collar attachments which fed the stemflow into the drums.

For the year December 1967 to November 1968, net rainfall under the trees was 92%; in absolute terms, net rainfall was 53 inches out of a gross rainfall of 57.55 inches. After subtracting the very small amount of stemflow, interception loss was 8% of gross rainfall. The low figure was ascribed by Raeder-Roitzsch & Masrur to the openness of the Chir pine stand (canopy closure 0.4).

Elsewhere in the Indian subcontinent, Ray (1970) worked in two pure stands: one of **Shorea robusta** (plot area 83 m^2 containing 14 trees at a density of 1678 trees per hectare; average tree height in December 1968 was 8.7 m, and average girth at breast height 34 cms) and the other of **Alstonia scholaris** (plot area 400 m^2 containing 67 trees at a density of 1675 trees per hectare; average tree height was 8.3 m, and average girth at breast 48 cm). The two plots were about 500 m apart.

Daily rainfall was measured by a standard gauge in the open, being sited 118 m and 590 m from the plots. Throughfall was measured in small troughs (35 cm x 24 cm x 11 cm deep) placed randomly on the floors of the plots; 36 such troughs were placed in the larger plot, 12 in the smaller. Stemflow was also measured by conical tin collars fixed to tree stems, but the number of trees measured is not stated.

Measurements were taken in the two rainy seasons of 1967 and 1968. Total interception losses are not given, but losses are given for rainfall "groups" of increasing magnitude; for storms between 1 and 10 mm, interception losses for **A. scholaris** and **S. robusta** were 30.9% and 33.7% respectively.

Low (1972) studied interception losses in the humid forested area at Lawiu, in the Sungei Lui Catchment, West Malaysia.

No account of the forest composition is given; one raingauge recorder was placed under a 25 ft specimen of **Shorea curtisii**, with its funnel above the canopy, whilst 3 non-recording gauges (dimension unspecified) were placed randomly under the canopy to measure throughfall. Stemflow was apparently not measured. During the period 17 April 1969 to 11 September 1969, for which unbroken records were available, gross rainfall was 38.89 inches, with an interception loss of 14.27 inches, representing 36% of rainfall.

Low's results must be open to some doubt. Of the three ground-level gauges, one was stolen shortly after the work began, and another was removed. For the period defined above, therefore, the instrumentation was limited to one gauge recording gross rainfall, and one recording throughfall. The questionable nature of the results is also suggested by the fact that between 21 and 28 August 1969, zero interception was recorded although 3 inches of rain were measured.

Elsewhere in Malaysia, Kenworthy (1969) reported results from a 31.5 ha site of Hill Dipterocarp Forest in the Ulu Gombak Forest Reserve, Selangor. The area lies between 800 and 1800 ft, the lower slopes having been selectively felled some 12-15 years previously, while the upper reaches remained under primary forest. Rainfall was measured by an unspecified number of raingauges; no information is given regarding their position. Throughfall was apparently measured by an unspecified number of 1 metre square trays. Stemflow was not measured. For the period August 1968 to January 1969, rainfall is quoted as 2500 mm, and interception as 450 mm (18%); this estimate of interception loss must be regarded with some reserve, however, both because of the absence of any justification for neglecting stemflow and because of the absence of information about the instrumentation used.

Tangtham (1981) states what will already be clear to readers of this paper. "The proportion of rainfall intercepted by tropical forests is very variable. In tropical Southeast Asia, interception measured in Thailand indicated high values of 63 per cent gross annual rainfall for the natural teak forest, 61 per cent for dry dipterocarp; 9 per cent for hill-evergreen forest; and only 4 per cent for the dry evergreen forest (Chunkao **et al**.,1971). This kind of investigation in the lowland rainforest of Malaysia gave a value of 22 per cent (Manokaran, 1979). It was also stated by Raros (1979) that intercepted water may exceed 60 per cent of gross rainfall for the humid tropical forest in the Philippines".

Finally, results are becoming available from a collaborative study between the United Kingdom Institute of Hydrology and the Indonesian Institute Pertanian Bogor IPB (Calder **et al**.,1981). A site has been instrumented in the Janlappa Nature Reserve, about 55 km north-west of Bogor at an altitude of 60-80 m above sea level. The reserve, containing one of the few remaining areas of lowland tropical rainforest in West Java, is 32 ha in extent, and is divided into 21 blocks by inspection paths of 3 m width.

Gross rainfall, net rainfall, and other meteorological variables are recorded at 5-minute intervals by two automatic weather stations; these have been modified somewhat from a standard Institute of Hydrology device. One weather stations is mounted in a clearing, over scrub vegetation, whilst the other is mounted above the forest canopy on a 14 m bamboo tower. Beneath the canopy are two large (37.7m^2) plastic net-rainfall gauges, which record the total of throughfall and stemflow.

Calder **et al.** show some of their extensive data on 5 minute totals of gross and net rainfall. For the month of September 1980, the measured interception ratio was 12.6%; however, September is on average the driest month at Janlappa, and further data are being collected to determine an annual interception ratio.

DISCUSSION

The results do not appear to be indicative of any consistent pattern, nor is it clear whether the differences can be attributed to measurement errors or whether they are real differences. It is also not possible to determine whether, if they are real differences, they are caused by differences in climate or forest structure. It might be helpful to consider the likely causes of differences in interception loss; using the framework of Gash (1979) simplified by Shuttleworth (1979, Equation 73) with the further simplification that small storms which do not saturate the canopy are neglected, the interception loss can be expressed as: $I = \frac{\bar{E}}{\bar{R}} P + nS$ where $\bar{E}$ and $\bar{R}$ are mean evaporation and rainfall rates during rainfall, n is the number of rainfall events and S is the canopy capacity. In temperate climates typified by long periods of low rainfall, the two terms on the right hand side of this equation contribute about equally to the total loss. However, in a climate dominated by local convective rainfall, with short-duration, high intensity storms, $\bar{R}$ will be perhaps an order of magnitude greater than the typical 1-2mm/hour found in temperate climates, and this might be expected to increase the relative size of the second term. Little is known about the size of $\bar{E}$ under tropical conditions; low wind speeds would tend to decrease it (see the Mauritius work above), higher radiation and vapour pressure deficits would tend to increase it. Conversely, in a monsoon-type climate with relativly few rainfall events but of long duration, the first term in the equation might be expected to dominate. The above argument suggests that future studies of tropical interception should include not only measurements of rainfall **rate** and an attempt at measurement of canopy capacity, but also meteorological measurements to enable the estimation of evaporation rate during rainfall.

It is clear that the loss, by evaporation, of rainwater intercepted by a tropical forest canopy can in some cases represent a considerable proportion of gross rainfall. It is important, also, to remember that any quoted interception ratio represents one aspect only of water loss from the forest; if, during any given time interval, there had been no rain, there would have been no interception loss, but water would still have been lost by transpiration. It is therefore necessary to consider the total water loss through both interception and transpiration, if forest water use is to be assessed adequately.

Where the interactions between wet leaves and the atmosphere (of which interception loss is a phenomenon) and between dry leaves and the atmosphere (of which transpiration loss is a phenomenon) are to be considered together, then the most satisfactory way in which total water loss can be assessed is by description of the processes in physical terms. Their complexity has been well described by Jackson (1975, op. cit.), who also sets out the difficulties of obtaining the measurements necessary for implementation of (for example) the Rutter model, which requires hourly gross rainfall, wind run and hourly mean temperature, humidity and net radiation above the canopy. "The comprehensive approach of Rutter ... may be limited in terms of application elsewhere, because such complete instrumentation is impossible" (Jackson, 1975).

Whilst the difficulties of assessing the total water loss from tropical forests should not be underestimated, they should not be exaggerated either. During the six years since Jackson wrote the above quotation, great advances have been made in the reliability and portability of the necessary hydrological instrumentation. Solid state memory for instruments with low power requirements, and with batteries rechargeable by solar power, is now a reality, and it will be unfortunate if work such as that of Calder (1981, op.cit.) is not repeated elsewhere within tropical forests, representing as they do an immensely important natural resource.

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RESUMO

É feita uma revisão da literatura sobre medidas de processos de intercepçao da água da chuva por florestas. São apresentadas informações da África, da América Central e do Sul, e da Ásia. É feita uma análise geral e são mostradas as necessidades de aprofundamento de medidas em condição de campo.

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